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COMPOSITES THEORY AND PRACTICE

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INSPECTION METHODS FOR QUALITY CONTROL OF FIBRE METAL LAMINATES (FML) IN AEROSPACE COMPONENTS

The advantages of FML structures (e.g. GLARE or CARAL) come from the improvement in durability of such structures, however, in such structures failure modes may also occur. Failure modes which may occur in such structures are similar to those in epoxy composites but some of them are associated with fracture mechanics similar to e.g. aluminium alloys. The quality control of materials and structures in aircraft is an important issue, also for FML laminates. For FML parts, a 100% non-destructive inspection for internal quality during the manufacturing process is required. In the case of FML composites, the most significant defects that should be detected by non-destructive testing are porosity, delaminations and cracks. In this paper, the use of non-destructive different methods for the inspection of Fibre Metal Laminates was presented. The novelty in the approach will include the use of multimode and highly specialized inspection methods such as: ultrasonics, thermography, air-coupled ultrasonics, and X-ray tomography.

Keywords: **Fiber Metal Laminates, non destructive testing, failure modes in composites**

METODY BADANIA WŁÓKNISTYCH KOMPOZYTÓW METALOWYCH (FML) DLA OCENY KONTROLI JAKOŚCI W KONSTRUKCJACH LOTNICZYCH

Zalety stosowania struktur FML (np. GLARE, CARALL) wynikają ze zwiększonych własności wytrzymałościowych takich struktur, jednakże w takich strukturach mogą również wystąpić uszkodzenia. Uszkodzenia, jakie mogą wystąpić w takich strukturach, są zbliżone do tych, które występują w kompozytach epoksydowych, jednakże niektóre z nich są związane z mechaniką pękania zbliżoną do analogicznej problematyki w stopach aluminium. W przypadku konstrukcji lotniczych kontrola jakości jest istotna również dla materiałów FML. Dla takich materiałów wymagane jest badanie całości struktur w szczególności podczas wytwarzania. W przypadku kompozytów FML uszkodzenia, jakie powinny być wykryte dzięki badaniom nieniszczącym, to porowatość i rozwarstwienia oraz pęknięcia. W artykule przedstawiono podejście do badań takich materiałów wykonanych z FML z wykorzystaniem badań metodami nieniszczącymi. Nowość w podejściu do badań to wyniki badań otrzymane różnymi metodami, w tym wysoko specjalistycznymi i takimi jak: ultradźwięki, termografia ultradźwięki propagujące w powietrzu i tomografia komputerowa.

Słowa kluczowe: **laminaty FML, badania nieniszczące, uszkodzenia w kompozytach**

INTRODUCTION

Composite materials have been applied in aerospace structures in recent years. Currently, the new generation of structural composite materials for modern aircraft which is under consideration are Fibre Metal Laminates (FML). The example of such a material is **GLARE** (**GL**ass/-fibre-reinforced-polymer/**A**luminium **RE**inforced). This particular material is a hybrid laminate consisting of thin aluminium layers and a fiber-reinforced epoxy composite. The metal often used for FML is aluminium, and the fibers are glass, Kevlar or carbon. FML with Kevlar fibers are called **ARALL** (**AR**amid/-fibre-reinforced-polymer/**AL**uminium **L**aminates) and with carbon fibers they are called **CARAL** (**CA**rbon/-fibre-reinforced-polymer/ **R**einforced **A**luminium **L**aminates). The considered application of FML for structural use in aircraft structures comes from the benefits over aluminium alloys which are low in weight and have good mechanical properties (high damage tolerance: fatigue and impact characteristics, corrosion and fire resistance). FML composites are built as laminar structures and sandwich structures [1, 2]. An FML layered structure is particularly susceptible to the possible occurrence of failure modes. As a result of the influence of compression stress, delaminations may occur. In consequence of impact damage or fatigue loads, cracks in the aluminium layers may arise [3-5].

The quality control of materials and structures in aircraft is an important issue, also for FML laminates. For FML parts, a 100% non-destructive inspection for internal quality during the manufacturing process is required [6, 7]. In the case of FML composites, the most significant defects that should be detected by non-destructive testing are: porosity, inclusions and delaminations as well as cracks in the aluminium layer. In this paper, a multimode approach for the inspection of a prepared control panel with the use of highly specialized, non-destructive testing methods are presented. The main goal of the investigation procedure presented in this paper was to show the possibilities of selected NDI techniques used in field and laboratory inspections of FML laminates. Moreover, detailed analysis of the accuracy of the selected techniques is presented.

EXPERIMENTAL PROCEDURE

For the purpose of the test, an FML control plate was prepared with different simulated failure modes (such as insert for modeling foreign object inclusion - or "*delamination*"). The control plate was manufactured by stacking alternating layers of 2024T3 aluminium alloy (0.3 mm per sheet) and T700GC-carbon fiber/epoxy prepregs (0.131 mm thickness; Hexcel Co., USA).

The defects (foreign object inclusions - FOD) were made from polytetrafluoroethylene and aluminium films of different sizes and thickness. The lay-up scheme, dimensions and specifications of the investigated plate are shown in Figure 1.

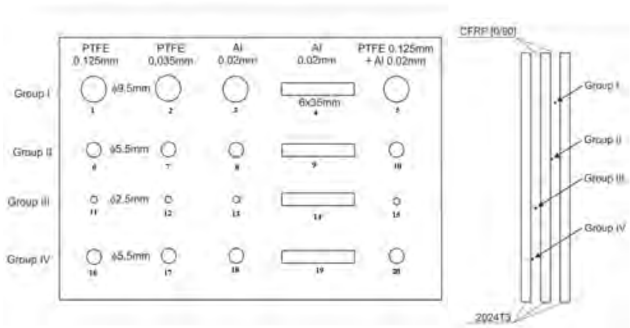


Fig. 1. Scheme of investigated FML laminate with modeled defects

Rys. 1. Schemat laminatu FML z symulowanymi wadami

As can be seen, there are groups of damages of different diameters as well as different materials and located at different depths. Such a layout enables the use of selected NDI techniques for efficiency description based on structure specification as well as based on material properties which influence the propagating signals. Each of the damages was labeled with a consecutive number for identification purposes.

The FML composite was produced at the Department of Materials Engineering - Lublin University of Technology by the autoclave technique (Scholz Maschinenbau, Germany) with the following parameters: heating and cooling of 2°C/min, curing of 2 h at 180°C, pressure of 700 kPa and vacuum of 20 kPa.

The approach for the inspection took into consideration the following NDI techniques:

- Ultrasonic (single sensor pulse echo technique with delay line)
- Impulse Thermography
- Air Coupled Ultrasonic
- X-Ray tomography (CT)

INSPECTION OF LAMINATE

Figure 2 shows the FML laminate after the curing cycle in the autoclave. Visual observations do not show any indication of failure mode presence in the structure.

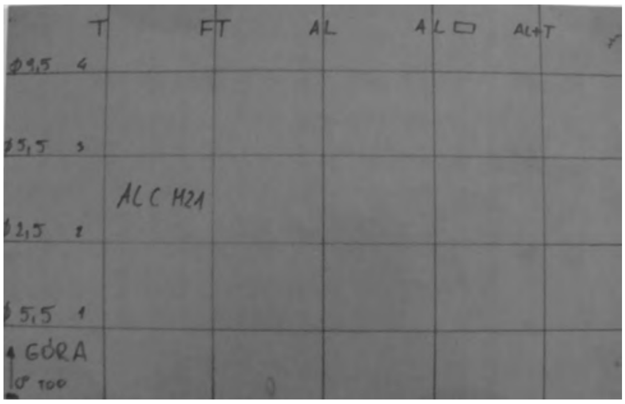


Fig. 2. Fibre Metal Laminate control plate

Rys. 2. Próbka badawcza wykonana z laminatu FML

The structure was inspected with single side access from the top side of the Group I damages location. For such a configuration it is possible to characterize the effect of the depth of the damage location on the detection capability of different methods (for similar size damages as group II and IV). Damages were located on the boundaries between the CFRP layers direction 0 and 90 (Groups I and III) as well as between the CFRP and the aluminium layer (Group II and Group IV).

The inspection was conducted with the use of automated scanning systems used in the NDE Laboratory of the ITWL (ultrasonic, thermography) as well as highly specialized techniques used in ILK TU Dresden (air coupled ultrasonic, X-Ray computer tomography).

- **Ultrasonic single sensor inspection results**

Ultrasonic single sensor inspection with the use of a 5 MHz central frequency was selected for the first structure inspection. Ultrasonics is one of the most suitable technologies for multilayer structure inspection when taking into consideration the possibility of damage detection, costs and accuracy, reliability and time required for inspection. However, it has to be highlighted that for higher sensitivity, a higher frequency should be used whereas for multilayer structures, the use of higher frequency greatly increases the acoustic signal attenuation. Frequency selection should be a compromise between the attenuation and the inspection resolution (accuracy in flaw characterization). The formula which theoretically helps to calculate the appropriate frequency for the inspection in fiber laminates may be expressed as follows [8]:

$$\lambda \cong n * d\,[\text{mm}]; \quad n \in N_+ \qquad (1)$$
$$f = \frac{c}{\lambda}\,[\text{Hz}]$$

where:
λ - wavelength of acoustic wave in material,
d - thickness of composite layer,
n - typically equals 4÷5.
Based on the material data such as: d÷0,131 mm and c÷2800 m/s, the calculated frequency for n = 4 equals 5 MHz.
Another issue in frequency selection is the influence of the layer thickness on multiple reflections (resonances) which due to the interferences, make inspection more difficult. Moreover, the thin layer structure of aerospace components requires the use of delay lines or focus transducers for the inspection.

For the data collection and presentation, an automated scanner enabling autonomous data collection and signal display in the selected visualization mode (C-scan) was used. The results of the inspection are presented in Figure 3a and C-scan data imaging. In Figure 3b the processed image based on the Signal to Noise Ratio SNR coefficient is calculated [5]. The use of such a signal coefficient highlights the damage visibility in the results of the signal processing. Moreover, the use of such criterion for signal processing enables data sizing and data comparison required for structure integrity monitoring.

As can be noticed, not all the damages are clearly visible (based on the 6dB SNR criteria). The Signal To Noise Ratio was calculated based on the following formula:

$$SNR\,[\text{dB}] = 20\log_{10}\frac{f(x,y)\_S}{f(x,y)\_B} \qquad (2)$$

where:
$f(x,y)\_S$ - average value of signal amplitude in damaged area,
$f(x,y)\_B$ - average value of signal around damage area (noise value).

In the results presented above, the total 14/20 (detected/overall) results were achieved which equals 70% damages detected. Mostly the inserts made of aluminium film were not detected. Moreover, a large diversity in the reflected amplitude of the inserts was observed which makes damage size characterization difficult.

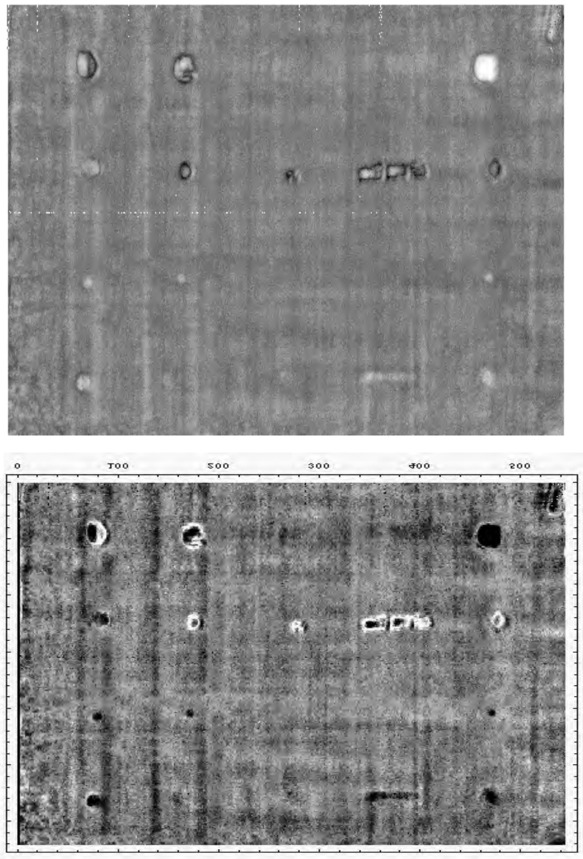
a)
b)


Fig. 3. Pulse echo single sensor ultrasonic results

Rys. 3. Wyniki badań z wykorzystaniem metody ultradźwiękowej (odbicia i pojedynczego czujnika)

- **Impulse thermography inspection results**

For the impulse thermography, the field deployable inspection system was used. As the excitation source, quartz flash lamps with a total 5 kJ energy were used, as well as a highly sensitive IR camera. The setup for the camera, as well as the flash duration is computer controlled. The exposure time was equal to 0.4 s with a maximum energy flash from the lamps. The setup was used from the experiment on aluminum bonded structures without FOD inspection. The inspection was based on flash thermography and Time Signal Reconstruction software. The result of the inspection as a time still image is presented in Figure 4.

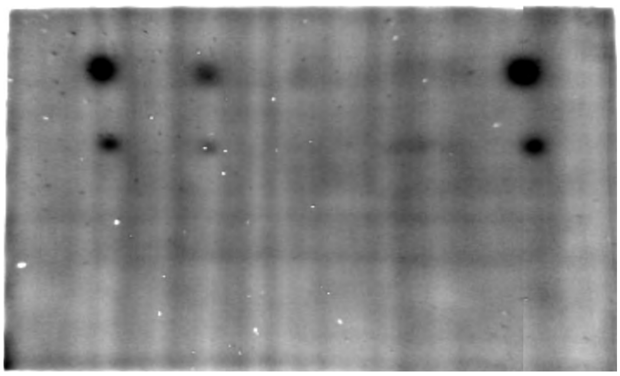


Fig. 4. Thermography Inspection Results

Rys. 4. Wyniki badania metodą termografii impulsowej

As can be noticed in Figure 4, indication of the damages in the two bottom rows is not visible, neither are the indications from columns 3 and 4 from the left in the two top rows. Such results are connected with the thermal phenomena which is the heat dissipation in the aluminum layers as well as in the carbon layers. That briefly means that damages located deeper in the structure may not be visible with thermography. The difficulty in finding damages especially in the top row similarly to the ultrasonic method may be associated with the larger amount of resin in the damage area, which influences heat dissipation in the potential damage area. Another issue is the fact that the undetected damages are made from aluminum inserts with a thermal conductivity similar to the composite metal layer. There are some shadings visible (damage contours similar to ultrasonic) but based on that indication, it is difficult to infer about the presence of damage. The detectability of the method was equal to 30%.

- **Air coupled ultrasonics**

Air coupled ultrasonics uses low frequency acoustic waves which may travel in the air. When acoustic waves go through the interface between two media, only a part of the sound is transmitted, the rest of the sound is reflected. The relation of the wave behavior on the media interface may be described with the use of the following formulas on the reflection (*R*) and transmission coefficient (*T*) based on the definition of the material acoustic impedance [9].

$$R = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad (3)$$

$$T = \frac{2Z_2}{Z_1 + Z_2} \quad (4)$$

$$Z_i = \rho_i c^{(i)_l} \approx \sqrt{\rho_i E_i} \quad (5)$$

The acoustic impedance is the value which describes the material stiffness (expressed as the product of material density ρ and Young's Modulus E_i or acoustic wave longitudinal velocity in the media - c). Depending on the acoustic impedance ratio, the value of the transmission/reflection coefficient on the media interface is going to change [10].

Moreover, the structural material imperfections act as the local impedance change, affecting the amplitude of the collected signal (attenuation). The reasons for the attenuation of the acoustics waves in the media for linear acoustics assumption are as follows [10]:
- Reflection from acoustics boundaries
- Absorption (material properties dependant)
- Scattering at discontinuities (size similar to wavelength)
- Diffraction (depending on material properties)

Inspection with the use of air coupled ultrasonics takes into consideration the measurements inthe signal amplitude changes which are affected by the abovementioned factors.

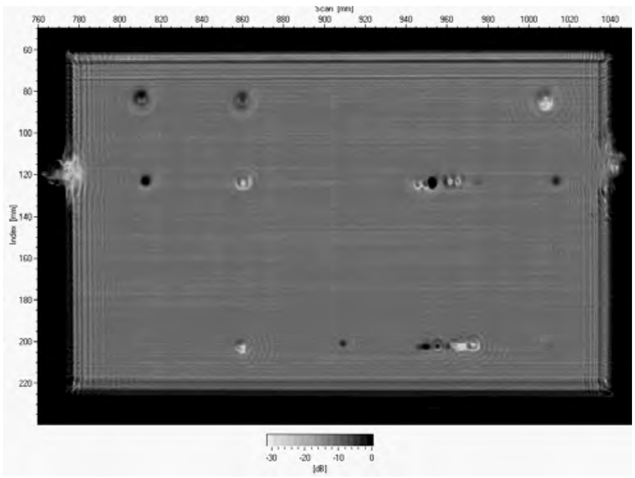


Fig. 5. Air coupled ultrasonic inspection results

Rys. 5. Wyniki badania metodą ultradźwiękową (sprzężenie powietrzne)

One of the main advantages of the use of air coupled ultrasonics in the composite inspection is the use of low frequency waves travelling through the material. In the case of composite materials with a higher attenuation or a multilayer material, the inspection may be easier due to the lower attenuation of the acoustic wave. On the other hand, the transmission technique used in this method does not allow one to determine the depth of the failure mode location. Additionally, the effects of scattering especially on the edges of the failure may distort the damage size evaluation (see the scattering pattern on the edges of the damages - Figure 5). Finally a small frequency gives lower resolution results (which means possible detectability of larger size defects than in MHz range).

- **X-Ray computer tomography (CT)**

X-Ray tomography is regarded as one of the best NDT techniques for structure characterization. There are some limitations to laminates inspection (especially for delamination detection). However, this technique enables 3D material characterization due to the turntable positioning of the object relating to the radiation source. The use of special software gives the possibility of enhanced object reconstruction and image processing (such as: cross-section analysis, slice processing, region of interest analysis etc.)

Due to the high spatial resolution nature of the CT signal, the results of the CT were used for damage size verification in the control panel. The results of the inspection with CT are presented below.

Figure 6 presents the location of the damages labeled as no 13 and 18 in Figure 1. The picture on the left presents a cross-section of the analyzed area around the mentioned damages. CT enables detailed cross-section analysis which shows the damage shape, location and structure. The picture to the right presents the top view of the damages which is similar to the C-scans presented in the previous section. The damages are located in different layers which is clearly visible on the cross-section image of the CT.

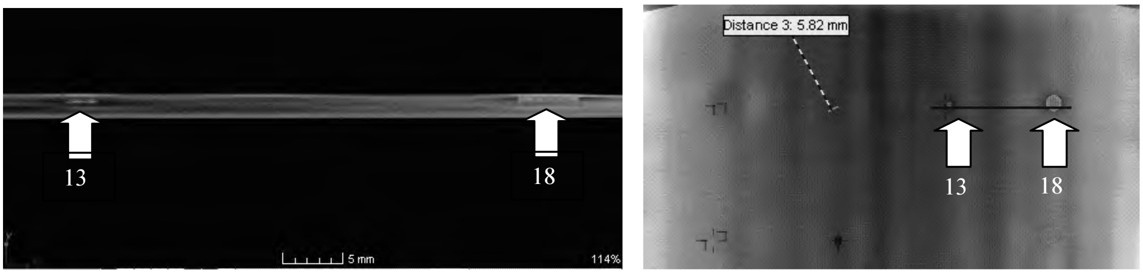


Fig. 6. CT results of FML inspection

Rys. 6. Wyniki badania FML metodą tomografii komputerowej

Figure 7 presents the results of the measured values of the damages with CT vs the expected size of the manufactured damages in the control plate. Verification of the size of the selected 6 damages gave the result of a mean error value equal to 6%. Due to the lack of data about the exact size of the mentioned damages, the error estimation data obtained from the CT may be used as a boundary condition for the accuracy estimation of the selected techniques.

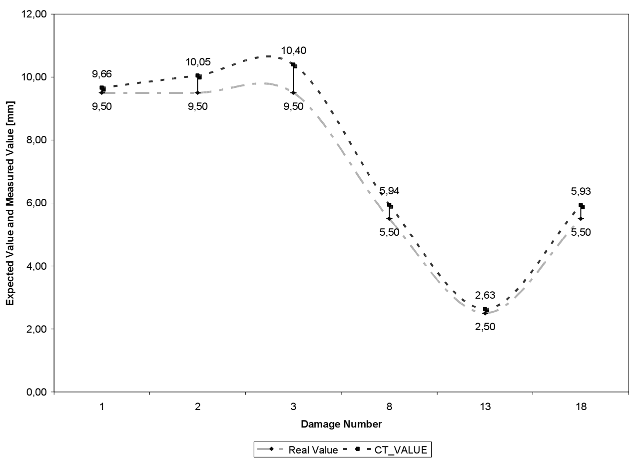


Fig. 7. Results of damage size estimation with CT vs real size

Rys. 7. Wyniki wyznaczenia rozmiaru uszkodzenia z wykorzystaniem CT i rozmiaru rzeczywistego

DISCUSSION OF ACHIEVED RESULTS

The prepared control plate was tested with multi-mode inspection. First, CT tomography was employed in order to verify the capability of finding the damage location as well as to estimate the size of the damage. The main issue in NDI delivery is the estimation of the Probability Detection of the Damage of a certain size (PoD) or the damage detection capabilities of a selected method. Next, there is the estimation of the damage size. Figure 8 presents the achieved results of the damage detection capabilities of the described damages in the FML panel. The presented results are described for: pulse-echo ultrasonic, air coupled ultrasonic and impulse thermography. As can be noticed, none of the applied techniques achieved complete detection of all the damages. The average values in the described detectability are the following:

- Pulse - Echo ultrasonic - 70 % damages detected
- Air Coupled Ultrasonic - 50 % damages detected
- Impulse Thermography - 30 % damages detected

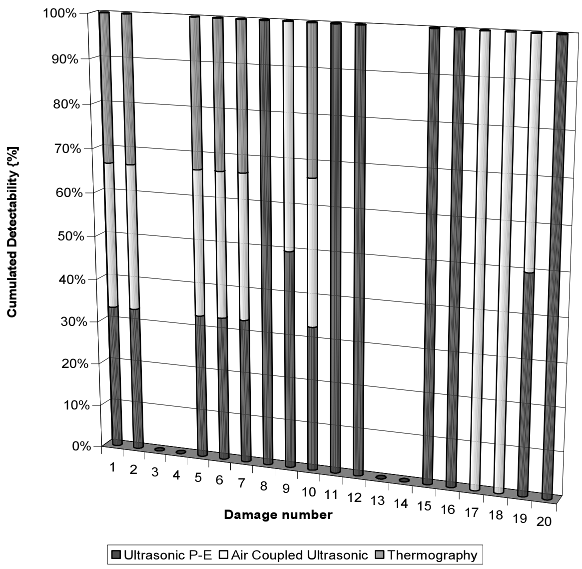


Fig. 8. Results of cumulated damage detection capabilities

Rys. 8. Połączone wyniki możliwości wykrycia poszczególnych metod

The low detectability of the thermography is connected with the high thermal emissivity of the aluminum alloy layers. Additionally, carbon fiber layers give a much higher thermal conductivity along the direction of the fibers which makes thermal expansion inside the structure difficult. For the considered panel, only the two top layers of the damages were detected. Moreover, the PTFE film inclusions were only detected, whereas the aluminium inserts, which have similar thermal properties to the metal layers, were not visible in the image.

For the ultrasonics (air coupled and single sensor), a higher detectability was achieved. However, similar groups of inserts were found. The reason for the much worse detectability of the aluminum inserts may be explained as the greater influence of resin penetration in the inserts structure which makes acoustic impedance (Eq. (5)) mismatch smaller. That makes the amplitude of the reflected signal much smaller over the background noise (difficulty in SNR determination). Such phenomena was observed mostly for aluminium inserts, especially for the aluminium rectangle shape inserts (no 4, 9, 14, 19 where only two were found), the 6 dB value of the SNR was fulfilled mostly on the edges of the inserts. In connection with that, the estimated size of the damage was much smaller than the expected value. Therefore, this group of damages was not included in further damage size analysis.

For the purpose of the signal processing technique verification it was assumed that the damages were manufactured with the described size. Based on such an assumption, the study of the damage size estimation for the CT, UT and Air Coupled UT was presented. For the CT, the use of specialized software for verification of the selected damage size estimation was used. The average value of CT error calculated for 6 selected damages was equal to 6%.

The size estimation of the damages detected with UT and Air Coupled UT was calculated with the use of an automated image processing procedure which fulfills the criteria presented in Equation (2).

The results of the relative error estimation of selected damages for the ultrasonic Pulse Echo and Air Coupled Ultrasonic (and detected damages) are presented in Figure 9. The average value of error in the size estimation was equal to 18% for the ultrasonic and 68% for the Air Coupled Ultrasonic. The main reason for these results is connected with the alternating attenuation of the ultrasonic signal. Damages which were created with the use of inserts in the intra-laminar structure may be acoustically distorted during the curing process (resin flow affects structure of insert). The process of size determination was based on the 6 dB signal to noise damage quantification which was not fulfilled for all the implemented damages. A larger error value for the size estimation (much smaller size of the damages) in the air coupled ultrasonic method was connected with the large size of the transducer which was used for inspection. This is a typical problem of the damage size in ultrasonics. From the point of view of damage size estimation, the best accuracy is achieved when the transducer size is at least two times bigger than damage size [9].

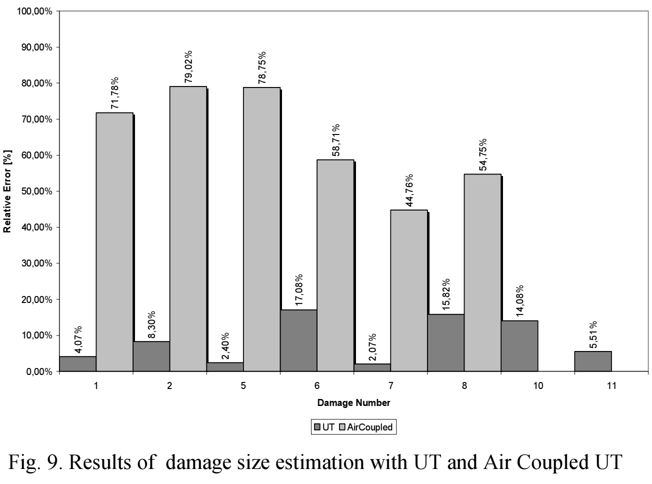


Fig. 9. Results of damage size estimation with UT and Air Coupled UT

Rys. 9. Wyniki wyznaczenia rozmiaru uszkodzenia z wykorzystaniem UT i Air Coupled UT

Taking into account the above mentioned data, important information obtained during the inspection of the specimen is following:

- for the inspection of the laminates, from the maintenance point of view, the ultrasonic method shows the best performance,
- there is a necessity to estimate the balance between the frequency and required resolution for the ultrasonic inspection taking into account the inspected structure materials,
- average value of error for the ultrasonic size estimation was equal to 18%,
- air coupled ultrasonics is a relevant tool especially for high attenuative materials. Limitations are connected with a lower resolution of inspection,
- calculated error of the damage size estimation for the Air Coupled UT was bigger than for the single sensor UT mainly due to the large size of the transducer,
- CT proved the highest accuracy, however, a cost/accuracy benefit is not achievable.

At present, further work is going to be conducted for the design of the set of specimens with an accurate size of damages for methods classification. The aim of this task is to create models for damage size accuracy estimation which is an important part of the damage tolerance philosophy of aircraft maintenance.

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REFERENCES

[1] Dragan K., Bieniaś J., Sałacinski M., Synaszko P., Inspection methods for quality control of fibre metal laminates in aerospace components, Research Journal of the Polish Society of Composite Materials, Quarterly, 2011, 2, 130--135.

[2] Vogelesang L.B., Vlot A., Development of fibre metal laminates for advanced aerospace structures, J. Mater. Process. Technol. 2000, 103, 1-5.

[3] Villanueva G.R., Cantwell W.J., The high velocity impact response of composite and FML-reinforced sandwich structures, Composites Science and Technology 2004, 64, 35-54.

[4] Song S.H., Byun Y.S., Ku T.W., Song W.J., Kim J., Kang B.S., Experimental and Numerical Investigation on Impact Performance of Carbon Reinforced Aluminum Laminates, Science Direct J. Mater. Sci. Technol. 2010, 26(4), 327-332.

[5] Botelho E.C., Silva R.A., Pardini L.C., Rezende M.C., A review on the development and properties of continuous fiber/epoxy/aluminum hybrid composites for aircraft structures, Mat. Res. 9, 3 São Carlos July/Sept. 2006.

[6] Sinke J., Some inspection methods for quality control and in-service inspection of GLARE, Appl. Comp. Mater. 2003, 10, 277-291.

[7] Ibarra-Castanedo C., Avdelidis N.P., Grinzato E.G., Bison P.G., Marinetti S., Plescanu C.C., Bendada A., Maldague X.P., Delamination detection and impact damage assessment of GLARE by active thermography, 4th International Conference on non-destructive testing, October 2007, Crete, Greece.

[8] Mierzwa J., Michnowski W., Badania ultradźwiękowe zbiorników kompozytowych, Seminarium UDT, Wrocław, czerwiec 2005.

[9] Graff K.F., Waves Motion in Elastic Solids, Dover Publications, Inc., New York 1991.

[10] Stoessel R., Air Coupled Ultrasound Inspection as a New Non Destructive Testing Tool for quality assurance, PhD dissertation, Stutgart University, 2004.

