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METHODS OF ULTRASONIC TESTING, AS AN EFFECTIVE WAY OF ESTIMATING DURABILITY AND DIAGNOSING OPERATIONAL CAPABILITY OF COMPOSITE LAMINATES USED IN AEROSPACE INDUSTRY

METODY BADAŃ ULTRADŹWIĘKOWYCH, JAKO EFEKTYWNY SPOSÓB SZACOWANIA TRWAŁOŚCI ORAZ DIAGNOZOWANIA ZDOLNOŚCI EKSPLOATACYJNYCH LAMINATÓW KOMPOZYTOWYCH STOSOWANYCH W LOTNICTWIE*

The paper presents selected issues in the field of exploitation research and the prediction capabilities of durability of composite laminates by ultrasonic methods used in the aerospace industry. Some research methods allow to set the quality parameters and operating in real aircraft structures. The study determined the relationship between the amplitude decrease of the ultrasonic wave and the level of porosity for hand lay-up manufactured glass / epoxy laminate using the method Through-Transmission of representative in C (TT C-Scan). In addition, showing the ability of amplitude attenuation imaging methods to detect and determine the extent of damage of high quality laminate and metal fiber composite after at low-dynamic velocity. It was specified real area an internal damage in FML laminates subjected to dynamic impact on low-energy, for which there was no visible damage in the outer layers. The study also determined the relationship between energy and the impact of dynamic surface area in testing laminates.

Keywords: *composites , impact resistance, porosity, ultrasonic testing.*

W pracy przedstawiono wybrane zagadnienia z zakresu badań zdolności eksploatacyjnych oraz prognozowania trwałości metodami ultradźwiękowymi laminatów kompozytowych stosowanych w przemyśle lotniczym. Wybrane metody badawcze umożliwiają określenie parametrów jakościowych jak i eksploatacyjnych rzeczywistych struktur lotniczych. W pracy określono zależność pomiędzy wartością spadku amplitudy fali ultradźwiękowej a poziomem porowatościdla wytworzonego metodą laminowania ręcznegolaminatu szklano/epoksydowego przy użyciu metody Through-Transmissionw zobrazowaniu w trybie C (TT C-Scan). Dodatkowo pokazano zdolność metody obrazowania tłumienia amplitudowego do wykrywania i określania wielkości uszkodzeń wysokojakościowych laminatów kompozytowych i metalowo włóknistych po uderzeniach dynamicznych o niskich prędkościach. Określono rzeczywiste pola powierzchni uszkodzeń wewnętrznych laminatów FML poddanych uderzeniom dynamicznym o niskich energiach, dla których nie odnotowano widocznych uszkodzeń w warstwach zewnętrznych. W pracy wyznaczono również zależność pomiędzy energią uderzenia dynamicznego a polem powierzchni uszkodzenia badanych laminatów.

Słowa kluczowe: *kompozyty, odporność na udar, porowatość, badania ultradźwiękowe.*

1. Introduction

The modern aircraft structures belong to those main fields of technology where the performance and reliability characteristics are of primary importance. This is due to ensuring an adequate level of stability and safety of aircrafts. Materials engineering developing innovative technologies and advanced materials plays particularly important role in this area.

Composites are a leading and prospective group of construction materials used in the aerospace industry. Among them, the biggest development trend is attributed to fibre reinforced polymer matrix composites and to hybrid materials. This is due to the modification of the physical and mechanical characteristics influenced by the introduction of the reinforcement to the matrix, considering the tendency to reduce the density of a finished composite product. The composites are characterized by high strength-to-density ratios, unattainable for other groups of materials [6, 22, 32, 35].

Currently, a group of modern hybrid composites encompasses the fibre metal laminates consisting of alternately stacked layers of metal and fibre-reinforced polymer composite. These laminates are characterized by high fatigue strength, high strength properties, corrosion resistance and to dynamic impact (impact) [1, 4, 14 ,33 ,36 ,38].

Composite materials are used to manufacture critical components of aircraft structures referred to as the primary structures (primary structure) and other responsible structures (secondary structure) as: skin elements, fuselages, spars, blades, landing gears, stabilizers, flaps and many others. Initially, the use of composites in aircraft structures has only reached a few percent (aircrafts and military structures), currently is equal to about 20–30%. The flagship product is the Boeing 787 "Dreamliner" made with more than 50% composite materials [7, 33, 13].

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Performance and reliability features of composite aircraft structures may be attributed to their individual elements ensuring their ability to perform specific tasks in determined period of time and operational conditions. Therefore, the principal requirements to be met by composites can include inter alia.: to obtain a material with high mechanical properties and low density. Reliability aspects should be taken into account in composite elements design, fabrication and operation phase of [22, 6, 37].

The assessment of quality of received composite and structures is of extreme importance at the manufacturing stage. The presence of defects such as pores and delaminations can have a significant impact on the reduction of composite properties and consequently deteriorate its functional characteristics [6, 19, 21, 37, 39].

One of the essential problems occurring in course of operation of composite structures is their resistance to dynamic impact (impact). There is a high risk of developing this type of phenomena denoted in the operation of aircraft. This is associated with e.g. operations performed by ground handling services, solid bodies thrown from under the wheels of an airplane or moved by the wind. Dynamic impact can cause visible damages in composite structure, which can be detected during routine inspections as well as the invisible internal ones, particularly dangerous residual strength [11, 20, 26, 27].

The principal non-destructive methods i.e. mainly ultrasonic flaw detection, thermography, eddy current method and X-ray computed tomography are the principal methods in the scope of quality control and evaluation of composite structures [22].

The paper presents a characterization of the structure of selected composite materials by means of a non-destructive method - ultrasonic flaw detection, in order to identify and characterize structural discontinuities associated with the manufacturing process and the possibility of using ultrasonic method to diagnose internal failures in fibre metal laminates caused by dynamic low-velocity impact.

2. Structural characteristics

The detection of discontinuities in the form of porosity and delaminations is an essential factor in the scope of quality inspection of manufactured composite structures. The minimization of porosity level is possible thanks to the use of advanced manufacturing methods e.g. autoclave process. Nevertheless, some of less responsible elements of airspace structures are still produced in manufacturing processes generating unavoidable porosity [6, 10]. The occurrence of porosity leads to the disturbance in the structural uniformity and to the changes in mechanical characteristics of fibre polymer laminates. The ultrasonic inspection is used as one of the non-destructive methods used for quality testing of composite materials structures. This technique is based on the use of physical phenomena associated with ultrasonic waves propagation in materials.

The object of study was a laminate made of fibre glass fabric (fibre type E) and epoxy resin. The laminate was made by hand lay-up method and tested in the form of a plate using the Through-Transmission (TT C-scan) method by means of an ultrasonic detector. The plate was scanned at the frequency of 1 MHz. The areas of constant drop of ultrasonic wave amplitude have been determined on the basis of the map generated. The level of porosity was determined by means of microscopic image analysis using Nikon MA200 optical microscope.

Figure 1 shows TT C-Scan map for tested composite panel. The areas with diversified colours are visible, which correspond to specific levels of ultrasonic waves absorption. It has been observed that the level of amplitude reduction is related to the intensity of occurrence of the structural discontinuity. Red colour represents a decrease in amplitude greater than 20 dB. The level of porosity marked in this area was equal to about 15%.

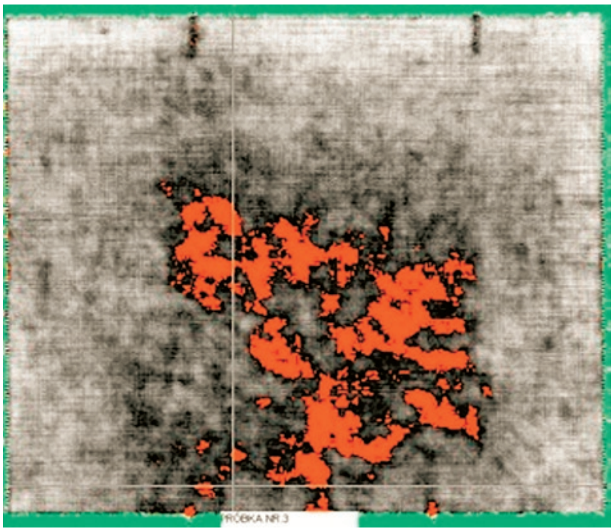

Fig. 1. C-scan imaging of glass epoxy plate

The level of porosity in composite structures significantly affects the operational capability and durability of composite aircraft components. The percentage of porosity, as well as their distribution and shapes have a significant impact on their fatigue life and delamination tendency [15]. The relationship between the level of porosity and crack propagation process in a laminate structure has been also denoted [9]. An intensified impact of the occurrence of voids in the material, has been characterized by Chambers et al [9]. They distinguished four main levels of porosity depending on the size of voids occurring in the material. In the opinion of Purslow [25], the laminates containing more than 5% (v/v) of porosity are characterized by poor quality and should not be used in the aerospace industry.

A cross-section of the microstructure of an epoxy-glass laminate is shown in Figure 2. The value of determined porosity was equal to approximately 3%. The porosities visible in the microstructure as the dark areas with diversified shapes and dimensions are situated mainly in interlayer spaces. Porosity of larger size tend to form agglomerates. Fine porosities similar to the spherical shape are characterized by more dispersed distribution within laminate volume. In the paper [5] it was found that pores dispersion decreases in case of higher level of porosity. Staffan [31] identified two types of porosity i.e. cylindrical voids between the fibres and the spherical voids located between the bundles of fibres. Bowles and Frimpong [5] have achieved identical results determining the porosity characteristics for high quality laminates with a low pores content.

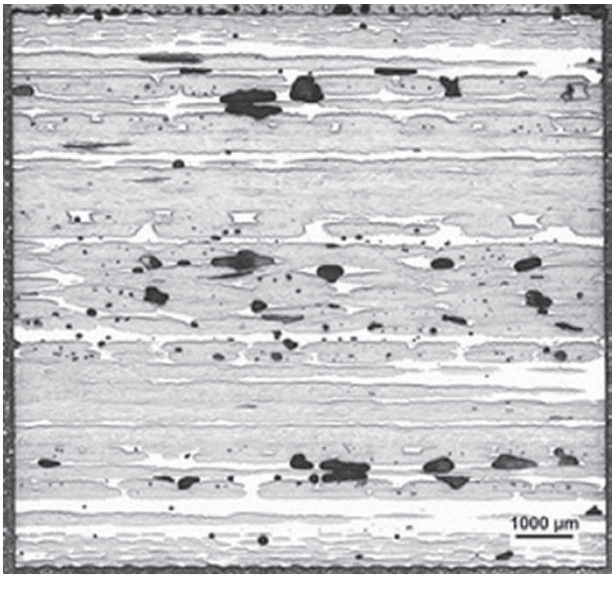

Fig. 2. The microstructure of the glass fiber reinforced polymer composite

Figure 3 shows the attenuation level of porosity vs. proportion of epoxy-glass laminate. The value of attenuation is associated with the porosity proportion in the composite structure and this relationship is approximately linear. The results are consistent with the results of studies obtained in the study [19], where Liu and co-authors noted that there is an approximately linear relationship between the level of discontinuity and elastic wave absorption coefficient for carbon-epoxy laminates. A lower content of porosity in structure has been found for lower attenuation values.

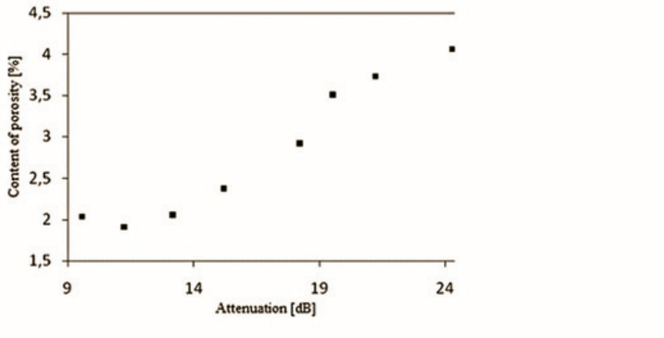

Fig. 3. The relationship between the percentage of porosity and the level of attenuation in epoxy-glass laminate

On the basis of obtained results, selected research method has been classified as a method useful for the detection of structural discontinuities in both carbon and glass epoxy laminates. Individual levels of attenuation reflect the contents of the porosity in a relatively accurate manner, which implies the possibility to determine the threshold limits assigning the attenuation value to the specific maximum porosity level.

3. Evaluation of operational capabilities after a dynamic impact

Under operating conditions, the fibre polymer composites and fibre metal laminates are exposed to unpredictable loads, first of all high or low speed single impact of concentrated force. As a result of high speed dynamic loads, a catastrophic structure failure takes place and usually said structure is eliminated from further operation or qualified for immediate repair [2, 30, 34, 36]. In case low speed dynamic impact of concentrated energy, internal structural failures are possible (delaminations, matrix cracking), particularly in case of energy not exceeding 5 J [17]. The phenomenon of inner failures propagation in composite structures makes it necessary to monitor their conditions by means of non-destructive methods, because the damaged composite material is unable to withstand the whole scope of loads assumed as early as in design phase [16, 29, 34]. In order to evaluate the possibility to diagnose the condition of composite laminates after single low speed impact by means of ultrasonic echo method, this type of loads has been simulated fully controlling the speed, energy and geometry of hitting body. The ultrasonic echo method is the most popular non-destructive testing method used in aircraft industry for flying objects in their operation phase due to limited, often one sided access to an element under test.The controlled dynamic impact test was carried out on the dynamic machine called drop-weight tester using a hemispherical indenter. The test was performed in accordance with ASTM D7136 standard [3] in energy range of 1,5 ÷ 25 J. The tests were carried out for carbon fibre reinforced polymer composite materials (CFRP) certified for the airspace applications in critical and high – loaded elements as well as for innovatory fibre metal laminates (FML) consisting of carbon fibre reinforced polymer composite materials (CFRP), alternately arranged layers in rectangular layout (0/90) and 2024-T3 (Al/CFRP) aluminium alloy. The materials for tests have been produced in autoclave process in the Materials Engineering Department in Lublin University of Technology.

The aim of the study was to analyze the influence of impact energy on character and range of failure in composite materials in the aspect of their further operation and possibility to apply the ultrasonic echo method for qualitative and quantitative description of their condition after single impact. OmniScan ultrasonic flaw detector with multi-transducer head (64 active elements) has been used for non-destructive analysis. Figure 4 illustrates the value of low speed impact energy vs. maximum force transmitted by the material and caused by the impact.

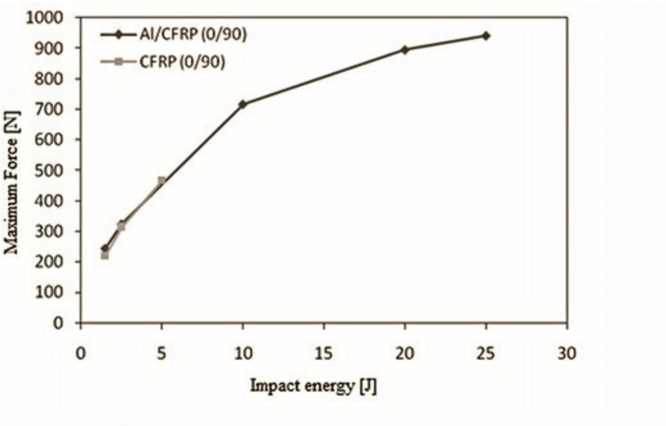

Fig. 4. The relationship between strength and maximum impact energy in a dynamic test

On the basis of obtained data (Fig. 4) it can be concluded that the force exerted on the material increased with increasing impact energy [28, 33, 34]. At low impact energies, CFRP laminates are characterized by force transmission capacity resulting from the dynamic load similar to Al/CFRP laminates. The impact energy of 10 J causes the complete perforation of CFRP laminate, as shown in Figure 5.

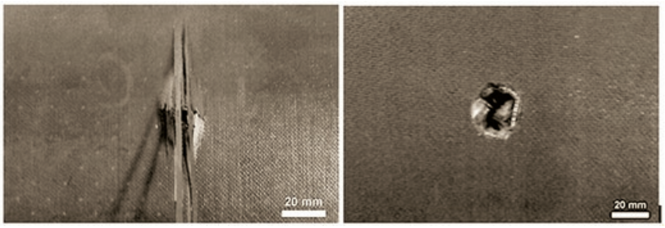

Fig. 5. CFRP laminate damage zone after being hit with the energy of 10J - bottom side (left), side impact (right)

Total disruption of the material eliminates it from further exploitation. However, fibre-metal laminates, subjected to further impact energy levels were gradually degraded, as shown in Figure 6.

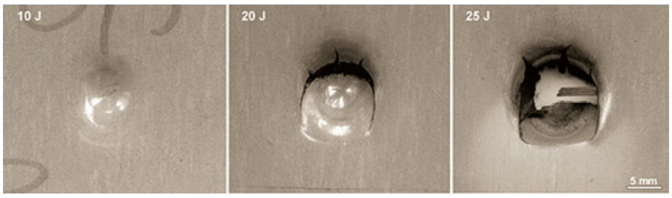

Fig. 6. Macroscopic figure of the extent of degradation fiber metal laminates after low velocity impact (impact side)

Finally, their complete perforation has been caused by impact energy of 25 J by means of an indenter. The phenomenon of structure destruction degree growth vs. energy increase has been described in studies [23, 34]. The cracks of bottom aluminium layer propagate perpendicularly to the orientation of bottom composite layer. The correlations between the orientation of composite fibres and the direction of metal layer cracking have been also described by Liaw B.M. et al. [18] who analyzed the direction of bottom aluminium layer cracking propagation in epoxy-glass aluminium-composite laminates. Liaw B.M. denoted that cracking direction in aluminium coincides with the orientation of bottom composite layer.

Any influence of metal sheet rolling direction on the direction of aluminium layers cracking propagation in laminates has been not found in the tests, this fact has been also denoted by Caprino G. et al. [8]. On the basis of macroscopic analysis, it can be found that Al/CFRP laminates are characterized by higher resistance to dynamic loads than conventional fibre reinforced polymer composites. In case of metal fibre laminates used for aircraft skin elements it possible to increase durability and functioning possibility under more demanding operational conditions, this fact is also confirmed i.a. by Vlot A. [34].

However, the low energy dynamic loads are of greater importance for operational reliability and safety because the materials are still subjected to the full spectrum of loads and additionally to fatigue without causing any visible changes of the surface. Nevertheless, quantitative and qualitative identification of potential internal structural discontinuities after low energy impact is possible by means of ultrasonic non-destructive methods [26]. Fig 7 illustrates selected amplitude representations (Type B and C) presented in gray scale for composite and metal-fibre laminates being tested after low energy impact.

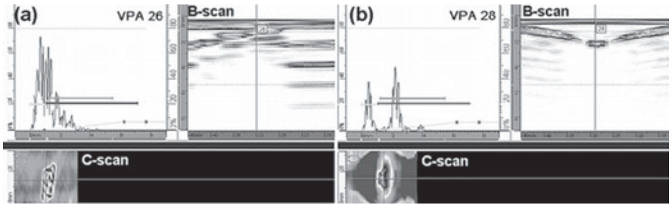

Fig. 7. Identification of CFRP laminates damaged area (a) and Al / CFRP (b) the low-speed impact energy of 2.5 J

The application of multi-transducer techniques in ultrasonic non-destructive tests makes it possible to precisely perform quantitative identification of the area influenced by an impact with specified energy. It is important in the operational aspect, because it is more easy to carry out potential repairs of damaged structures fragments. In case of conventional polymer fibre composites, an amplitude representation makes it possible to determine the type of occurred failures e.g. delaminations (amplitude change), determined by fibres orientation. Furthermore, C representation indicates to multilevel character of delaminations occurred after the impact, as represented by diversified colours of individual failure zones at various depths. Similar conclusions have been presented by Pearson M.R. et al. in their studies [24]. By means of B representation it is possible to determine the depth of individual delaminations and to determine their axial-lateral dimension. Furthermore, the image analysis makes it also possible to determine the surface area of identified discontinuities. In case of Al/CFRP laminates, it is difficult to precisely identify potential discontinuities due to numerous signal noises represented by multiple secondary reflections generated as a result of acoustic impedance change on metal-composite interface. Permanent plastic strain occurring after impact generates an additional amplitude reduction and amplifies recorded noises. C image representing the failures in a view parallel to laminate surface is the response to the lack of an explicit image of discontinuities in FML laminates. Impossibility to separate the image of plastic strain from potential delaminations and cracks is of importance in repair process and consequently in further operation. On the basis of performed non-destructive tests using ultrasonic echo method it has been found that there was no propagation of structural discontinuities out of zone of permanent plastic strain caused by indenter. Similar problems in the scope of identification of structural discontinuities in metal-fibre laminates have been denoted and described by Dragan K. at al. [12].

The macroscopic analysis of damage zones was performed in order to verify the ultrasonic echo method. Selected images of CFRP and Al/CFRP laminate microstructure are illustrated in Figure 8.

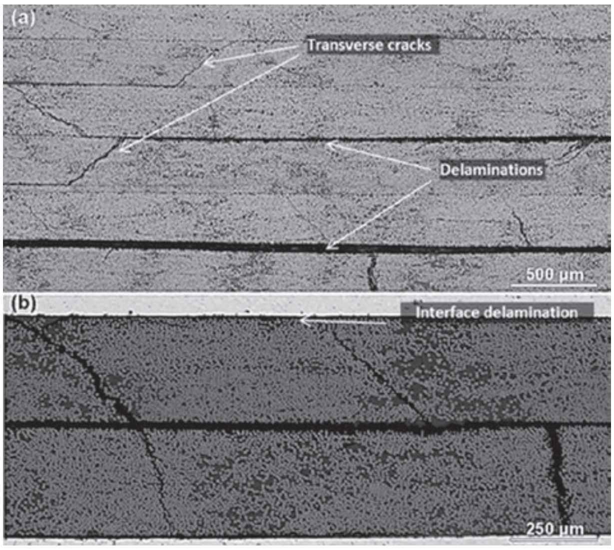

Fig. 8. CFRP laminate cross-section (a) and Al / CFRP (b) the impact of energy – 5 J

The microstructural analysis confirms that the dynamic impact with low-speed and low energy cause internal degradation of the polymer-carbon composites and fibre metal carbon laminates. CFRP composites are characterized by a more complex nature of the breakdown of the structure. Delaminations occurring under the influence of dynamic impact and transverse cracks connecting said delaminations are prevailing in tested materials. Additionally, longitudinal matrix cracks are formed on metal-composite interface, which results from the hybrid nature of components and adhesive bond between them. Delaminations between the composite layers are limited. Similar observations are described among others H. Nakatani et.al [23]. As a result of performed tests, the authors have denoted the relationship between the total area of cracks and delaminations and impact energy in CFRP composite and Al/CFRP laminates. The relationship between damaged surface area and impact energy is shown in Figure 9.

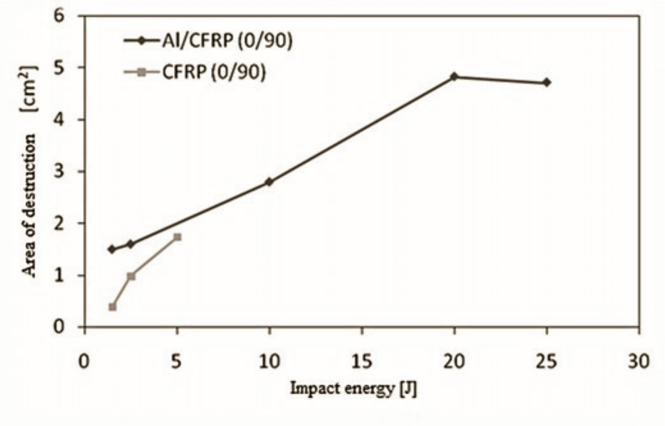

Fig. 9. The area of damage after impact in composite laminates at a low speed, depending on the impact energy.

It was observed that the growth of the destruction surface area vs. impact energy is almost linear. The damage area in CFRP composites detected by means of ultrasonic echo method is lower than in Al/CFRP laminates, which is a direct result of permanent deformation of laminates as a result of contact with the indenter. However, the energy of 10 J causes their complete perforation. Fibre-metal laminates are resistant to significantly higher energies of dynamic loads and are subject to proportional failure expansion. Polymer-fibre laminates have an evident limit of low speed impact loads capacity regardless of less negative influence of said loads in low energy range. Due to operational reasons, the use of fibre-metal laminates seems to be justified for those components exposed to dynamic loads, for which high strength and fatigue properties are also required.

4. Conclusions

1. Fibre-metal laminates are the materials with a higher potential in the scope of reliability and operation in comparison to conventional fibre-reinforced polymer composite materials.
2. The level of porosity in composite structures has an important impact on their service life and operational capabilities. Demonstrated relationship between the decrease in amplitude of ultrasonic wave passing through the laminate and porosity percentage indicates the potential of ultrasonic methods in the testing of structural condition of fibre reinforced polymer composites.
3. During aircrafts operation, the skin materials are exposed to the unpredictable phenomena of dynamic impact with specified speed and energy. Fibre metal laminates carry the loads induced by supplied energy in the scope of energies many times higher in comparison to conventional composite materials. Failure mode of composite laminates as a result of low speed dynamic loads is complex. Delaminations and extensive polymer matrix cracks prevail. Sufficiently low impact energy causes internal failures in composite structures without possibility to assess its condition by means of macroscopic methods.
4. Ultrasonic echo method with multi-transducer technique allows qualitative and quantitative identification of negative effects of low speed and low energy dynamic loads in composite materials.

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