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Investigation of the delamination type defects parameters in multilayered GLARE3-3/2 composite material using air – coupled ultrasonics technique

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Abstract

Air – coupled ultrasonic investigation possess a great potential for investigation of aerospace composite materials, because it avoids disadvantages caused by immersion or contact techniques. In the work the test sample of the GLARE3-3/2 composite material with artificial delamination type defect was investigated. Numerical and experimental investigations using focussed air – coupled ultrasonic transducers were carried out in a through transmission mode. Numerical investigation was carried out using the Wave 2000 software based on a finite differences method. The interaction of ultrasonic wave with a delamination type defect was investigated. Dimensions of the delamination type defects were measured experimentally.

Keywords: Air – coupled ultrasonics, non destructive evaluation, multilayered materials, composite materials, delamination type defects.

Introduction

Nowadays composite materials, such a GLARE type (GLAss fibre REinforced aluminium) and CFRP (carbon fibre reinforced plastic) are used in design of modern aerospace structures. Due to the safety reasons these materials must be tested during manufacturing and maintenance. Ultrasonic testing using couplants is most popular technique for non destructive testing of solid materials. In the most non – destructive evaluation tasks such as investigation of materials whose properties may be changed or even destroyed by liquid contact this technique can not be used. Because of that the air – coupled ultrasonic technique is very attractive for inspection of composite materials. Due to the fact that the attenuation of ultrasonic waves in air increases with the frequency the air – coupled ultrasonic measurements are performed at lower frequencies. This leads to reduction of a spatial resolution and accuracy of ultrasonic imaging. Qualitative evaluation of aerospace materials using air – coupled ultrasonic technique is presented by many authors [1-4].

The objective of this paper was to present results of the investigation of accuracy of ultrasonic air – coupled imaging of the delamination type defects in GLARE3-3/2 type composite material.

Test sample

GLARE composite material consists of aluminium alloy and prepreg layers which are bonded together. GLARE composite material is used for fuselage constructions of the biggest two deck passenger plane Airbus A380. The investigated GLARE3-3/2 composite test sample consists of three 0.3 mm thickness aluminium alloy layers and two 0.25 mm thickness prepreg layers between aluminium (Fig. 1). Each prepreg layer consists of two glass fibre plies laid perpendicularly to each other and glued with epoxy. The GLARE3-3/2 composite test sample contains artificial delamination defects with different diameters. Delamination type defects were simulated using circular teflon inserts between aluminium and prepreg layers.

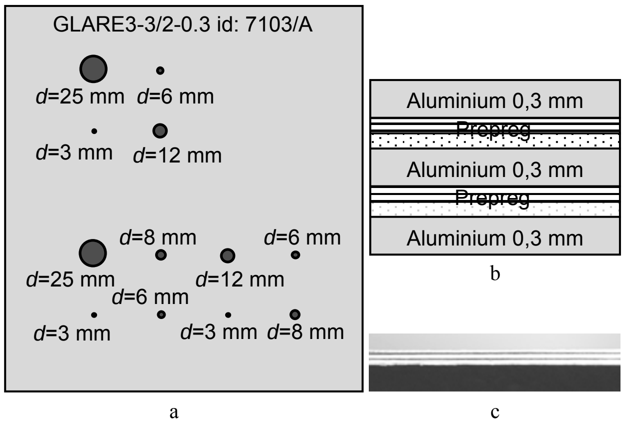

Fig. 1. **GLARE3-3/2 test sample (a); drawing of the cross – section of the test sample (b); image of the cross – section of the test sample (c);**

Numerical investigation and experimental verification

In order to understand the regularity of interaction of the ultrasonic waves with a delamination type defect in the GLARE3-3/2 composite 2D simulation using the Wave2000 software was carried out. The Wave2000 software is based on a finite differences method.

The 2D model of propagation of ultrasonic waves in a defective GLARE3-3/2 composite sample with 25 mm delamination defect is presented in Fig. 2.

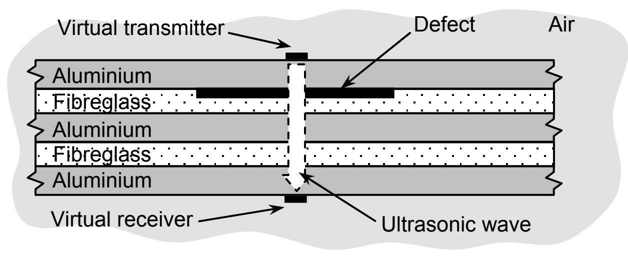

Fig. 2. **Model of propagation of ultrasonic waves in defective GLARE3-3/2 sample**

Parameters of aluminium and prepreg used in the model are presented in Table 1:

Table 1. **Parameters of materials used in model**

	Density, kg/m^3	Longitudinal velocity, m/s	Shear velocity, m/s
Aluminium	2770	6374	3150
Prepreg	1930	3170	1569

The delamination defect is modelled like a thin air layer between the aluminium and the prepreg layers. The width of the defect is 25 mm. The test sample is surrounded by air. Modelling and experimental investigations using focused air-coupled ultrasonic transducers were carried out in a through transmission mode.

Due to the lack of computer resources it is complicated to simulate the complete field of focused ultrasonic transducers. Therefore, the model was simplified. For excitation and detection of ultrasonic waves two small 1 mm width virtual transducers in contact with the test sample surface were used. The width of the virtual transducers matches the diameter of the focal point of the focussed transducers which were used in experimental investigations. The virtual transducers were placed on both sides of the sample opposite to each other. The excitation frequency of the virtual transmitter was 470 kHz; the excitation signals were 3 and 9 cycles bursts with the Gaussian envelope. Three periods excitation signal was used in the model for a better separation of signals and nine periods excitation signal was used for comparison of modelling and experimental results.

Displacement fields at different time instants are presented in Figure 3.

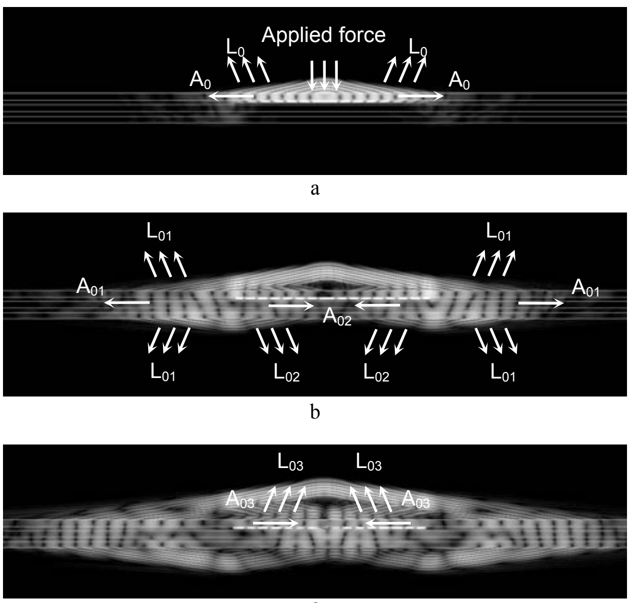

Fig. 3. **Displacement field at different time instants: a - 5µs; b - 10µs; c – 15 µs;**

The simulation results show that in the GLARE3-3/2 composite sample the incident wave above the delamination defect excites two waves, which propagate in opposite directions from the excitation zone and cause the leaky waves. The propagation angle of these leaky waves is 12°. The calculated velocity of the waves is 1649 m/s. This velocity corresponds to the velocity of A_0 mode of the Lamb wave in the GLARE3-3/2 sample [5, 6].

At the edges of the delamination type defect diffraction and reflection of the A_0 Lamb wave waves occur. The wave A_{01} propagates along the sample in the previous direction and causes the leaky wave L_{01}. Due to the diffraction effects the Lamb waves A_{02} are generated. These waves propagate underneath the defect towards the centre of a defect and cause leaky waves L_{02}. When the waves A_{02} overlap then their interference occurs. The reflected waves A_{03} propagate above the defect and cause the leaky waves L_{03}.

The longitudinal wave transmitted through the delamination due to a high impedance mismatch is not observed, because the delamination defect was modelled like a thin air layer between the aluminium and the prepreg layer.

Simultaneously moving the virtual transmitter and receiver along the sample by 1 mm step, the data for B-scan image was collected. The simulated B-scan image is presented in Fig. 4.

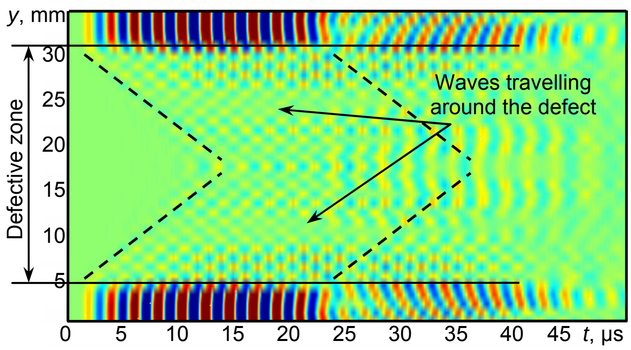

Fig. 4. **Modelled B-scan image of the defective zone in GLARE3-3/2 composite sample**

The simulation results were compared with experimental results. The block diagram of the experimental system is shown in Fig. 5.

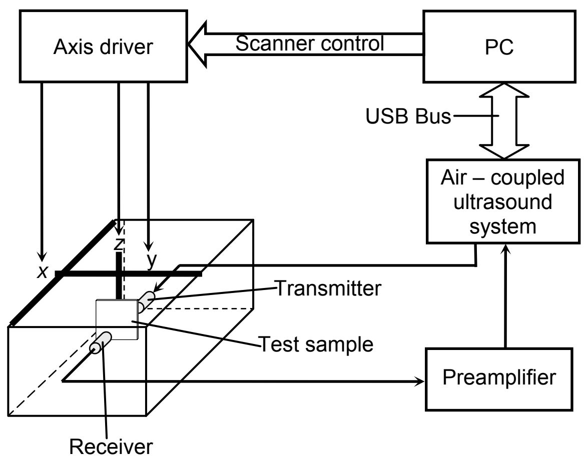

Fig. 5. **Block diagram of the experimental system**

Two channels air–coupled ultrasonic system consists of a high voltage generator, a low noise amplifier and an analogue – to – digital converter. The maximal output voltage of the generator is 750 V. Gain of the amplifier can be changed from 10 dB to 50 dB. The low noise 13.4 dB preamplifier is connected directly to the receiver in order to improve the signal to noise ratio. Experimental signals are collected and stored in the PC. Also there is possibility of the real time presentation of B and C – scan images.

The scanning system is designed in such a way that the ultrasonic transducers are at the fixed position and the test sample is moved during the scanning process with step 0.2 mm.

The ultrasonic transmitter was excited by 9 cycles 750 V rectangular burst of 470 kHz. The B–scan image of the sample along the defective zone with the artificial circular delamination type defect is presented in Fig. 6. The diameter of the delamination defect was 25 mm. The real delamination defect was simulated by insertion of thin teflon film. Usually it is assumed that it is not acoustically contacting with the sample material.

In the B-scan image the waves travelling around the defect are clearly seen. The time of flight of these waves increases approaching to the centre of the defect. A very weak through transmitted wave is seen as well. Origin of this wave can be explained by bonding of the artificial delamination defect to the aluminium and fibreglass layers.

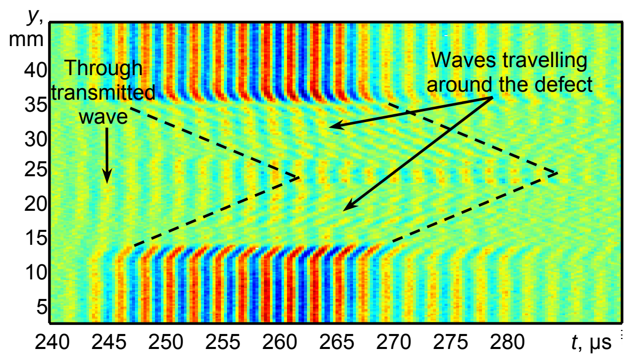

Fig. 6. **Experimental B – scan image of the defective zone in GLARE3-3/2 composite sample**

Using results of the 2D simulation and experimental investigation, the model of interaction of the incident ultrasonic wave with a delamination type defect in GLARE3-3/2 composite was proposed. The graphical representation of the model is shown in Fig. 7.

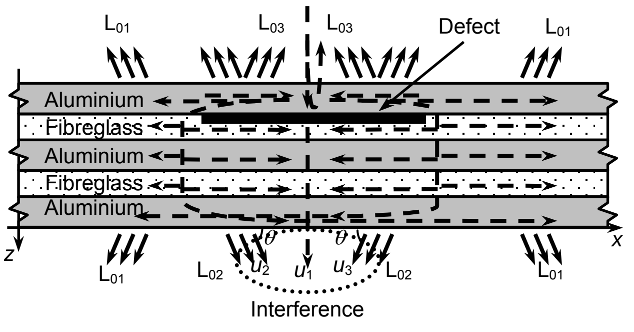

Fig. 7. **Interaction of the ultrasonic wave with delaminaction type defect in GLARE3-3/2 composite material**

Making an assumption that the interference occurs in the focal zone of the ultrasonic receiver, the signal at the output of the receiver is given by:

$$U(t,x,z)=u_1(t,x,z)+u_2(t,x,z)+u_3(t,x,z), \quad (1)$$

where u_1 is the through transmitted ultrasonic wave, u_2 and u_3 are the ultrasonic waves travelling around the defect, t is the time, x and z– coordinates.

The partial waves are given by:

$$u_1(t,x,z)=A_1(x,z)\cdot e^{j(\omega(t+\Delta t_2)-k_1 z)}, \quad (2)$$

$$u_2(t,x,z)=A_2(x,z)\cdot e^{j(\omega(t+\Delta t_2)+k_2(\sin\theta)z+k_2(\cos\theta)x)}, \quad (3)$$

$$u_3(t,x,z)=A_3(x,z)\cdot e^{j(\omega(t+\Delta t_3)+k_2(\sin\theta)z-k_2(\cos\theta)x)}, \quad (4)$$

where A_1, A_2, A_3 are the amplitudes of the signals, k_1, k_2 are the wave numbers, θ – the propagation angle of the leaky waves L_{02}, Δt_1 – the time of flight of the through transmitted wave, Δt_2, Δt_3 – the time of flight of the waves travelling around the defect.

The calculated B–scan image using Eq. 1-4 is shown in Fig. 8. The calculation was carried out using a real signal experimentally obtained in a non defective zone of the GLARE3 – 3/2 composite. Fig. 8 shows that the calculation results well correspond to the experimental one.

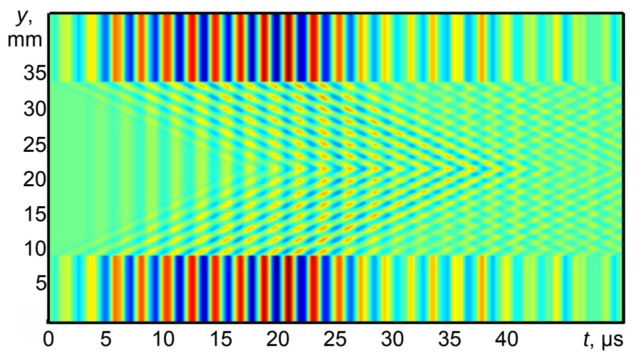

Fig. 8. **Calculated B – scan image of the defective zone with 25 mm delamination type defect**

Experimental investigation of the defect parameters in GLARE3-3/2 composite material

Experimental investigation of the defect parameters was carried out using experimental system presented in Fig. 5.

The amplitude C-scan image of the defective zone with the 25 mm diameter circular delamination type defect is shown in Fig. 9. In this case diameter of the defect is bigger than length of the A0 Lamb wave and the ratio d/λ=7. The periodical oscillations of peak to peak amplitude of the collected signals were noticed inside the delamination defect zone. The origin of these oscillations can be explained by the interference of the through transmitted wave with the waves which are caused by diffraction and travelling around the defect. Absolutely different results were obtained after scanning of the GLARE3-3/2 sample with the 3 mm diameter delamination defect (Fig. 10). In this case ratio d/λ=0.8 – diameter of the defect is smaller than length of the A0 Lamb wave. Instead of reduction of the amplitude in the defective zone, due to interference the significant increase of the amplitude is observed. This is very important because demonstrate that the defect detection technique based on the reduction of through transmission signal amplitude is not reliable and can miss small delamination areas.

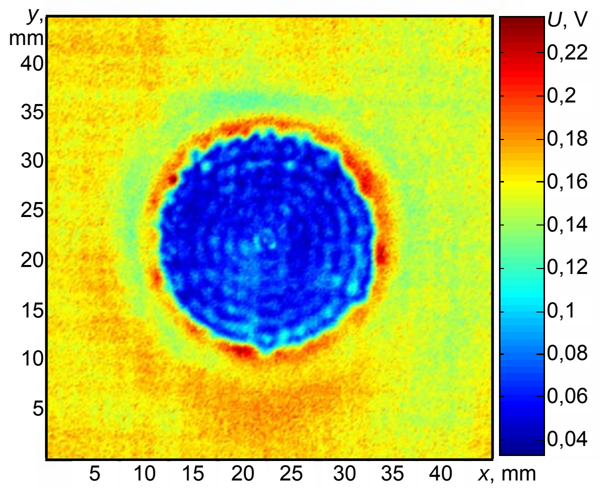

Fig. 9. **Amplitude C – scan image of the 25 mm diameter delamination type defect in GLARE3-3/2 composite**

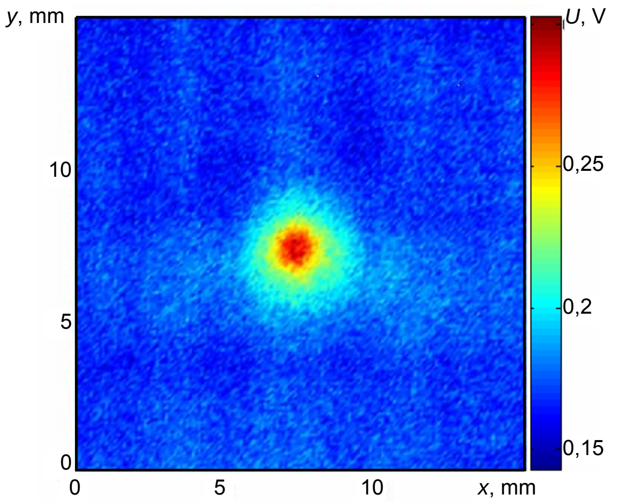

Fig. 10. **Amplitude C – scan image of the 3 mm diameter delamination type defect in GLARE3-3/2 composite**

The cross – section of the amplitude C-scan images of the 25 mm delamination type defect at the -6 dB level is presented in Fig.11. The measured area of the delamination defect at the -6 dB level is 384 mm^2. The measured mean diameter of the delamination defect is 22 mm. It is only known, that the true diameter of the delamination defect is 25 mm and the area of the defect is 491 mm^2. So, in this case the absolute measurement error is 107 mm^2.

During modeling of interaction of the ultrasonic wave with a delamination type defect has been shown that in a defective zone additional A0 Lamb waves are generated. A0 Lamb waves travel around the defect due to diffraction and interference of these waves with the through-transmitted wave occurs. The influence of these effects can be used for measurement of the defect area. The cross section of the amplitude C-scan image at the zone of maximum of the signal amplitude is presented in Fig.12. In this case the measured area of the 25 mm delamination type defect is 441 mm^2. The absolute measurement error is 50 mm^2.

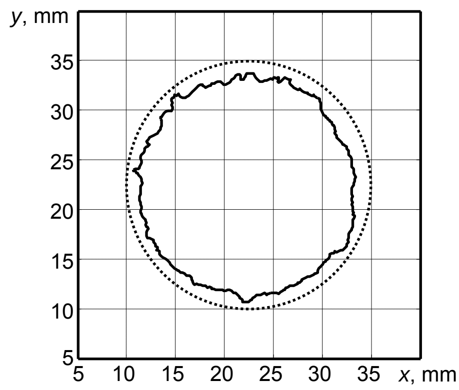

Fig. 11. **Cross – sections of amplitude C-scan image of 25 mm delamination type defect at the -6 dB level. Dotted line is real contour of the 25 mm delamination type defect**

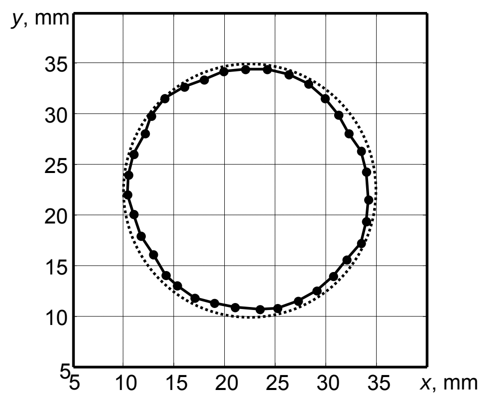

Fig. 12. **Cross – sections of amplitude C-scan image of 25 mm delamination type defect at the zone of amplitude maximum. Dotted line is real contour of the 25 mm delamination type defect**

The cross – section of the amplitude C-scan images of the 3 mm delamination type defect at the -6 dB level is presented in Fig. 13.The real area of the 3 mm delamination type defect is 7.1 mm^2. The area of the defect at the -6 dB level is 10.7 mm^2. The absolute measurement error is -3.8 mm^2.

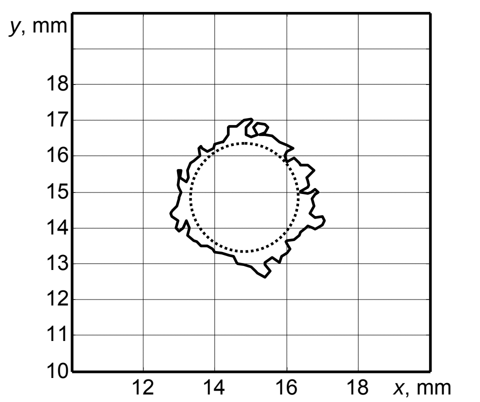

Fig. 13. **Cross – sections of amplitude C-scan image of 3 mm diameters delamination type defect at the -6 dB level. Dotted line is real contour of the 25 mm delamination type defect**

Conclusions

Interaction of the incident ultrasonic longitudinal wave with a delamination type defect in GLARE3-3/2 composite sample in the through-transmission mode was investigated both numerically and experimentally. In has been shown that in a defective zone additional A_0 Lamb waves are generated. These waves travel around the defect due to diffraction and cause leaky waves in air on both sides of the sample. Interference of the Lamb waves and the through transmitted longitudinal wave affects B and C-scan images of the delaminated zone. The analysis of experimental results showed that taking into account the phenomenon of interaction of the ultrasonic wave with delamination type defects allows measurement of dimensions of delamination type defects in GLARE3-3/2 material with a two times smaller error than at the -6 dB level.

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Atsisluoksniavimo defektų GLARE3-3/2 kompozite tyrimas ultragarsiniu nekontaktiniu metodu per oro tarpą

Reziumė

Kompozitų tyrimas nekontaktiniu ultragarsiniu metodu per oro tarpą patrauklus tuo, kad leidžia išvengti imersinio arba kontaktinio metodo trūkumų. Šiame darbe tirtas GLARE3-3/2 kompozito bandinys su dirbtiniais atsisluoksniavimo defektais. Atlikti teoriniai ir eksperimentiniai tyrimai tiesioginio perėjimo būdu. Teoriniai tyrimai atlikti baigtinių skirtumų metodu naudojant programinės įrangos paketą „Wave 2000“. Atliktas ultragarso bangos sąveikos su atsisluoksniavimo defektu tyrimas, taip pat eksperimentiniai defektų matmenų matavimai. Nustatyta, kad, naudojant ultragarso bangos sąveikos su atsisluoksniavimo defektu mechanizmą, defektų ploto matavimo paklaida gali būti du kartus mažesnė.

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