# INVESTIGATION OF ACCURATE IMAGING OF THE DEFECTS IN COMPOSITE MATERIALS USING ULTRASONIC AIR-COUPLED TECHNIQUE

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## Introduction

The modern aircrafts are built using various composite materials such as carbon/glass fibre reinforced plastics, GLARE and honeycombs. Manufacturing technologies of composite materials are complicated and include many stages. Small deviations from the technology parameters may cause relatively small defects, but influence of these defects on a total strength of a construction may be essential. So, due to safety reasons they should be inspected during manufacturing process and exploitation, using accurate non destructive testing techniques.

Conventional ultrasonic inspection techniques require liquid acoustic coupling, but wetting of composites with coupling liquids in different manufacturing cases is unacceptable or even not allowed because they may cause additional technological failures. Because of that the ultrasonic air coupled technique is very attractive for inspection of composite materials. On the other hand, the complex structure of composite materials causes big losses and scattering of ultrasonic signals. Additionally, the attenuation of ultrasonic waves in air increases with the frequency. Due to these facts the ultrasonic air coupled measurements are performed at lower frequencies, what leads to reduction of a spatial resolution and accuracy of ultrasonic imaging. So, the objective of this paper was to present results of the investigation of accuracy of ultrasonic air coupled imaging of defects in composite materials.

## Numerical investigation of interaction of ultrasonic wave with delamination type defect

In order to investigate interaction of the ultrasonic waves with a delamination type defect in 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 is presented in Figure 1. The GLARE3-3/2 composite consists of three 0.3 mm thickness aluminium alloy layers ($\rho_{Al}$=2770 kg/m$^3$, $c_l$=6374 m/s, $c_s$=3150 m/s, where $\rho$ is the density, $c_l$ is the velocity of the longitudinal ultrasonic wave and $c_s$ is the velocity of the shear ultrasonic wave) and two 0.25 mm thickness prepreg layers ($\rho_{prepreg}$=1930 kg/m$^3$, $c_l$=3170 m/s, $c_s$=1569 m/s) between aluminium layers. Each prepreg layer consists of two glass fibre plies laid perpendicularly to each other and glued with epoxy. 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 which is the most common and well known technique for ultrasonic non-destructive testing.

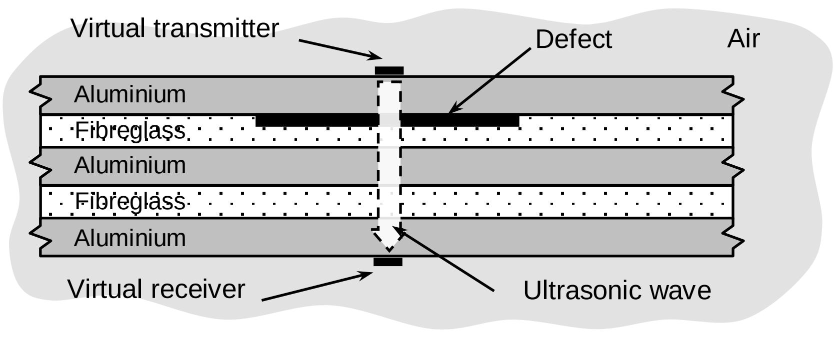


Fig.1. Model of propagation of ultrasonic waves in GLARE3-3/2 sample

Due to limited computer resources it is complicated to simulate the complete ultrasonic field of focused 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 the 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.

Snapshots of displacement fields at different time instants are presented in Figure 2.

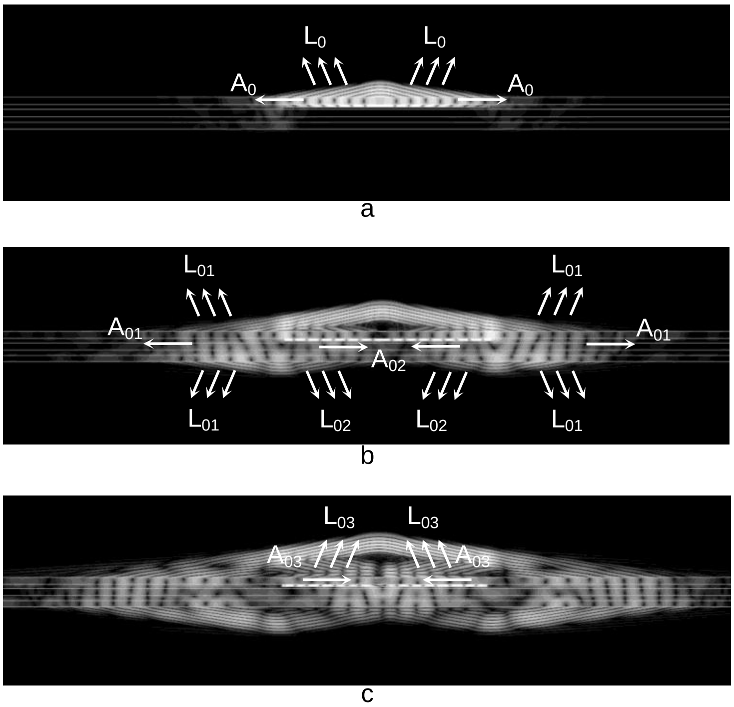



Fig.2. Displacement fields at the different time instants: a) 5μs, b) 10μs, c) 15μs

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 waves is 1649 m/s. This velocity corresponds to the velocity of $A_0$ mode of Lamb wave velocity in GLARE3-3/2 sample [1, 2].

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 defective zone of the test sample by 1 mm step, the data for B-scan image was collected. The simulated B-scan image of the defective zone is shown in Figure 3, where waves which travelling around the defect can be clearly seen. The time of flight of these waves increases approaching to the centre of the defect.

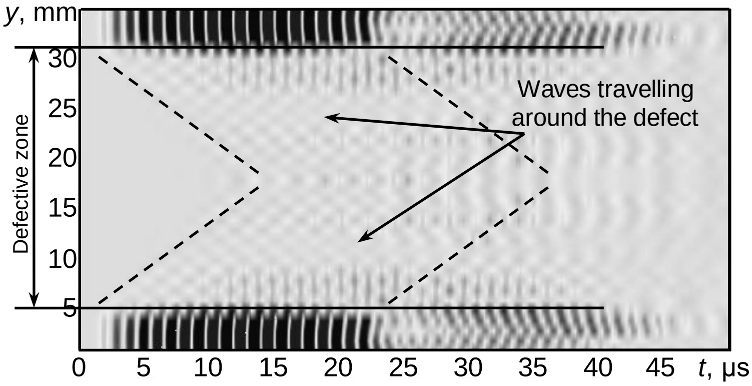



Fig.3. The simulated B-scan image

**Experimental investigation of interaction of the ultrasonic wave with delamination type defect**

The simulation results were compared with experimental results. The block diagram of the experimental system is presented in Figure 4.

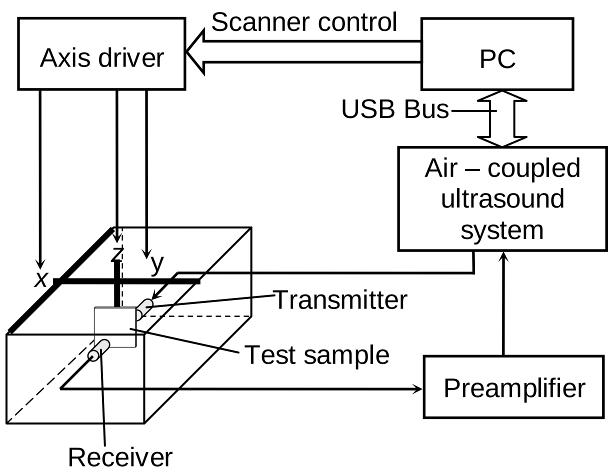



Fig.4. Block diagram of the experimental system

The whole system is controlled by a personal computer. 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 Figure 5. 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.

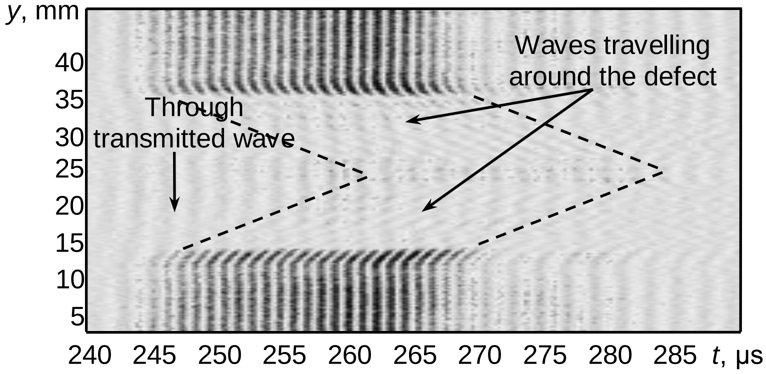



Fig.5. The experimental B-scan image

In order to prove presence of the through transmitted wave, scanning of the GLARE3-3/2 sample with the bonded porous rubber in the defective area was carried out (Figure 6). The porous rubber should absorb the waves travelling around the defect.

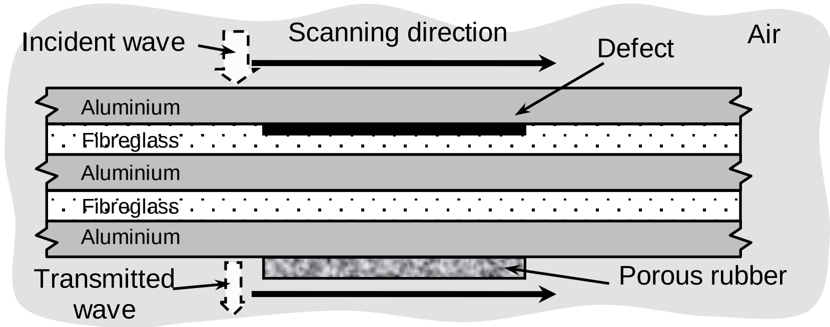



Fig.6. Experimental setup with bonded porous rubber in defective area

The experimental B–scan image of the defective area is shown in Figure 7. In spite of the fact that in a zone of the defect the porous rubber is bonded, a very weak signal is still observed. This signal corresponds to the through transmitted wave and confirms the fact that the insertion of theflon film does not completely simulate delamination between the GLARE3-3/2 layers.

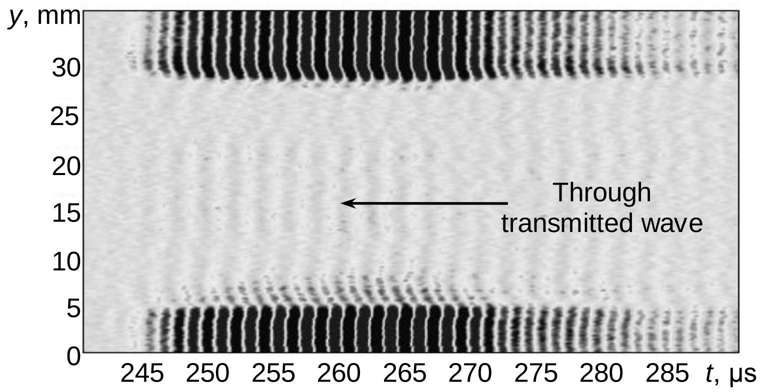



Fig.7. The experimental B-scan image of the defective zone with bonded porous rubber

Using results of the 2D simulation and the experimental investigation, the model of interaction of the incident ultrasonic wave with a delamination defect in GLARE3-3/2 composite was proposed. The graphical representation of the model is shown in Figure 8.

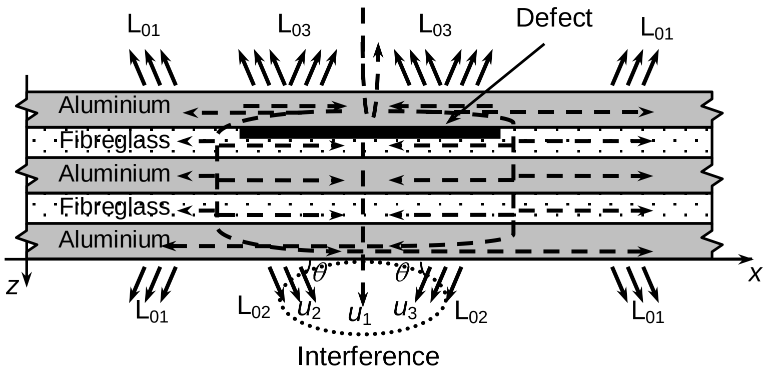



Fig.8. Interaction of the ultrasonic wave with delamination defect in GLARE3-3/2 sample

Making on 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 wave, $u_2$ and $u_3$ are the waves travelling around the defect, $t$ – is the time, $x$ and $z$ – are the 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, $\theta$ – the propagation angle of the leaky waves $L_{02}$, $\Delta t_1$ – the time of flight of the through transmitted wave, $\Delta t_2$, $\Delta t_3$ – the time of flight of the waves travelling around the defect.

The B–scan image calculated using equations (1-4) is shown in Figure 9. The calculation was carried out using a real signal experimentally obtained in a non defective zone of the GLARE3 – 3/2 composite. Figure 9 shows that the calculation results very well correspond to the experimental one.

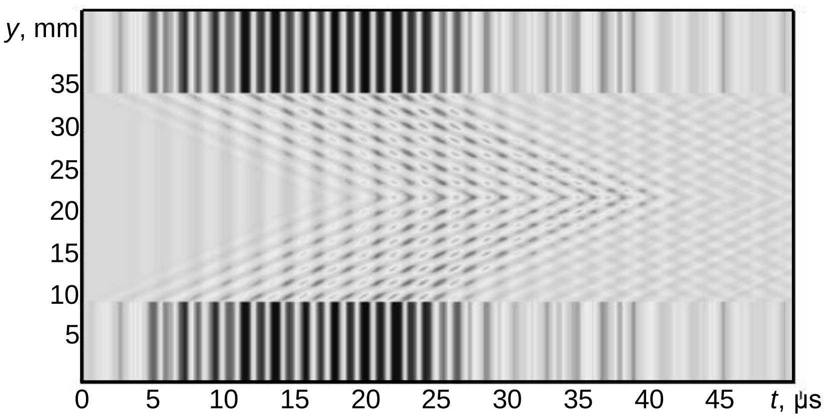
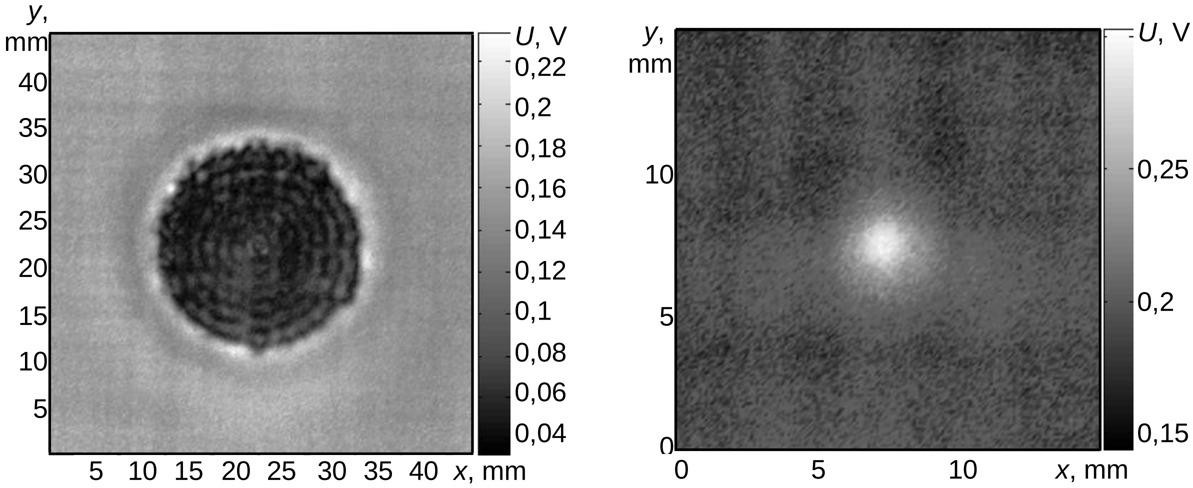



Fig.9. Calculated B-scan image of defective zone with 25 mm delamination type defect

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

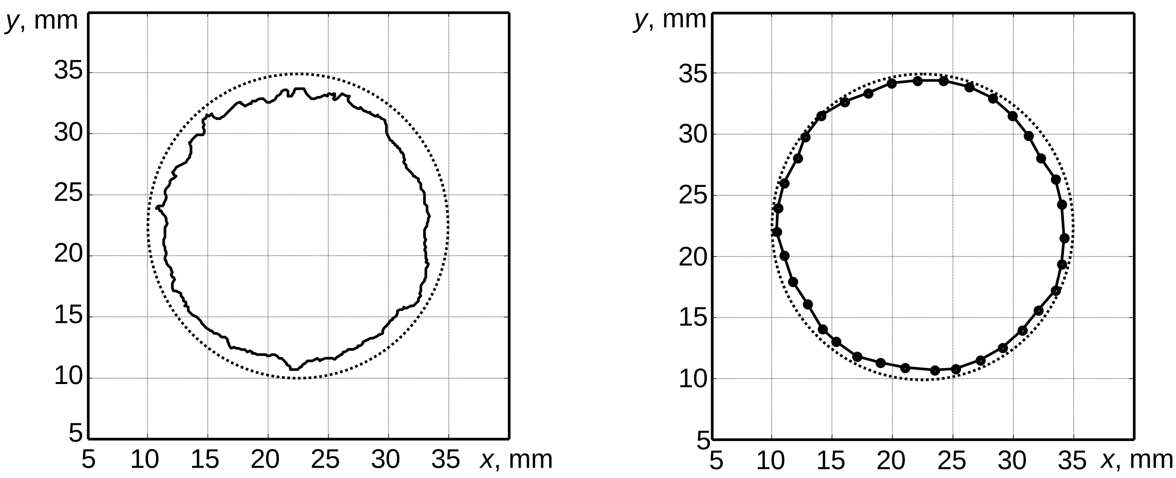
The amplitude C-scan image of the defective zone with the 25 mm delamination type defect is shown in Figure 10a. In this case diameter of the defect is bigger than length of the $A_0$ Lamb wave. Ratio $d/\lambda$=7. The periodical oscillations of peak to peak amplitude of collected signals were noticed 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. 10b). In this case ratio $d/\lambda$=0.8 – diameter of the defect is smaller than length of the $A_0$ 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 delamination small delamination areas.




a) b)

Fig.10. Experimental C scan images of the artificial delamination defects in GLARE3-3/2 sample. Diameter of the defect is a) 25 mm, b) 3 mm.

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.11a. 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 $mm^2$.




a) b)

Fig.11. Cross – sections of amplitude C-scan images of 25 mm delamination type defect: a) at the -6 dB level, b) at the zone of amplitude maximum. Dotted line is real contour of the 25 mm delamination type defect

During modeling of interaction of the ultrasonic wave with a delamination type defect has been shown that in a defective zone additional $A_0$ Lamb waves are generated. $A_0$ 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.11b. In this case the measured area of the 25 mm delamination type defect is 441 $mm^2$. The absolute measurement error is 50 $mm^2$.

## 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. Therefore, the influence of these effects on NDT results, especially when estimating parameters of defects, should be taken into account.

## References

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