Determination of composite patch thickness on the accuracy of nondestructive testing of the repaired structure of PZL-130 ORLIK aircraft

Michał Sałaciński MSc. Eng[1], Lt. Col. Andrzej Leski Ph.D.(Eng.), D.Sc. [1],
Piotr Synaszko MSc. Eng[1] Michał Stefaniuk MSc. Eng[1], Lt. Col. Krzysztof Dragan Ph.D.[1] (Eng.)

[1] *Air Force Institute of Technology, Ksiecia Boleslawa 6, 01-494 Warsaw, PO BOX 96, Poland*

Abstract

To determine its durability, the PZL-130 ORLIK military trainer aircraft has been subjected to a full scale fatigue test. In the course of the test defects and cracks appear. Periodically, the test has been stopped and the newly formed defects were subjected to repairs. After the repair procedures were complete the test was restarted and the repaired locations were monitored afterwards.

Composite patch repair has been utilized for the cracks in the area of lower wing skin. Because the cracks nucleated symmetrically on the left and right wing, two different patches were employed, for comparison. On one side, a boron-epoxy patch was used, and a carbon-epoxy patch was used on the other.

Additional research took place to determine the proper NDT methods suitable for detection of defects in the repaired wing regions. This research also determined the influence of the patch thickness on the accuracy of nondestructive inspections. A series of metallic skin coupons with fatigue damage were created for the research. Partially disbonded composite patches of different thickness were applied to these coupons.

In the next step, the coupons were subjected to nondestructive testing: thermography, ultrasonics, and low-frequency methods were used to detect the disbonds, while eddy current methods were used to detect cracks. Thermal Wave Imaging system was used for the thermographic methods, while classic A-scan defectoscopes as well as C-Scan imaging of the MAUS V system have been used for the ultrasonics and low-frequency methods.

The research results have been processed and a dependency between the patch thickness and inspection accuracy has been obtained. Subsequently, nondestructive testing has been performed on the repaired surfaces of the aircraft, and, based on the results of the aforementioned additional research, the crack dimensions were determined. The results of the research are presented in the paper.

Keywords: NonDestructive Inspection, Composite Patch Bonded Repair, aerospace, PZL-130 „Orlik”.

Introduction

Composite Patch Bonded Repair (CPBR) [1] has been for years one of the basic methods used for repair of metallic aircraft structures. Until recently, boron-epoxy composite material was most often used for this purpose, however in recent years the use of carbon-epoxy composites is gaining popularity.

Both materials are characterized by good mechanical strength, although use of each of those materials has its particular drawbacks and advantages. Electrical neutrality is one of the most important advantages of BFRP – in contrast to CFRP, it does not form a galvanic connection to the repaired metallic material - this prevents galvanic corrosion. Therefore, use of CFRP requires that a isolation layer (for example a glass-epoxy composite sheet) is put between the patch and the repaired surface. On the other hand, the CFRP in pre-cure state is highly plastic, which makes forming and shaping of the bonded patch easier and the patch can conform better to the repaired surface. Also, in the cured state, the CFRP can be easily machined, and processed mechanically.

To compare the two patch materials, authors performed an experiment during a full-scale fatigue test of a PZL-130 TC-II Orlik trainer aircraft. Two patches were applied on the test article, in crack areas located symmetrically on the both sides of the wing. One patch was made of CFRP, the other was made of BFRP (Fig.1).

Fig. 1 *Location of composite repair patches on the PZL-130 Orlik TC-II aircraft test article*

The present paper describes the potential Non-destructive tests (NDT) that could be used to assess the composite patch repaired structure. For this purpose comparative structural samples were manufactured, which were used to establish the relationship between precision of the NDT measurement and the composite patch thickness.

Eddy-current inspection was used for assessment of the repaired metallic structure, and ultrasonic methods, as well as low-frequency acoustic methods were used for inspection of the composite patch, as recommended [3]. In addition, impulse thermography was employed for inspection of the composite patch. Effectiveness of composite patch repair inspection was evaluated and results of the evaluation are presented in the paper.

Design and manufacturing of the repaired structure coupons

Aircraft skin in the repaired area is a made of the 2024-T3 alloy and has a 2mm thickness. The fatigue defects have the form of cracks propagating from rivet holes.

The repair of the full-scale fatigue test article was performed while the cracks were 20 mm long. The comparative samples were also made of the 2024-T3 alloy. The cracks were

modelled in the comparative coupons by introducing a 0,5mm wide notch on a rivet hole circumference, and propagating it with the use of a material test system machine.
A case of local debonding of the composite patch was also modelled by performing an incomplete adhesion of the test patch to the metallic surface.

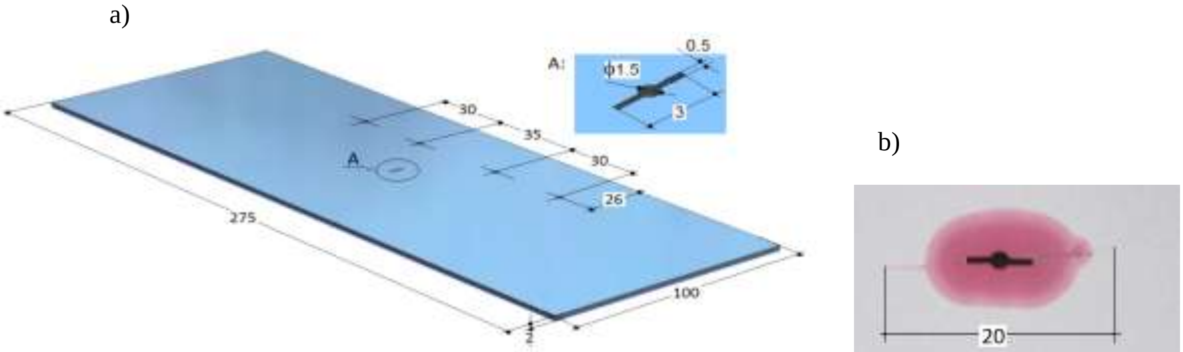


Fig. 2 Comparative coupon without patch: a) schematics – defect dimensions, b) view of actual modelled damage article code no 22

On Fig. 2b the actual coupon article is shown, including the modelled crack defect. A dye penetrant was used to highlight the crack.
The CFRP patch used in the experiment consisted of 8 layers of CFRP, an isolation layer and also a protective layer of a single GFRP sheet. The BFRP patch consisted of 8 BFRP layers and a single GFRP protective layer.
To determine the influence of the patch thickness on the NDT result, a range of patch thicknesses was evaluated. 20 coupons were manufactured; increment of one layer was used.

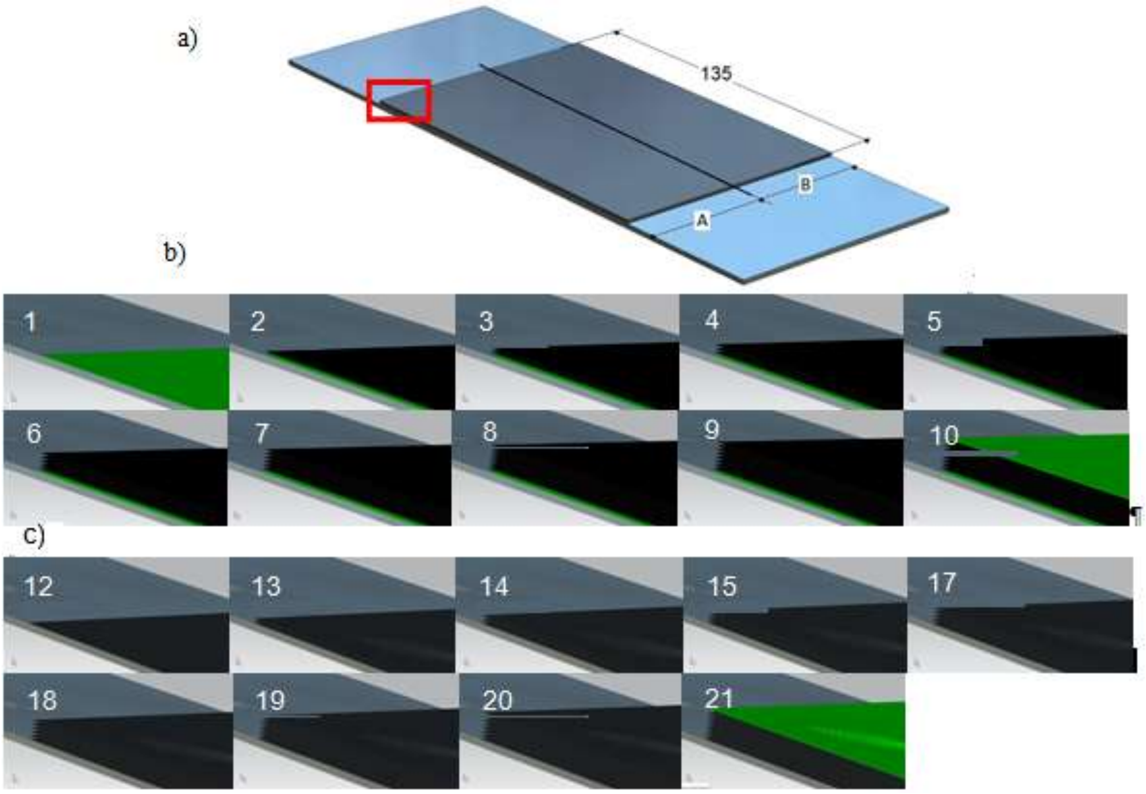


Fig. 3 Test article schematics, including article code number: a) patch dimensions A-patch applied, B- patch debondings, b) CFRP patch samples and layer count (layer thickness 0,15mm), b) CFRP patch samples and layer count (layer thickness 0,15mm)

The patches were manufactured with the use of prepreg technology. The curing cycle was analogous to the one used for fatigue test airframe repair – i.e. a heating blanket With a control unit and negative pressure was used. The metallic surfaces were prepared with the use of Sol-Gel technology. Debondings were modelled by introducing patches of non-adhesive layers.

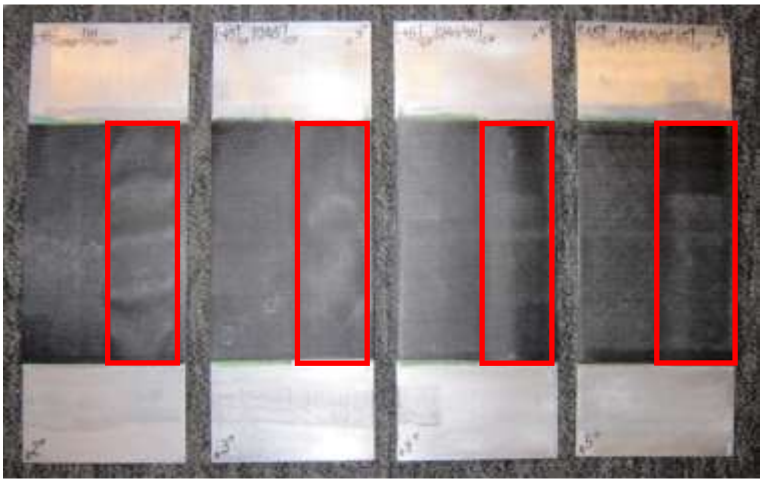


Fig. 4 coupon examples; red are is the debonding region

Fig.4 shows the debonding regions. Because of the asymmetry of the composite in the debonding region, patch warping occurred.

Impulse Thermography

Fig. 5 EchoTherm Inspection system

The thermography NDI test used for inspection of the composite patch consists of inducing a high-temperature thermal impulse in the inspected object and recording of the material response. The impulse is produced by a set of strong electric flash lamps installed under the flash hood – the response is recorded by a camera. Recoridng and analysis of the response signal is performed by the processing unit (Fig.5).
The method enables detection of polymer composite defects such as inclusions, delaminations and surface debondings. The defect causes a change in the thermal conductivity of the material, inducing a variation in the material cooling curve (1) which is schematically shown on Fig.6.

$$f = f(T_s(t), t) \quad (1)$$

T_s – recorded surface cooling temperature;

t – measurement time

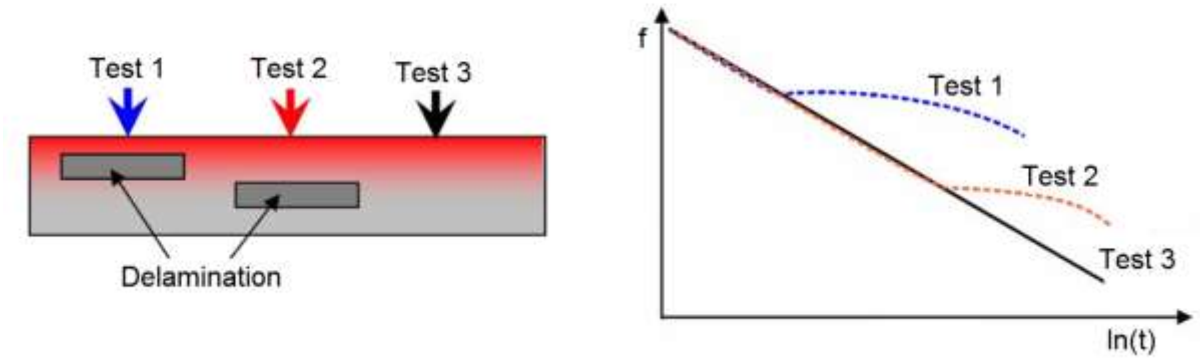


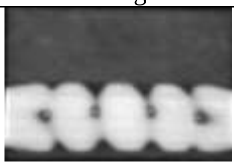
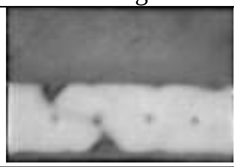
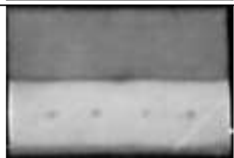
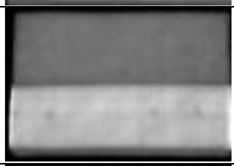
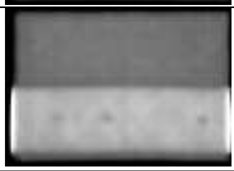
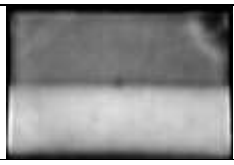
Fig. 6 Defect detection with the use of impulse thermography

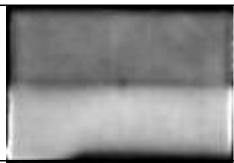
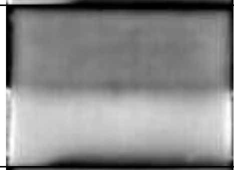
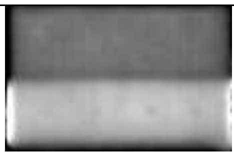
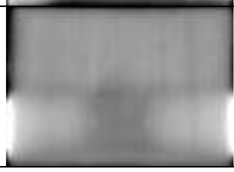
Thermal WAVE IMAGING EchoTherm system and a FLIR SC7000 camera was used in the presented experiment, with the use of following parameters :

- Sampling frequency – 54,7 Hz;
- Flash lamp energy 5kJ;
- length of thermal impulse – 4,0 ms;
- exposure time – 5 s.

In the first stage of the thermography test, baseline tomograms of the specimens were taken. Based on the contrast difference, the deboning areas can be indicated. The results suggest that CFRP patches are better suited to the thermography method, as the results are of higher definition and precision. This a result of the difference of the material's heat transfer coefficient in the direction normal to the patch.

Table 1 Coupon thermograms, the debonding region can be seen in the lower portion of the images

Orientation	CFRP		BFRP	
	Thermogram	Code	Thermogram	Code
[0]		2		12
[0/+45]		3		13
[0/+45/90]		4		14
[0/+45/90/-45]		5		15
[0/+45/90/-45/-45]		6		16

[0/+45/90/-45/-45/90]		7		17
[0/+45/90/-45/-45/90/+45]		8		18
[0/+45/90/-45]2		10		21

The cooling curves can be used to make a qualitative assessment of the bonded patch. Based on the cooling curves, an empirical formula or a reference diagram will be elaborated and used for inspection precession assessment, depending on the number of layers or the patch material used.

a) b)

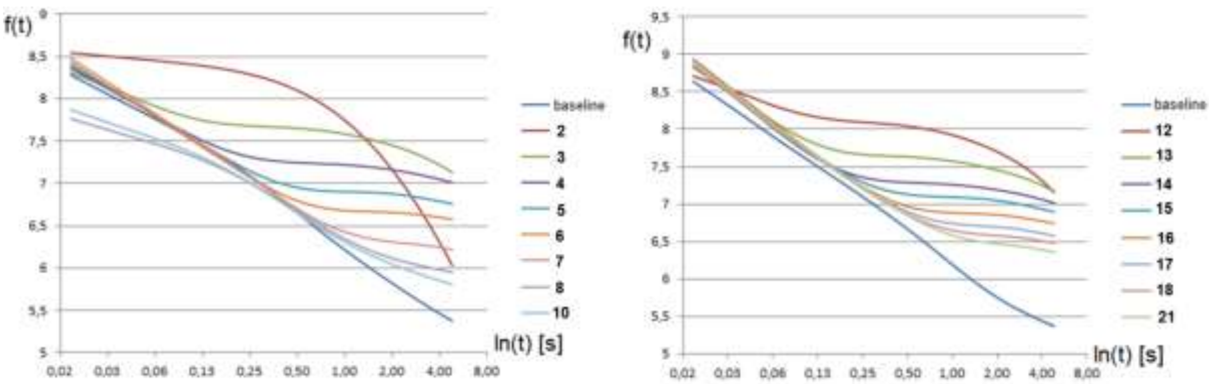


Fig. 7 Cooling curves: a) CFRP patch coupons, b) BFRP patch coupons

Non-intrusiveness of the thermographic inspection method is one of the advantages of the method, which suits it well for composite patch inspection. The method is practical both for inspection of flat, as well as of curved (encountered in aircraft structures) surfaces. The measurement time is low and the processing is instantaneous, and does not require much analytical post-processing as the thermograph images themselves give a clear indication of the extent of damage.

Digital recording of the test signals enable storage of many cooling curves, which subsequently may be processed by an analytical algorithm that will quantify the area and depth of the defect.

However, there is a limit material thickness for which the method is effective, Also the method is sensitive to material type and the material condition on the surface, which may introduce an interpretation error.

Acoustic methods

The classic ultrasound method, despite using measurement frequencies in the range of 1 – 5 MHz, proved to be ineffective for detection of disbond defects. Ineffectiveness of the ultrasound method was a result of high damping material factor which is caused by material porosity. Because of that fact, other acoustic methods were also evaluated. The ultrasonic methods that rely on kilohertz-range measurement frequencies rely on physical phenomena

different to the classical high frequency UT methods. RT(resonance test method) and MIA (mechanical impedance analysis) were the low frequency methods used.
The RT method is based on measuring resonant vibrations of the tested material and utilizes measurement frequencies in the range of 100 to 300 kHz. The measurement device head consists of a piezoelectric crystal that is excited to vibration by a continuous sinusoidal voltage, The vibration induces a continuous wave (as opposed to wave packs used by the high frequency methods) in the tested structure. The wave is deflected multiple times in the material, and resonant amplification or damping takes place.
Amplitude and phase of the surface vibration depends on the tested material's modulus of elasticity. When a structural discontinuity is encountered, the measured material thickness differs and a different reading of amplitude and phase is recorded.
The changes in structural continuity are measured by the device as a change in piezoelectric sensor impedance. The measurement sensor needs to be calibrated before the measurement process. For this, a reference sample of the same material as the one that will be inspected is used. The discontinuity has to be modelled in the reference sample, so that parameter ranges can be established for damaged and undamaged areas. A layer of conductive coupling medium is needed between the sensor head and the inspected surface (water is used).
The MIA method utilizes wave frequencies in the range of 2,5 do 20 [kHz]. The sensor head consists of two piezocrystals – an emmiting crystal is placed above the receiver crystal. Continuous signal is emitted and a standing wave is generated in the receiver and the emitter signals. When a change in measured amplitude and phase angle occurs, a discontinuity in the material has been encountered (assuming that the inspected material is homogenous). No coupling medium is needed in this method
The UT, RT and MIA tests were made with the use of an automated MAUS V measurement system (Fig.8), which provides results in the form of C-Scan images.

Fig. 8 MAUS V

Table 2 Method inxpection capability matrix – acoustic methods

	Code															
Method	2	3	4	5	6	7	8	10	12	13	14	15	16	17	18	21
UT 5 MHz	-	-	-	-												
RT 110 kHz	-	-	-	-												
RT 320 kHz	-	+	+	+												
RT 170 kHz	-	+	+	+	-	+	+	-	+	-	-	-	-	-	-	-
RT 270 kHz	-	+	+	+	+	-	+	+	-	-	+	-	+	+	+	+
MIA 18 kHz	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

In Table 2 the composite patch deboning detection capabilities for the methods is summarized. MIA was the most effective method, as it detected the debond regions in all of the tested specimens. However use of relatively low frequencies results in a lower definition of the measurement image compared to other methods (Fig. 9).

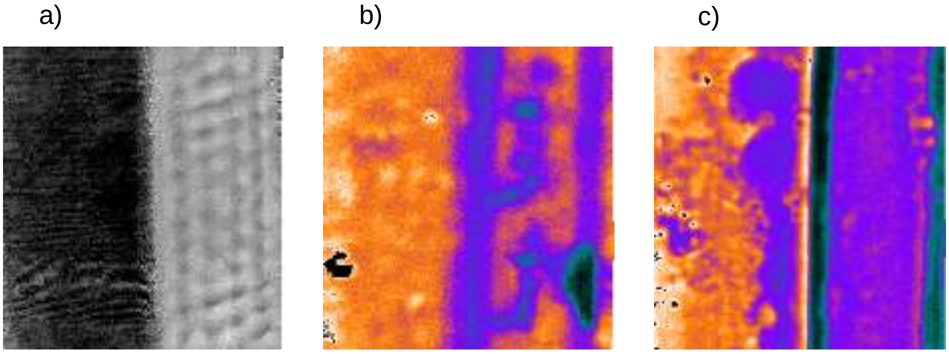


Fig. 9 Example inspection results (coupon no 5): a) MIA -18kHz, b) RT-170kHz, c) RT-270kHz

Based on the findings in Table 2 it is possible to selected the correct method for the given patch-material configuration.

Eddy current and crack detection

For measurement and inspection of the defect growth under the patch eddy current ET method was utilized. The ET method is a surface NDI method as it enables inspection only of structural discontinuities that are on the surface of the measured object or just below the surface. Only electrically conductive materials can be inspected with the use of this method as only in those materials electromagnetic field can induce the flow of eddy currents.

The measurement consists of creating eddy currents in the surface layer of the measured object, with the use of a local, fast alternating magnetic field. Fluctuatuins of the eddy current field are recorded by the device.

During the inspections, the change in signal amplitude and phase serves as a diagnostic signal. The magnetic induction amplitude is related to length and width of the discontinuity area, and the phase angle gives information about the depth of the defect .

The MAUS-V automated inspection system was used for the eddy current inspection. The system was calibrated to suit the damping parameters of the patches with the highest damping. The amplification parameters were set automatically by the device and the set independently for each of the measurement frequency used

i.e. - 1, 2, 4, 8, 20, 40 and 80 kHz – a subset of the device frequency range (500 Hz – 100 kHz) was used.

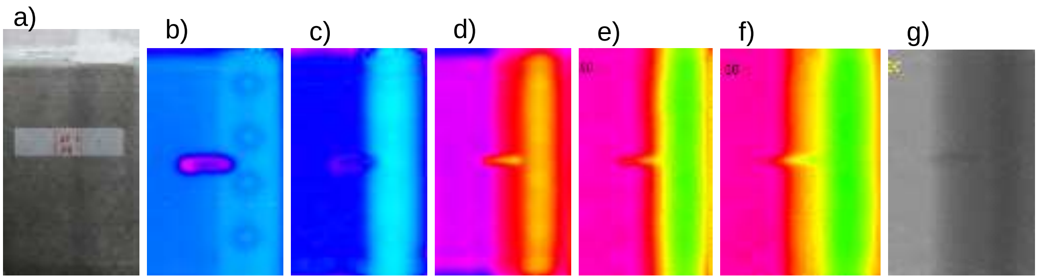


Fig. 10 *Coupon no 5: a) view of the coupon, b) ET – 2kHz, c) ET – 4kHz, d) ET – 8 kHz, f) ET – 20kHz, g) ET – 40kHz, h) ET – 80kHz*

Fig.10 shows influence of the test frequency on the results. The low frequencies enable measurement of cracks under a thicker patch, but the resulting definition is lowered as a tradeoff. The converse is true for higher frequencies [3].
Result post-processing analysis done by different ET-certified operators shows that the lower frequency range enables better evaluation of the under-patch crack, as the signal strength is higher, and a precise crack dimensions measurement is possible (Fig.11).
In addition, thanks to the clarity of C-scan images ET, detection of disbond defects was also possible.

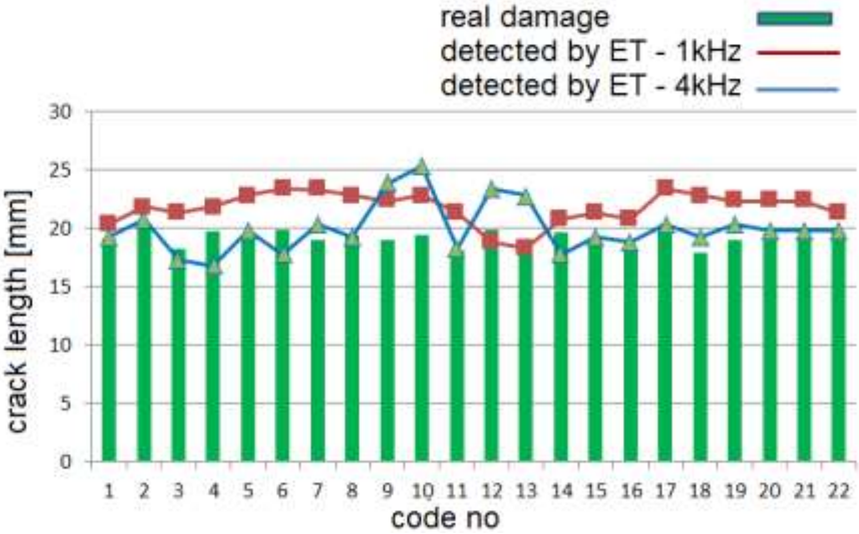


Fig. 11 Compariosn of the actual crack length with operator measurements after patch application

Further analysis of the C-scan images consisted of determination of the patch thickness and material influence on the measurement precision. Fig.11 suggests that the patch introduces a measurement error. Percentage deviation of the measured defect sizes and comparison to actual sizes is showcased on the graph on Fig.12.

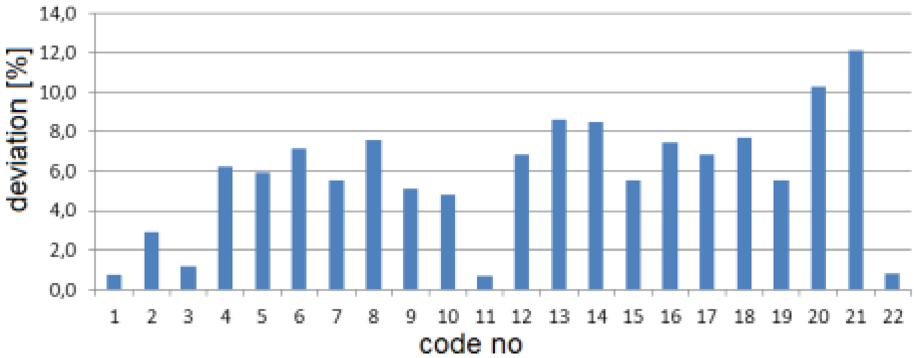


Fig. 12 *Deviation of the crack length measurement, ET method*

Diagram on Fig.12 shows that the BFRP patch causes greater inspection errors.

Summary

1. The impulse thermography method enables detection of disbonds of the CFRP and BFRP patches. The CFRP composite is better suited to disbond detection measurements.
2. Increase in patch thickness limits the use of the thermography methods, however the patch thicknesses used in the described experiments was below the limit.

3. Detection of patch disbond with the use of 5MHZ and 110 kHz ultrasound measurements (table nr 7) was not effective.
4. Frequencies of 170, 270, 320 kHz as well as the 18khz Mechanical impedance method (MIA) enabled detection of composite patch disbonds (table 7).
5. Based on the results the thermography method is recommended as the basic method for disbond detection, with the MAI as an alternative. The resonance method is only seen as a supplementary method.
6. The automated eddy current inspection was also able to the detect disbonds of the patch from the metallic surface.
7. Eddy current inspections (both automated and manual) enabled detection and sizing of cracks and other discontinuities in the airframe structure under the composite patch.
8. With the increase of BFRP patch thickness the detectability of disbonds worsens, especially for higher frequencies.

References

1. Baker A. A., Rose L. R. F., Jones R.: "Advances in the Bonded Composite Repairs of Metalic Aircraft Structure", Vol. 1, Elsevier Science Ltd., 2002 r.
2. Heatcon® Abaris Training: "Advanced Composite Structures, Fabrication And Damage Repair, Training materials", Training materials, Cwmbran, May 1998.
3. Roach D., Rackow K.: "Development and Validation of Bonded Composite Doubler Repairs for Commercial Aircraft", SAND2007-4088, Sandia National Laboratories, 2007.