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Neutron radiography and other NDE tests of main rotor helicopter blades

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Abstract

A few nondestructive examination (NDE) techniques are extensively being used worldwide to investigate aircraft structures for all types of defects. The detection of corrosion and delaminations, which are believed to be the major initiators of defects leading to aircraft structural failures, are addressed by various NDE techniques. In a combined investigation by means of visual inspection, X-ray radiography and shearography on helicopter main rotor blades, neutron radiography (NRad) at SAFARI-1 research reactor operated by Necsa, was performed to introduce this form of NDE testing to the South African aviation industry to be evaluated for applicability. The results of the shearography, visual inspection and NRad techniques are compared in this paper. The main features and advantages of neutron radiography, within the framework of these investigations, will be highlighted.
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1. Introduction

Failure of aluminium structures due to aluminium corrosion that lead eventually to metal fatigue, as well as disbonding of parts of integrated airframe structures, has always been a major concern throughout the aircraft industry. Detection of the causes of airframe failures by means of various nondestructive examination (NDE) techniques, including neutron radiography (NRad), the improvement thereof and research development of new detection methods like shearography, constantly received much attention (Rant et al., 1986a, b; Han et al., 1998; Leeflang and Markgraf, 1994; Erdman, 1960; Peters, 1965).

All aging aircraft suffer the same fate—to be attacked by aluminium corrosion due to ingress of water and/or moisture, and subsequently leading to their withdrawal from service. The quest to extend the aircraft structures lifetime to avoid the high replacement cost of new aircraft, tends to load a major task on the NDE fraternity to detect aluminium corrosion products or subsequent material loss as well as delaminations.

NRad has the distinct advantage to detect hydrogenous materials efficiently because of the large neutron absorption cross section of hydrogen and thus poses an attractive alternative to be utilized by the general total aircraft industry, including the evaluation and inspection of helicopter rotor blades (Balasko, 1998).

Tap testing is an official NDE method for the detection of debonded areas on the main rotor blades of helicopters. The limitations of this technique ranges from reduction of sensitivity due to an increase in skin thickness, to the dependency on the use of skilled operators, which make the results highly subjective. Preliminary results from helicopter main rotor blade investigation concluded that the repair scheme does not make any provision for the detection of moisture or corrosion during the repair process, although there are

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potential for corrosion and corrosion related fatigue in the area of the main rotor spar. A new repair investigation scheme, which includes NDE techniques to detect aluminium corrosion as well as debonding, will be followed after the outcome of this feasibility study of several NDE techniques, including NRad and Shearography, to evaluate each method's qualitative detection ability.

In this paper the results of this feasibility study will be discussed with respect to defect detection. To evaluate the detection efficiency of NRad and Shearography (Jones and Wykes, 1989), the blades were stripped and visually inspected. No quantitative measure of the thickness of the detected faults was made. The apparatus and principles used in this study of both the NRad facility at the SAFARI-1 research reactor and the Shearography technique at University of Cape Town are briefly described.

2. Experimental setup

The tests were conducted on 20 used main rotor helicopter blades due for repair. Each blade weighs 35 kg and is 4 m long. The blade consists of a 4 cm thick foam core area imbedded in an aluminium spar, all covered with a thin Al layer to hold all the pieces together. The outside area of the thin Al layer is being painted. The areas of interest were the tip of the blade as well as the cuff to leading edge area. Figs. 1 (Areas nos. 3–4) and 2 (Areas nos. 5–6) are diagrams of the areas of investigation.

NRad and Shearography were performed prior to visual inspection. During visual inspection the blades were stripped and photographed layer-by-layer. The results were documented to be compared with the NRad results for the successful detection of corrosion and to the Shearography results for the detection of debonded areas. Four blades, based on the initial NRad and Shearography results that showed major faults, were also chosen for X-ray radiography and ultrasonic inspection, but are not reported on in this paper.

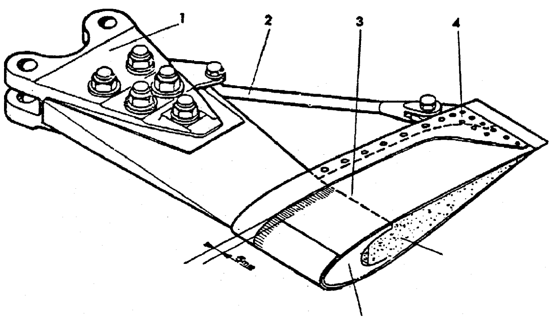

Fig. 1. Schematic diagram of cuff area.

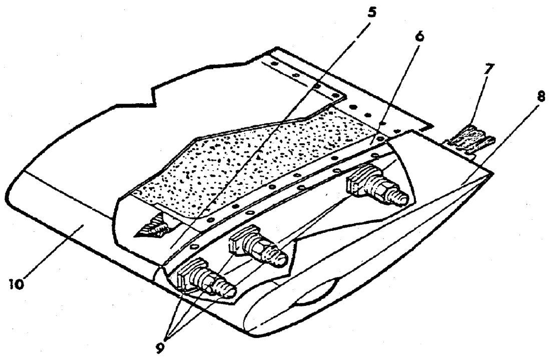

Fig. 2. Schematic diagram of tip area.

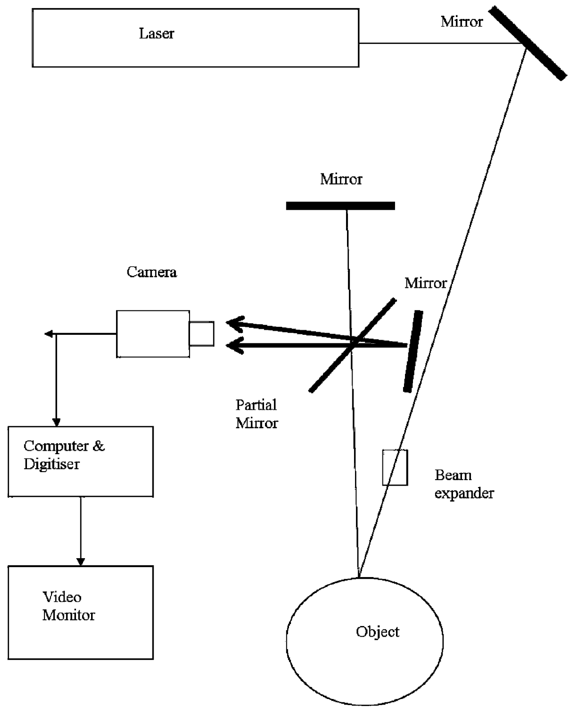

Fig. 3. Typical Shearography set-up.

2.1. Shearography

2.1.1. Principle

Digital Shearography is a laser light based, full field, non-contacting, optical interference technique, used primarily for NDE (Han et al., 1998). When applied, the result is a set of fringe patterns, which are representative of an objects' surface displacement in response to a mechanically applied stress. The presence of a defect locally influences the object's surface deformation when stressed, which can be detected in the contours of the produced fringe patterns.

The Shearography process, which measures the rate of object deformation, is shown in Fig. 3. Monochromatic laser light, which reflects off the illuminated object surface, is viewed through a set of shearing optics. The function of the shearing optics is to laterally shear the image of the object into two overlapping images, causing them to interfere and produce a unique speckle pattern, which is captured and digitized by a computer.

By comparing the speckle interference pattern of an object both before and after object stressing, areas of correlation and decorrelation are noted, which when mapped, produce the familiar zebra-striped fringe pattern. Eq. (1) represents this process mathematically

$$\Delta\phi = \frac{4\pi}{\lambda}\left(\frac{\delta d}{\delta x}\right)S, \tag{1}$$

where $\Delta\phi$ is the correlation phase, S the magnitude of shear, $\delta d/\delta x$ the displacement rate, and λ the wavelength of the laser light.

2.1.2. Equipment

The equipment used is shown in the Fig. 4. To the left of the image the Shearography head unit plus tripod can be seen. This unit contains the laser head, the camera unit as well as the image shearing optics and controls. Two power supplies, one for the laser and one for the camera, connect to the right hand side of the Shearography head. The camera output is connected to the digitiser input, which is housed in the computer seen in the left of the picture. Custom written software is used to control the image acquisition, processing, manipulation and the display routines (Findeis and Gryzagoridis, 1996).

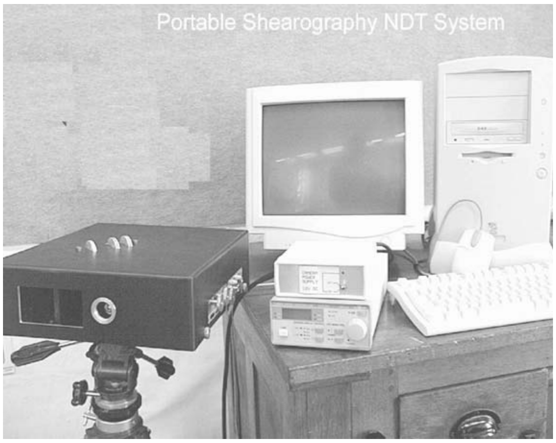

Fig. 4. Shearography equipment.

2.1.3. Visual inspection

Visual inspection was used in this study to qualify the results obtained by shearography and NRad. During visual inspection, the blades were stripped layer-by-layer and affected areas or areas of interest were photographed. The observations were documented recording to: Corrosion found, delaminations detected, oily substances observed, resin buildup and water seepage into an area. No quantification of the defects was done, only their detection. These visual inspection results are the major key to qualify what are observed on the neutron radiographs and in the Shearography results.

2.2. Neutron radiography

2.2.1. Principle

As a complement to X-ray radiography, NRad comprises of a similar setup whereas the auxiliary equipment needed consist of a radiation source, and a detection system. For any radiation, which passes through matter, Eq. (2) describes the attenuation of the beam of radiation.

$$\phi = \phi_0 e^{-\Sigma\rho x}, \tag{2}$$

where ϕ is the radiation intensity after attenuation by sample ($n\,cm^{-2}\,s^{-1}$), ϕ_o the radiation intensity without sample ($n\,cm^{-2}\,s^{-1}$), Σ the attenuation coefficient ($cm^2\,g^{-1}$), ρ the density of sample ($g\,cm^{-3}$), and x the thickness of sample (cm)

In the detection of $Al(OH)_3$ (hydrargilite of bayerite), AlO(OH) and water in aluminium structures, the high scattering neutron attenuation cross section of hydrogen ($2.4\,cm^{-1}$) vs. the low neutron attenuation cross section of Al ($0.086\,cm^{-1}$), makes aluminium almost transparent to neutrons but the corrosion products, oil or water ingress are highly opaque (Rant et al., 1986a).

2.2.2. NRad equipment and experimental procedure

The thermal NRad facility is situated on the beam port floor of the SAFARI-1 nuclear research reactor, which is located at Pelindaba, 30 km west of Pretoria. A maximum thermal neutron flux of $1.2 \times 10^7\,n\,cm^{-2}\,s^{-1}$ is delivered at the object under investigation within the NRad facility (Fig. 5).

In addition to direct neutron radiography performed with the aid of a 0.01 mm Gd converter screen, T200 Kodak film and vacuum cassette, which have an intrinsic spatial resolution of 50 μm, the thermal neutron flux available at this beam port enables the utilization of a low light level charged couple device (CCD) camera detection system (de Beer and Strydom, 2000).

Prior to radiography, the blades were cleaned with acetone to remove all visible contaminants from the samples. Part of the roof of the facility was removed and the samples were hoisted by crane into the containment and into the neutron beam path.

Because of the higher spatial resolution of the direct film method (50 μm) as well as the low gamma component of the neutron beam, it was decided to perform direct film neutron radiography. An exposure of 45 s with a vacuum cassette, together with a new type of T200 Kodak film and normal machine processing, produced high quality radiographs. The images were placed on a light table for evaluation and digitized with a commercial digital camera for reprint.

For CCD imaging, 50 frames were integrated to obtain a high S/N ratio digitized image or radiograph. The resultant image was subtracted from the background image to improve on the S/N quality. The final image was again electronically enhanced to obtain a full dynamic range (8 bit) image.

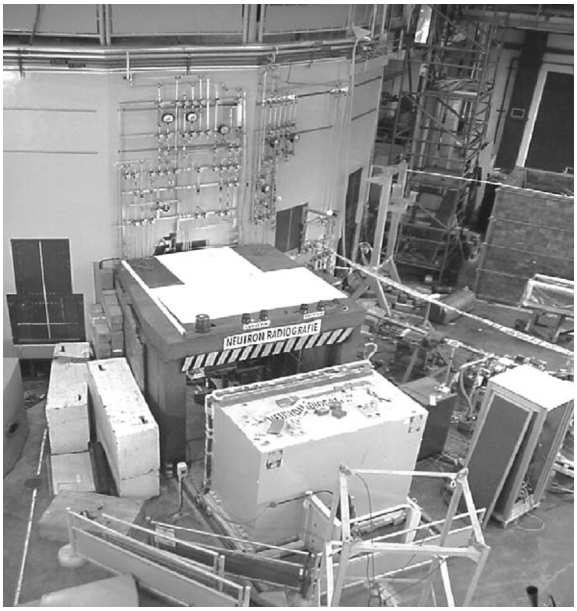

Fig. 5. NRad facility at NECSA.

3. Results

3.1. Quality of film vs. CCD NRad radiographs

NRad-radiographs (CCD image left and direct film image right) of the same blade area are shown in Fig. 6. The difference in detection capability of the defect due to the higher spatial resolution of the film method versus the CCD imaging method can be clearly seen. On this radiograph, corrosion products are found on the tip area of the blade marked by the rectangle.

3.2. Defects observed by the NDE methods

3.2.1. Water and oil

Water and/or oil ingress in the structure of the rotor blades are the most common defect detected by NRad because of the high neutron attenuation ($>2.0\,cm^{-1}$) of these substances with respect to aluminium ($0.098\,cm^{-1}$). Fig. 7 shows the spar area on the blade with ingress of oil, as anomaly occurred normally in the spar region of the cuff area and is seen as black areas on both the images.

3.2.2. Corrosion

Aluminium corrosion can only be detected with NRad by its corrosion products, if present. In practice, Bayerite constitutes 60–90% of the corrosion products while other organic compounds like various Al-salts, oxides and monohydrates are also present (Rant et al., 1986b). The detect ability of these compositions depends heavily on their thickness and composition. Fig. 8 shows clearly the corrosion products on the blade indicated by the oval.

3.2.3. Delaminations

Shearography results. Using Digital Shearography, irregular fringe patterns indicate a deviation from the expected deformations due to heating of the helicopter blade. Fig. 9 (left) is a good fringe representation of a

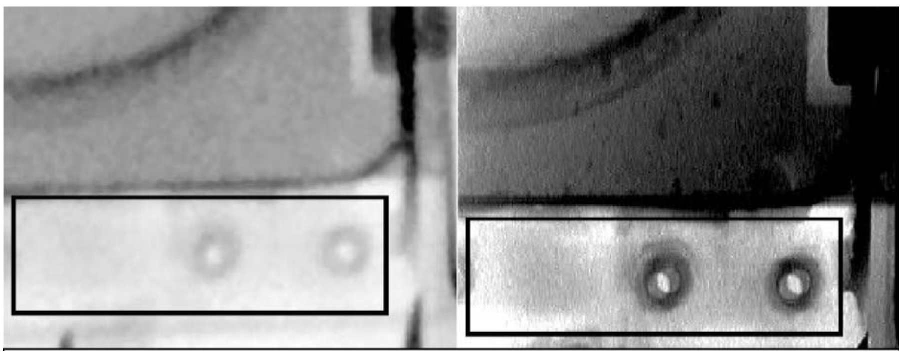

Fig. 6. CCD-neutron radiograph (left) and Direct film neutron radiograph (right).

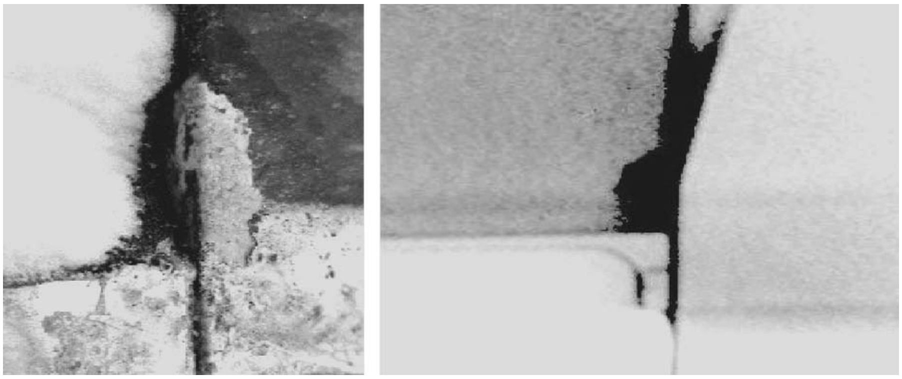

Fig. 7. Photograph (left) and NRad (right) show ingress of oil.

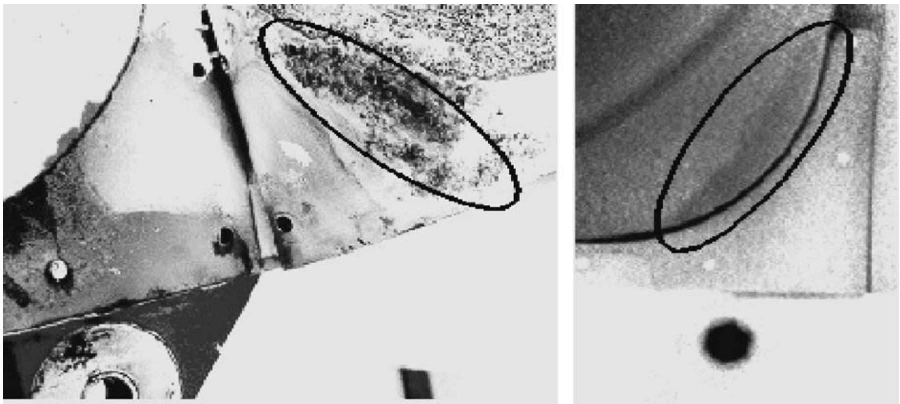

Fig. 8. Photograph (left) and neutron radiograph (right) shows corrosion products.

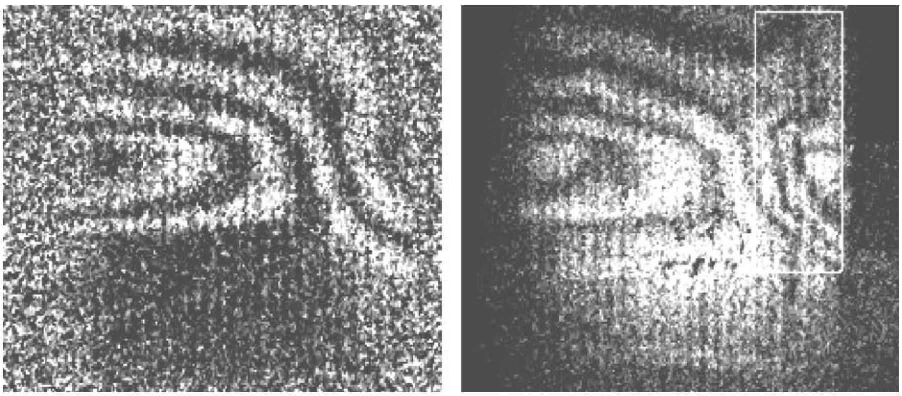

Fig. 9. Good fringe pattern (left) and irregular fringe pattern (right).

defect-free section from a section of a blade while an irregularity in fringe pattern Fig. 9 (right) indicates an anomality in the same region of another blade.

White boxes are added to Fig. 9 (right) and Fig. 10 to indicate the area where irregularities exist. These irregularities indicate a subsurface defect within the structure. The exact type of defect cannot be determined without a "fingerprinting" database, which can be created from a set of known types of defects. Fig. 10 shows a delamination in the cuff area of

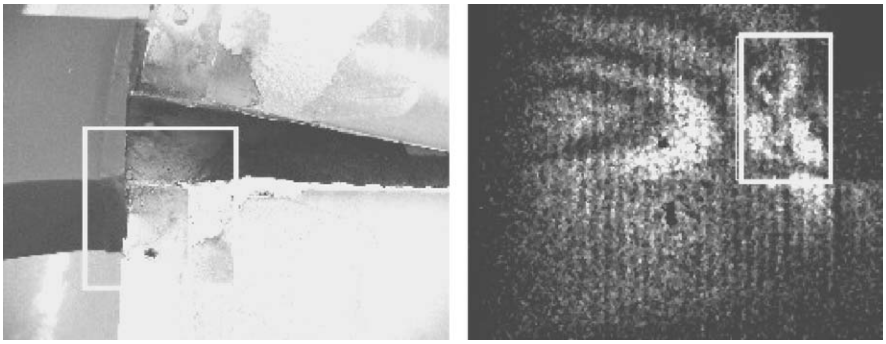

Fig. 10. Photograph (left) and Shearograph (right) of a delamination.

Fig. 11. Photograph (left) and NRad image (right) of delaminations.

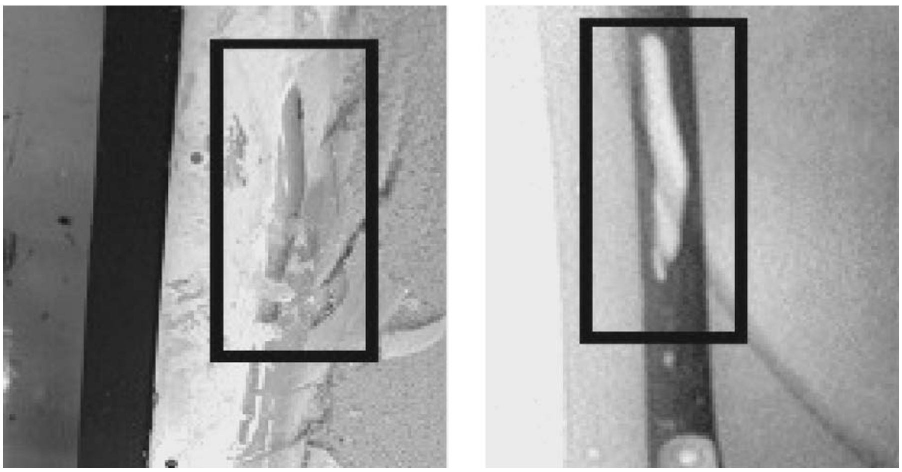

Fig. 12. Photograph (left) and NRad image (right) of lack of resin.

the blade on the photograph (left) which is presented as an irregularity in the fringe pattern on the Shearograph (right).

Neutron Radiography results. Although delaminations are associated with oil, water and corrosion product anomalies, some other delaminations occur due to improper adhesive or contact. With NRad some delaminations (white on the radiograph) of the outer skin at the foam area on the blade was detected as Fig. 11 shows.

Table 1
Number of anomalies detected by NDE method in 20 inspected blades

Type of defect	CUFF AREA			TIP		
	Visual inspection	NRad	Shearography	Visual inspection	NRad	Shearography
Oil and water	12	12	2	2	2	No detection performed/no results
Corrosion	5	2	0	5	3	
Delamination Leading edge	20	1	18	3	0	
Delamination Trailing edge	17		1			
Resin buildup Lack of resin	1	1	0	1	1	
Previous repairs	11	0	6	0	0	

3.2.4. Resin buildup/lack of resin

Within the blade, resin helps to bond the relevant parts of the blade together. A lack of resin, which can be described as an abnormality, occurs in a minor number of blades and could be detected by NRad due the high neutron attenuation of resin. An abnormality within the resin is shown white on the neutron radiograph as Fig. 12 indicates.

3.3. Summary of results

Table 1 is a summary of the number of anomalies detected by the three different NDE methods.

From Table 1 it is evident that the Shearography method produced excellent results in the detection of the delaminations found by visual inspection on the leading edge of the cuff area while NRad successfully could identify the oil/water ingress. The lack of detection in early stages of corrosion with NRad is due to the "masking" effect of other sources of attenuation like paint, adhesive and foam core.

4. Conclusion

This paper shows that NRad and Shearography complement each other in the detection of anomalies in helicopter structures. Where Shearography shows potential to detect delaminations at the skin interface of the blades, NRad shows potential for the detection of corrosion and oil ingress. In certain areas previous repairs that had been performed by adding a new bonding agent to that area. Shearography has revealed that the object's response to an applied stress in that area is affected and that the stress distribution is irregular.

The lack of detection in early stages of corrosion with NRad can be ascribed to the "masking" effect of other interfering sources of attenuation like paint, adhesive and foam core. Although NRad to a certain extent successfully detected corrosion, which was the main objective for this study, abnormalities other than corrosion, was also detected e.g. oil/water ingress into certain areas, delaminations and lack of resin.

In order to increase the effectiveness and sensitivity of NRad for corrosion detection, reference specimens have to be prepared which include all the attenuation sources to be considered for the quantification of the masking effect and further development of NRad in this regard.

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