Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Evaluation of in-service non-destructive inspection methods for composite aerospace structures

Report no.
NLR-TP-2011-336

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Report classification
UNCLASSIFIED

Date
November 2011

Knowledge area(s)
Levensduurbewaking en onderhoud van vliegtuigen

Descriptor(s)
Non-destructive inspection
Composite
Ultrasonic phased array
Shearography
Thermography

Problem area

The use of composite components in military primary aircraft and helicopter structures is increasing gradually due to the opportunities they present for weight saving. In addition to their high specific stiffness and strength, other advantages include their superior fatigue performance and the possibility to integrate sensors or actuators. For present generation fighter aircraft approximately 5% to 10% of the structural weight consists of composite materials. For the next generation fighter aircraft and helicopters, however, the use of composites will increase to approximately 40% to 50% of the structural weight.

To anticipate on the increasing use of composites a National Technology Programme (NTP) was initiated on the in-service non-destructive inspection (NDI) and repair of composite structures. The NTP was funded by the Ministry of Defence in The Netherlands. The aim of the NTP was to develop tools and procedures that enable cost-effective inspection and repairs of composite structures for the next generation aircraft and helicopters with spin-off to naval applications.

Description of work

This report describes the NDI relevant aspects of the NTP. Successively, the following topics

This report is based on a presentation held at the VIth International Workshop NDT in Progress, Prague, 10-12 October 2011.

are addressed: relevant structural details and type/size of damage, manufacture of specimens, selection of in-service NDI methods, and evaluation of the selected NDI methods. An important aspect of the evaluation is the capability of the NDI methods for the detection, sizing and depth estimation of the defects present in the specimens. Further evaluation parameters are the portability of equipment, field of view, couplant requirements, speed of inspection, level of training required and the cost of equipment.

Results and conclusions

There is no single in-service NDI method that scores positive for all inspection characteristics. All methods have their specific advantages and limitations that make them more or less suitable for a particular inspection application.
Visual inspection will always be a primary method for the in-service inspection of composite structures. It is capable of detecting relevant impact damages and other surface irregularities.
Automated tap test is low-cost, couplant-free and suitable for smaller areas where impact damage is suspected.
The *BondMaster™* is a relatively low-cost, couplant-free instrument for local inspection of structures. It has, however, a limited detection performance for in-service defects.
Ultrasonic inspection is the primary NDI method for in-service inspection of composite structures, especially regarding its capability for the detection, sizing and depth estimation of defects. A limitation can be the requirement to use a couplant between probe and test part.
The *AcoustoCam™* is a handheld, real-time ultrasonic imaging camera but with a limited field of view.
Ultrasonic phased array (UT-PA) inspection provides the best capabilities for in-service inspection. A position encoder is required in order to produce a C-scan image. The *RapidScan™* uses a UT-PA handheld roller probe that works almost couplant-free. Together with a multi-axis scanning arm it can be used for fast and real-time inspection of relatively large areas.
Shearography and *thermography* are relatively fast, non-contact methods that require no coupling or complex scanning equipment. Impact damages are readily detectable but the detectability for delaminations and disbonds is poor to moderate when compared with UT inspection. The detectable defect size decreases with increasing defect depth. Both methods are not suited for defect depth estimation. However, shearography seems promising for the inspection of honeycomb sandwich structures and thermography for the inspection of water ingress in composite structures.

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Evaluation of in-service non-destructive inspection methods for composite aerospace structures

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This report is based on a presentation held at the VIth International Workshop NDT in Progress, Prague, 10-12 October 2011.

This publication has been refereed by the Advisory Committee AEROSPACE VEHICLES.

Customer	Defence Materiel Organisation
Contract number	N04/27
Owner	Defence Materiel Organisation
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	November 2011

Approved by:

Author	Reviewer	Managing department
8/11/11	8/11/11	8/11

Summary

This report describes an evaluation of promising, mobile non-destructive inspection (NDI) methods for the in-service inspection of composite aerospace structures. The evaluation makes use of carbon fibre reinforced specimens representative for primary composite structures in current and next generation aircraft and helicopters. The specimens comprise solid laminates and sandwich structures with/without stiffeners, and include relevant damage types such as impact damage, interply delaminations and disbonds. A range of promising, mobile NDI methods are evaluated including visual inspection, vibration analysis, ultrasonic inspection (including different phased array methods), shearography and thermography inspection. An important aspect of the evaluation is the capability of the NDI methods for the detection, sizing and depth estimation of the defects present in the specimens. Further evaluation parameters are the portability of equipment, field of view, couplant requirements, speed of inspection, level of training required and the cost of equipment. The report gives an overview of the advantages and limitations of the different NDI methods, and concludes with general guidelines for the in-service inspection of composite aerospace structures.

Contents

Abbreviations

BVID	Barely Visible Impact Damage
CFRP	Carbon Fibre Reinforced Plastic
FLIR	Forward Looking InfraRed
IR	Infrared
LCD	Liquid Crystal Display
NDI	Non-Destructive Inspection
NTP	National Technology Programme
PA	Phased Array
PC	Pitch Catch
PE	Pulse-Echo
PTFE	Polytetrafluoroethylene
TOF	Time-Of-Flight
UT	Ultrasonic Testing

1 Introduction

The use of composite components in military primary aircraft and helicopter structures is increasing gradually due to the opportunities they present for weight saving. In addition to their high specific stiffness and strength, other advantages include their superior fatigue performance and the possibility to integrate sensors or actuators. For present generation fighter aircraft approximately 5% to 10% of the structural weight consists of composite materials. For the next generation fighter aircraft and helicopters, however, the use of composites will increase to approximately 40% to 50% of the structural weight.

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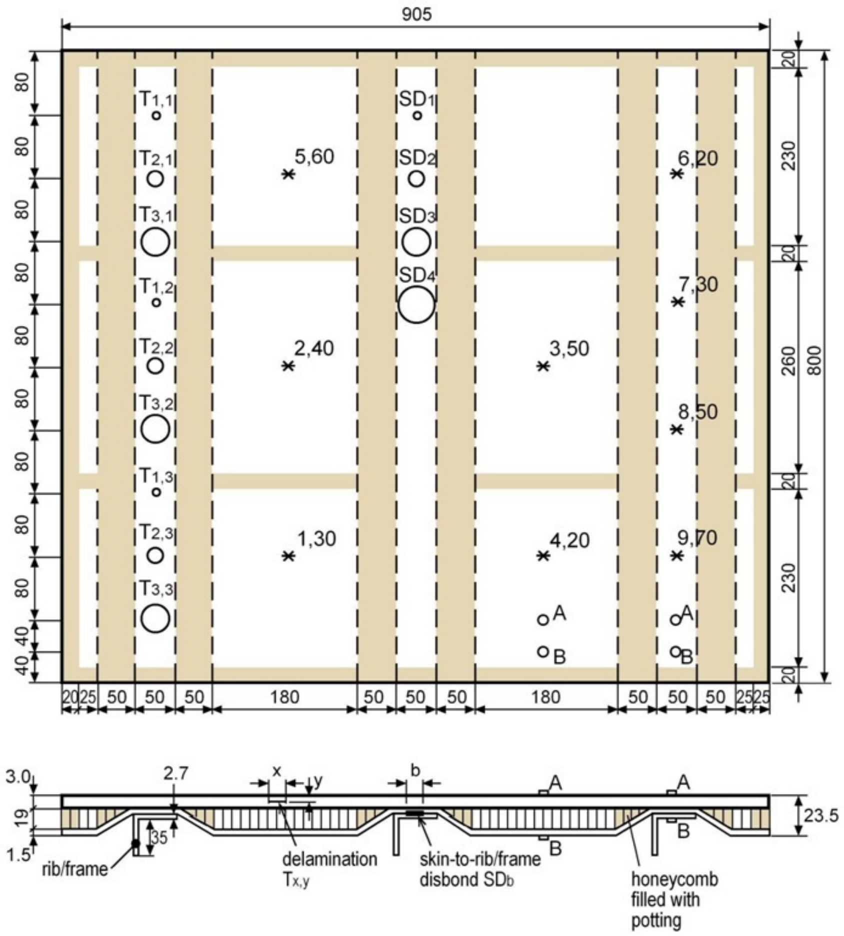
This report will describe the NDI relevant aspects of the NTP. Successively, the following topics will be addressed: relevant structural details and type/size of damage, manufacture of specimens, selection of in-service NDI methods, and evaluation of the selected NDI methods. The report will conclude with general guidelines for the in-service inspection of composite aerospace structures.

2 Composite benchmark

A composite benchmark was defined to serve as reference for the evaluation of NDI methods. First, a selection of structural details in primary composites being relevant for next generation aircraft and helicopters was made. This resulted in the following four structural details: solid laminate, solid laminate with T-shaped stiffeners, plain sandwich structure, and chamfered sandwich structure with L-shaped ribs/frames. These structural details were used in the manufacturing of five carbon fibre reinforced plastic (CFRP) reference panels (of the laminate configuration two different thicknesses were used: 2.7 and 5.4 mm). Figure 1 gives a depiction of the most complex structural detail, viz. a chamfered sandwich structure with L-shaped ribs/frames. Complete information on all structural details is given in reference 1.



Defect type	
Delamination $T_{x,y}$	x = 1, 2 or 3 Diameter 0.25; 0.5 or 1.0 inch y = 1, 2 or 3 Depth 0.75, 1.50 or 2.25 mm
Skin-to-rib/frame disbond SDb	b = 1, 2, 3 or 4 Diameter 0.25; 0.5; 1.0 or 2.0 inch
Impact $+^{x,y}$ $*^{x,y}$	+ / * Impactor tup diameter 0.5/1.0 inch x = Impact number; y = Impact energy [J]
Adhesive sticker	A ∅12 mm on top side of skin B ∅12 mm on bottom side of skin/stiffener

Fig. 1 Chamfered sandwich structure (NTP-D) with 3 L-shaped ribs/frames

The material of the CFRP specimens is based on carbon fabric (HTA Aerospace grade carbon fibres and HexPly M18-1 resin); a certified material used for instance in the NH90 helicopter. For the sandwich specimens a Hexcel HRH-10 Nomex honeycomb core with thickness 19 mm and cell size 0.25 inch was used. Three specimens (NTP-A1/A2/C) were partly covered by a copper wire mesh (Spörl KG, embedded in the resin of the surface layer) functioning as a surface protection system for e.g. lightning strike occurrence.

All specimens include a number of the following real and artificial defects, depending on the panel configuration:

- Range of impact damage with sizes relative to the BVID-value. Barely visible impact damage was herewith defined as impact damage with an initial dent depth of 1.0 mm.
- Interply delaminations in the (outer) skin with diameter in the range of 0.25 to 1.0 inch.
- Skin-to-stiffener disbonds with diameter in the range of 0.25 to 2.0 inch.
- (Outer) skin-to-honeycomb core disbonds with diameter in the range of 0.25 to 2.0 inch.

The interply delaminations and disbonds were simulated by Tygavac TFG 075/1 foils of different diameter. Tygavac TFG 075/1 (Fothergill Tygaflor Ltd.) is a non-porous PTFE (Teflon) coated glass fabric with a nominal thickness of 0.075 mm. The low-velocity impact damages in the specimens were created by means of a guided drop weight device with an impactor with hemispherical steel tup of diameter 0.5 or 1.0 inch. All specimens were provided, before impact, with a standard paint system used on military weapon systems (Aerodur 37047 CF primer and PUR-Declack topcoat).

3 Base-line ultrasonic C-scan inspection

Ultrasonic C-scan inspection of the specimens was done to provide a base-line view of the present defects against which the selected mobile *in-service* NDI methods would be compared. UT C-scan is currently the primary *production* inspection technique for composite structures after manufacturing. Figure 2 shows the NLR C-scan equipment and an example of the base-line inspection for panel NTP-B (solid laminate with 3 T-shaped stiffeners). Both the immersion and water-jet method (for the sandwich structures) were used for the base-line inspection.

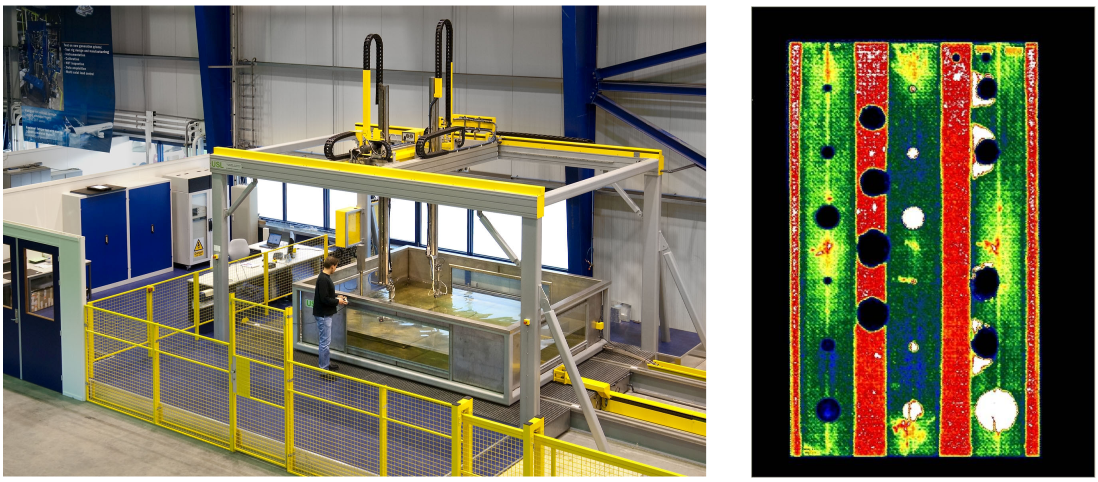


Fig. 2 Ultrasonic C-scan equipment (left) and an example of the inspection of panel NTP-B (solid laminate with 3 T-shaped stiffeners; pulse-echo inspection with monitoring of the backwall-skin reflection)

4 Selection of in-service NDI methods

Promising, mobile NDI methods for the in-service inspection of composite aerospace structures were selected using the following criteria:

- Practical in use (portable, one-sided accessibility, limited safety precautions, etc.).
- Proven applicability for the in-service inspection of composite materials, and more specifically, for the detection of the defect types mentioned in Chapter 2.
- Cost-effective.

Many NDI methods were down-selected because of these criteria, e.g. laser-ultrasonics because of its relatively high cost, low kV radiography because of the necessary safety precautions, and some speckle techniques because of the sensitivity to vibration. Finally, the following NDI methods were selected for inclusion in the NTP inspection programme:

- Visual inspection.
- Vibration analysis, mechanical impedance inspection.
- Ultrasonic inspection (handheld UT camera, dry-coupling roller probe, phased array UT).
- Shearography inspection.
- Thermography inspection.

Figure 3 gives a presentation of the selected NDI methods.

Fig. 3 Selected in-service NDI methods for inclusion in the NTP inspection programme

5 Evaluation of in-service NDI methods

Reference 1 presents in detail the results of the evaluation, with emphasis on the capabilities of the different NDI methods for the detection, sizing and depth estimation of defects present in the NTP panels. The following, qualitative description can be given for the NDI methods:

5.1 Visual inspection

Visual inspection is a primary method for the in-service inspection of composite structures. It is relatively fast and has a large field of view. General visual inspection of the NTP panels was performed with the naked eye under conditions of good lighting and surface cleanliness. The sensitivity of inspection was enhanced by using a pocket-torch and by viewing the surfaces also from a low angle. The evaluation showed that visual inspection is capable of detecting impact damages with an initial impact dent depth larger than 0.5 mm (actual impact dent depth larger than 0.3 mm considering relaxation of the dent depth in-service), well below the BVID value of 1.0 mm. On the other hand, it can not detect delaminations and disbonds and it is not suited for defect sizing and defect depth estimation.

5.2 Automated tap test

Automated tap test of the NTP-panels was performed by NDT personnel of the Netherlands Defence using the Woodpecker WP-632 (Fig. 3). The Woodpecker is a light-weight hand-held device (about 0.5 kg) that uses a battery-driven solenoid hammer with a force sensor (accelerometer) built in the hammer tip. Practically, the time during which the hammer is in contact with the surface of the test part is measured. This contact time will increase in areas with defects such as disbonds that lower the local contact stiffness of the part. The Woodpecker is a low-cost, couplant-free inspection unit for smaller areas where damage is suspected; for global inspection of large surface areas it is less suited because of its spot measurement performance. Impact damages are generally well detectable; only a few minor impacts were missed in the evaluation. The detectability for delaminations and disbonds, on the other hand, was varying and not always consistent. Furthermore, a varying skin thickness (e.g. lay-up differences) or the presence of back-up structure can influence the tap tester response. The capability for defect sizing is limited and the technique is not suited for defect depth estimation. The newer model WP-632AM (with LCD display that shows the measured contact times) together with a separate WP-632M monitoring unit may have an increased detection performance for in-service defects.

5.3 BondMaster™ inspection

The BondMaster™ was selected for the evaluation because of its relatively low cost and its multimode inspection capabilities (pitch-catch, mechanical impedance, resonance). Inspection of the NTP panels with a BondMaster 1000e+ (Fig. 3) was performed by Olympus France (Rungis Cedex, near Paris). The couplant-free pitch-catch (PC) technique proved to be the most promising inspection mode for the NTP panels, see figure 4. In the evaluation, however, the BondMaster showed a limited detection performance for in-service defects; the detectability was also quite varying. Impact damage is the defect type best detectable with the BondMaster and not, as might be expected, the different disbond types. Although couplant-free, the BondMaster is not well suited for global inspection of large surface areas (because of its spot measurement performance) but more for the verification of suspect areas.

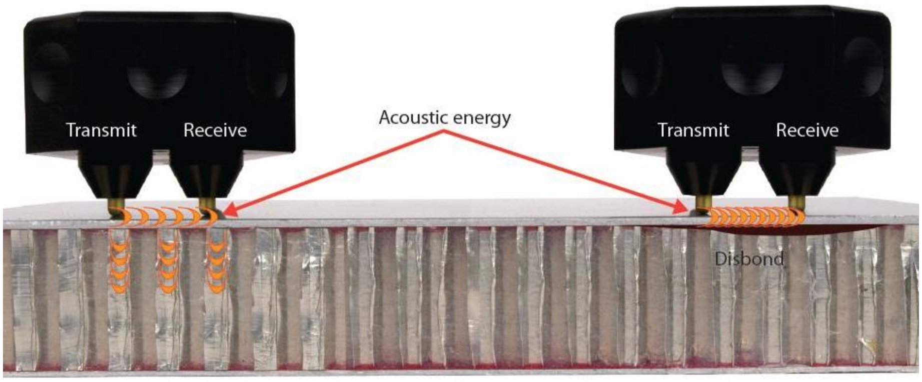
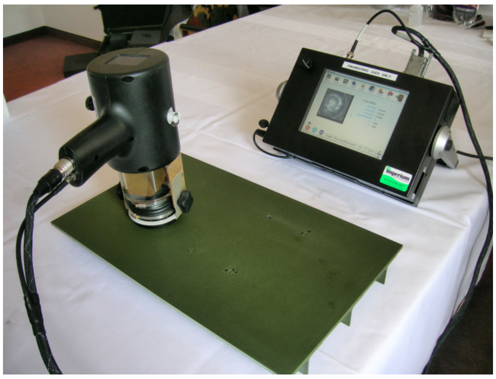


Fig. 4 BondMaster™ inspection with the pitch-catch technique (figure from reference 2)

5.4 Handheld UT camera

The AcoustoCam™ is a handheld ultrasonic imaging camera developed by Imperium, Inc. for fast and real-time UT inspection (Ref. 3). It produces a high-resolution C-scan image over an area of the specimen utilising an array of 120 x 120 piezoelectric sensing elements. The array is responsive over a wide array of ultrasound frequencies, although most imaging is done in the range of 1 to 7.5 MHz. A separate, 'transparent' PVDF sensor in front of the main UT transducer is used to provide a conventional A-scan presentation of the test part with information about the depth of present defects. Both the C-scan image and A-scan presentation are displayed on the control unit of the camera head, see figure 5.



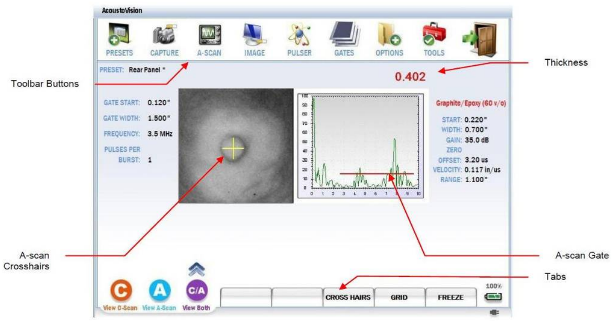


Fig. 5 Handheld ultrasound camera AcoustoCam™ i500 (left) and data presentation on the control unit (right)

Inspection of the NTP panels by Imperium showed that the AcoustoCam can indeed be used for relatively fast and real-time UT inspection of smaller areas where damage is suspected. For global inspection of large surface areas, however, the camera is less suited because of the limited field of view (about 1 square inch). A limitation, inherent to ultrasonic testing, is that a couplant is required between the camera and test part. The detectability for defects is generally good, especially when scanning the camera over the test specimen. For honeycomb structures the camera was somewhat less successful in the evaluation: some disbonds and impacts were only detectable with limitation. The AcoustoCam can further be used for defect sizing and for defect depth estimation when using the A-scan module of the camera.

5.5 Phased array UT

The ultrasonic phased array (UT-PA) method is a special UT method that makes use of transducers consisting of multiple ultrasonic elements that can each be driven independently. The PA transducers can have a different geometry (e.g. linear, matrix and annular) and the PA beams can be steered, scanned, swept and focused electronically (Ref. 4). The OmniScan™ of Olympus NDT was selected for the investigation because it is the instrument currently most often used and because of its availability at NLR. UT-PA inspection of the NTP-panels was done with an Olympus PA probe 5L128-I2 (frequency 5 MHz, 128 elements with pitch 0.6 mm) and matching wedge SI2-0L-IHC (thickness 22 mm), see figure 6. Ultrasonic coupling between transducer and test part was accomplished by applying a water film between the wedge and test part; the water is herewith guided through two small diameter holes machined in the wedge. Further, an encoder was attached to the wedge to enable the scanning and providing C-scan presentations of the NTP panels.

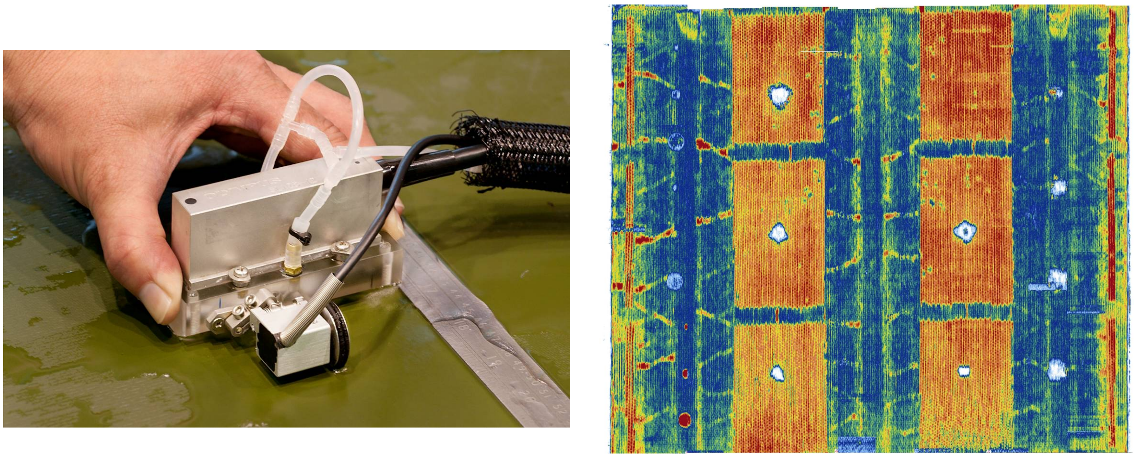


Fig. 6 UT phased array inspection of panel NTP-D (chamfered sandwich structure with 3 L-shaped stiffeners)

The evaluation showed that UT-PA is very suitable for the in-service inspection of composites. The handheld probe can be used for relatively fast and real-time UT inspection of larger areas. The detectability for defects such as delaminations, disbonds and impact damages is excellent. Only three small disbonds with size of 6 mm were qualified as not detectable, and three other defects detectable with limitation. The UT-PA technique can also be used for defect sizing and defect depth estimation with a fair accuracy (about 2 mm for defect sizing and 0.2 mm for depth estimation) and it provides information of the structure configuration of the component under inspection. Time-of-Flight (TOF) scan presentation allows further characterisation and discrimination of different damages by showing their depth differences. The UT-PA technique is however not couplant-free and that can be a limitation for in-service use. Also, careful scanning is necessary in order not to damage any surface protection system present (scratches can occur).

5.6 UT-PA dry-coupling roller probe

The RapidScan™ of Sonatest Ltd. employs a UT phased array probe housed within a rubber coupled and water-filled wheel probe (Ref. 5). The rubber tyre is acoustically matched to water, providing low loss coupling into the test part. The probe can be used without couplant but, generally, a fine water spray on the test part is used for optimum coupling. Wheel probes with 50 mm active array width (64 elements with 0.8 mm pitch) or 100 mm width (128 elements with 0.8 mm pitch) are available. The larger probe is meant for flat surfaces, the smaller one can also be used on slightly curved parts. The transducer frequency can be selected as 2, 5 or 10 MHz. The handheld roller probe together with a 7-axis Faro scanning arm can be used for fast and real-time UT inspection of relatively large areas (figure 7).

Fig. 7 UT-PA RapidScan^{TM} with 50 mm wheel probe and 7-axis Faro scanning arm (right)

Inspection of the NTP panels by Sonatest Ltd. showed that the RapidScan is very suitable for the in-service inspection of composites, being a special UT-PA technique. The detectability for defects such as delaminations, disbonds and impact damages is excellent. Figure 8 gives an example of the inspection of panel NTP-B (solid laminate with 3 T-shaped stiffeners). No defects were missed and only some small defects with size of 6 mm were qualified as detectable with limitation. The RapidScan can further be used for defect sizing and defect depth estimation with a fair accuracy (about 2 mm for defect sizing and 0.2 mm for depth estimation; only in some cases larger deviations occurred). The RapidScan scored best in the NTP evaluation but a limitation can be the relatively high cost of a complete inspection system including scanning arm. The portability of the system may limit its use for inspection areas with limited access.

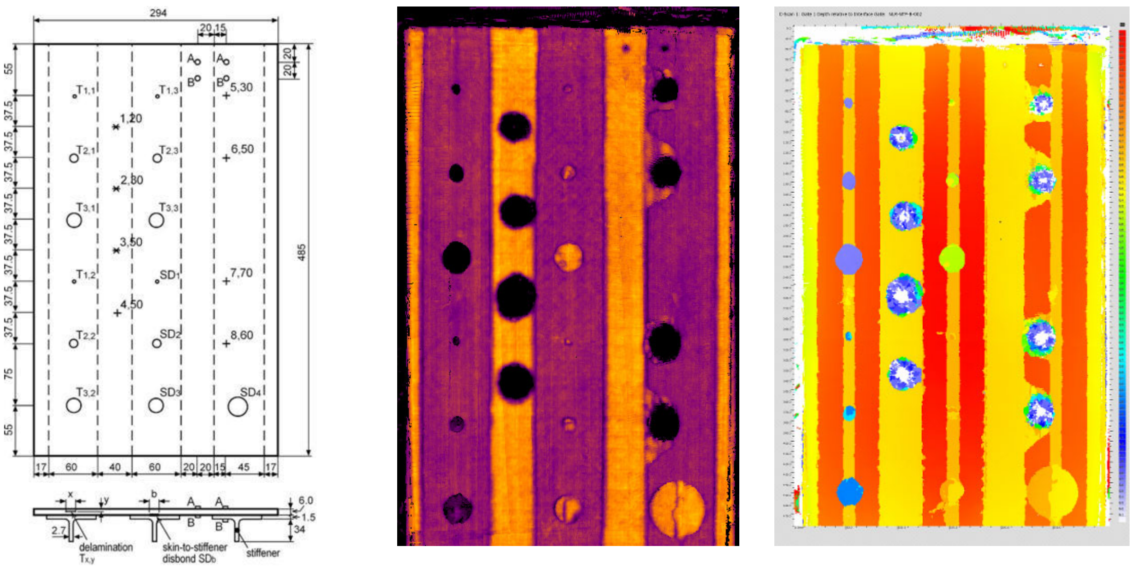


Fig. 8 RapidScanTM inspection of panel NTP-B (solid laminate with 3 T-shaped stiffeners). Amplitude backwall skin C-scan (middle) and TOF-scan (right)

5.7 Shearography

Shearography is an optical method, based on speckle interferometry, for the non-contact measurement of out-of-plane deformations of a material surface (Refs. 6-7). The method has been developed in particular to overcome the sensitivity to external vibrations that is common to standard interferometry techniques. This is achieved by not using a separate reference beam. Instead, the returning object beam is doubly imaged, with one of the coherent images slightly shifted or 'sheared' relative to the other image, see figure 9. Then, a second similar recording is made with the object put under a slight strain. The two speckle patterns are superimposed resulting in a fringe pattern. The fringes do not show the contours of the displacement but of the derivative of the displacement (gradient of deformation). Digital image processing of the data is further done to enhance the defect presentation (e.g. filtering and fringe unwrapping).

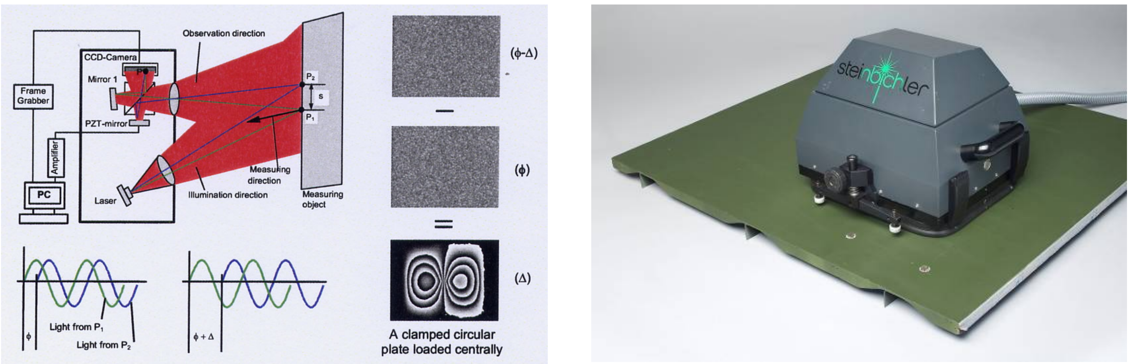


Fig. 9 Shearography inspection set-up (left, from Ref. 6) and ISISmobile 3100 (right, placed on panel NTP-D)

Shearography inspection of the NTP-panels was performed by Steinbichler Optotechnik GmbH (Neubeuern, Germany) using an ISISstation 1200 stationary system and an ISISmobile 3100 mobile system. The latter is a mobile, portable shearography system suitable for in-service inspections (Fig. 9). Thermal load can be applied by heating lamps, and vacuum load can be applied by connecting a vacuum hood which sucks directly to the surface to be inspected. The NTP evaluation showed that shearography is a relatively fast, non-contact technique that requires no coupling or complex scanning equipment. Because of the optical technique the specimen should not have a shiny surface (standard coating is acceptable). The inspection time is largely determined by the limitations of the field of view (220 x 160 mm for the ISISmobile 3100). The impact damages were readily detectable (including the non-visible impacts) but generally undersized when compared to the baseline UT results (Fig. 10).

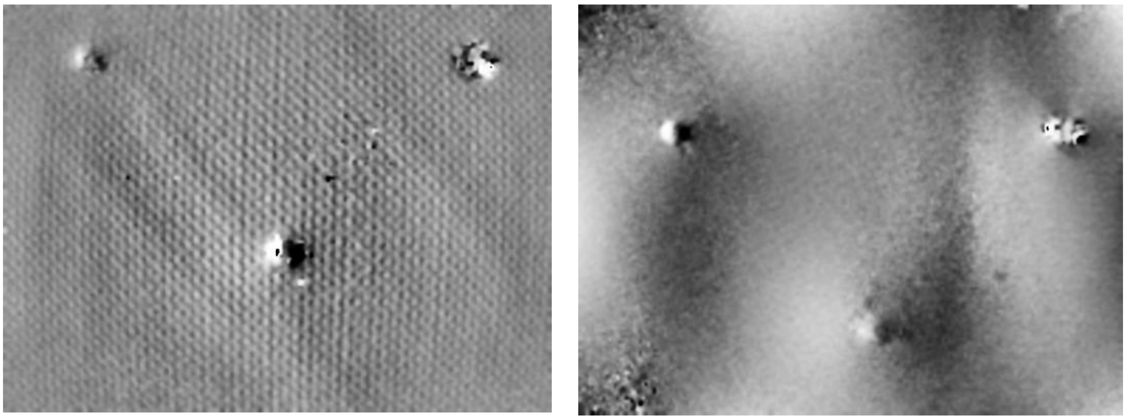


Fig. 10 Shearography inspection of panel NTP-C (sandwich structure, part with three impact damages). Thermal load (left) and vacuum load technique (right)

The detectability for artificial delaminations turned out to be poor; only the vacuum load technique was able to detect some delaminations. The skin-to-stiffener disbonds were not detectable, but the larger skin-to-honeycomb core disbonds were readily detectable, especially with the vacuum load technique. The detectable defect size decreases with increasing defect depth (defect diameter must exceed its depth). Shearography can be used with limitation for defect sizing but the technique is not suited for defect depth estimation. The optimum loading technique depends on the specific inspection configuration but, in general, defects at larger depth are better detectable with vacuum loading. Shearography inspection seems most promising for the inspection of honeycomb sandwich structures.

5.8 Thermography

Infrared thermography is a non-contact NDI method that monitors the heat radiation pattern on the surface of a test part (Refs. 8-9). The method employs light just above the visible part of the electromagnetic spectrum, in the range of about 2 – 14 μm. Passive and active IR techniques can be distinguished but for NDI purposes only the active technique is used: the object is herewith excitated either by an external heat source or by mechanical vibrations. Material defects are then detectable by the corresponding anomalies in the heat distribution pattern on the surface of the test part. Thermographic techniques are well applicable to composite materials because of their relatively low thermal conductivity which implies a slow lateral heat flow with closely spaced isotherms, resulting in a good defect resolution. The detectable flaw size is in general larger than the depth of the flaw.

Thermography inspection of the NTP-panels was performed by Theolt (Wellerlooi, Netherlands). Two inspection set-ups using an external heat source were used: Lockin thermography (low-frequency modulated heating) and transient thermography (transient heat pulse of relatively long duration, more than 10 sec). All inspections used a digital, portable IR camera of FLIR Systems, viz. a ThermoCAM SC6000 (Fig. 11). Recorded images were further analysed using a software package (IR-ndt 1.7) of Automation Technology GmbH, Germany (Ref. 8).

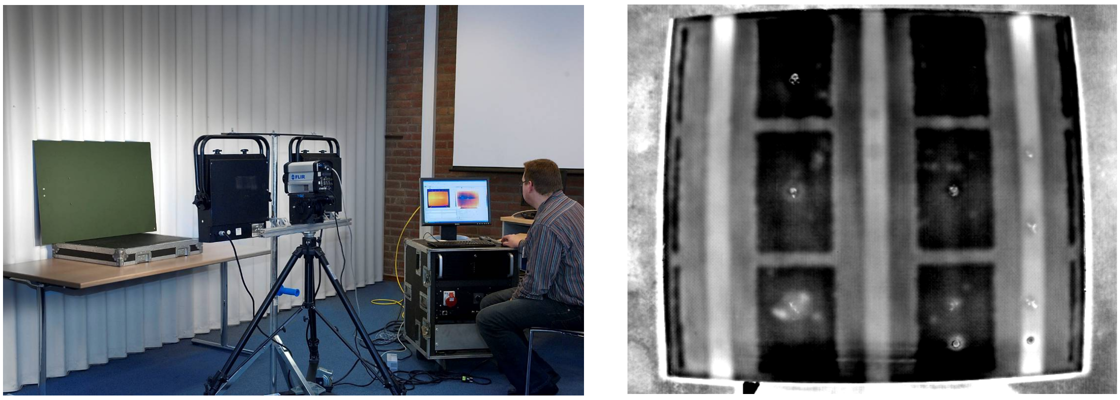


Fig. 11 Thermography inspection set-up (left) and result with Lockin technique for panel NTP-D (right, chamfered sandwich structure with 3 L-shaped stiffeners)

The evaluation showed that thermography is a fast, global and non-contact method that requires no coupling or complex scanning equipment. Panels with a surface area up to 1 m^2 can be inspected with a single exposure technique (Fig. 11, right). All-in-all, the Lockin technique demonstrated a somewhat better performance than the transient technique. The detectable defect size decreases, as for shearography, with increasing defect depth. Most impact damages were readily detectable, except for some smaller and non-visible impacts. The detectability for artificial delaminations turned out to be poor; only some larger, shallow delaminations were detected. The detectability for disbonds was somewhat better: the larger skin-to-stiffener disbonds and skin-to-honeycomb core disbonds were readily detected in the evaluation. Thermography can be used for defect sizing but the technique is not suited for defect depth estimation. Although not considered in this evaluation, thermography seems promising for the inspection of water ingress in composite structures.

6 Summary of the evaluation

Table 1 gives a summary of the capabilities of the different in-service NDI methods for the detection, sizing and depth estimation of defects present in the NTP panels. Furthermore, an estimation of other relevant evaluation parameters such as the portability of equipment, field of view, couplant requirements, speed of inspection, level of training required and the cost of equipment is given. The colours in the table give a rough qualification of the evaluation parameters for the different NDI methods (green – positive, yellow – with limitation, red – negative).

Table 1 Summary of the capabilities of the NDI methods evaluated in the NTP

Inspection Characteristic		NDE technique							
		Visual	Tap Test	Bondmaster	Ultrasonic Inspection			Shearography	Thermography
			Woodpecker	PC Swept/RF	Acoustocam	UT-PA	RapidScan	Heat/Vacuum	Lockin/Transient
Detection	Impact	+	+	0/+	+/++	++	++	++	+
	Delamin.	-	0	0	++	++	++	-/0	-/0
	Disbond	-	0	0	+	+/++	++	0	0/+
Defect sizing		-	0	0	+	++	++	+	+
Depth estimation		-	-	-	+	++	++	-	-
Portability		++	++	++	+	+	+	+	0
Field of view		~1 m2	Spot	Spot	25 mm2	68 mm	50-100 mm	220x160 mm	~1 m2
Couplant required		No	No	No	Yes	Yes	Minimal	No	No
Inspection speed		++	0	0	+	+	+	+	++
Level of training		Low	Low	High	Medium	High	High	High	High
Equipm. costs [k€]		0	< 10	12-15	40-60	40-60	95-110	100-120	130-150

The table shows that there is no single in-service NDI method that scores positive for all inspection characteristics. All methods have their specific advantages and limitations that make them more or less suitable for a particular inspection application. However, the following qualitative description can be given:

- *Visual inspection* will always be a primary method for the in-service inspection of composite structures. It is capable of detecting relevant impact damages and other surface irregularities.
- *Automated tap test* is low-cost, couplant-free and suitable for smaller areas where impact damage is suspected.
- The *BondMaster™* is a relatively low-cost, couplant-free instrument for local inspection of structures. It has, however, a limited detection performance for in-service defects.
- *Ultrasonic inspection* is the primary NDI method for in-service inspection of composite structures, especially regarding its capability for the detection, sizing and depth estimation of defects. UT inspection is relatively fast. A limitation can be the requirement to use a couplant between probe and test part.
  - The *AcoustoCam™* is a handheld, real-time ultrasonic imaging camera but with a limited field of view.
  - *Ultrasonic phased array* (UT-PA) inspection provides the best capabilities for in-service inspection. A position encoder is required in order to produce a C-scan image.
  - The *RapidScan™* uses a PA handheld roller probe that works almost couplant-free. Together with a multi-axis scanning arm it can be used for fast and real-time UT inspection of relatively large areas.

- *Shearography* and *thermography* are relatively fast, non-contact methods that require no coupling or complex scanning equipment. Impact damages are readily detectable but the detectability for delaminations and disbonds is poor to moderate when compared with ultrasonic inspection. The detectable defect size decreases with increasing defect depth. Both methods are not suited for defect depth estimation. However, shearography seems promising for the inspection of honeycomb sandwich structures and thermography for the inspection of water ingress in composite structures.

7 Recommendations

Further investigation is recommended on the following topics:

- Inspection configurations not considered in this evaluation, such as curved panels (curvature can limit the application of e.g. large phased array probes) and panels with other defect types (e.g. water ingress in honeycomb structures).
- In-service inspection of repaired composite structures. Topics of consideration are the monitoring of damage growth at/near the repair location such as delaminations within a repair patch, disbond (or poor bonding) between a repair patch and the sub-structure, and delaminations in the sub-structure underneath the repair. Also the detection of impact damage at/near the repair patch location needs attention.

For these items an NDI method that does not require a couplant would be highly beneficial.

Acknowledgements

The authors would like to acknowledge the support and funding of the Defence Materiel Organisation (DMO) of the Ministry of Defence (MoD) in The Netherlands. Further, the NDI participation of the following parties is acknowledged: MoD for Woodpecker inspection, Olympus France for BondMaster™ inspection, Imperium Inc. for AcoustoCam™ inspection, Sonatest Ltd. for RapidScan™ inspection, Steinbichler Optotechnik GmbH for shearography inspection and Theolt for thermography inspection.

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