Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2013-435

In-service inspection and monitoring of composite aerospace structures

J.H. Heida and J.M. Müller

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Anthony Fokkerweg 2
P.O. Box 90502
1006 BM Amsterdam
The Netherlands
Telephone +31 (0)88 511 31 13
Fax +31 (0)88 511 32 10
www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

In-service inspection and monitoring of composite aerospace structures

Report no.
NLR-TP-2013-435

Author(s)
J.H. Heida
J.M. Müller

Report classification
UNCLASSIFIED

Date
October 2013

Knowledge area(s)
Levensduurbewaking en onderhoud van vliegtuigen

Descriptor(s)
Non-destructive inspection
Composite
Impact damage

Problem area

The use of composites in military primary aircraft and helicopter structures has increased significantly in the last ten years 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. An example of the application of composites is the NH90 helicopter which already has an all-composite fuselage. To anticipate on the increased use of composites a National Technology Programme (NTP N04/27) was initiated in The Netherlands 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.

Description of work

This paper describes the NDI relevant aspects of the NTP. A range of NDI methods are evaluated such as visual inspection, vibration analysis, phased array ultrasonic inspection, shearography and thermography inspection. Furthermore, the results of a separate study on the detectability of impact damage due to runway debris on thick composite specimens are discussed (SRP project 59902N funded by NL Agency). Whether in-service damage has to be detected depends on the design philosophy of the aircraft structure. This paper discusses the main design philosophies and in more details the damage tolerance approach. Finally, an alternative to NDI at regular intervals (scheduled maintenance) is treated, so-called structural health

This report is based on a presentation held at the RTO AVT-224 Workshop on Advanced Non-Destructive Evaluation Techniques for Polymer Based Composites in Military Vehicles, Riga, October 10-11, 2013.

monitoring (SHM) techniques that are being developed to assess the real-time condition of a structure using on-board systems with advanced sensors that are permanently attached to the structure. The paper concludes with general guidelines for the in-service inspection and monitoring of composite aerospace structures.

Results and conclusions

Damage tolerance requirements for composite aerospace structures should be interpreted so that as long as damage occurring in-service cannot be detected visually, it should not be structurally significant in the sense that is does not affect the safety during the aircraft life. In terms of load capability this implies that such damage should never reduce the structural strength below ultimate load (UL) capability. Only detectable damage may cause structural degradation below UL (but never below LL, limit load – the maximum load per fleet lifetime) and should be timely detected by visual inspection or more advanced NDI methods. The inspection interval should be related to the probability of damage occurrence, depending e.g. on the structure type. In the period before detection, any damage should not show significant growth. After detection, the damage should be repaired to restore UL capability or the component should be replaced.

The recommended in-service NDI method is ultrasonic conventional or, preferably, ultrasonic phased array inspection for the detection and characterization (size, depth) of relevant impact damage, delaminations and disbonds. Automated tap test may be considered for low-cost, couplant-free detection of relevant impact damage. Shearography and thermography are considered to be less applicable because of their poor to moderate defect characterization capabilities, when compared to ultrasonic inspection. But, thermography and shearography may be optional, non-contact techniques (especially thermography) for specific inspection configurations such as curved panels and repaired structures, and for the inspection of specific defect types such as water ingress in honeycomb structures.

The statement about visual inspection as a primary inspection method should also be the basis for implementation of an SHM program for composite aerospace structures, especially for the global monitoring of large surface areas. Local SHM application employing on-board sensors, on the other hand, is thought to have potential for composite structures, especially for the monitoring of local, critical areas or areas that are poorly accessible.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 88 511 31 13, Fax +31 88 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2013-435

In-service inspection and monitoring of composite aerospace structures

J.H. Heida and J.M. Müller

This report is based on a presentation held at the RTO AVT-224 Workshop on Advanced Non-Destructive Evaluation Techniques for Polymer Based Composites in Military Vehicles, Riga, October 10-11, 2013.

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

Customer	Ministry of Defence, NL Agency
Contract number	NTP N04/27, SRP 59902N
Owner	NLR
Division NLR	Aerospace Vehicles
Distribution	Unlimited
Classification of title	Unclassified
	October 2013

Approved by:

Author	Reviewer	Managing department
J.H. Heida	D.J. Platenkamp	A.M. Vollebregt
Date: 02-10-2013	Date: 03-10-2013	Date: 22/10/'13

Summary

The use of composites in military aircraft and helicopter structures has increased significantly in the last ten years. To anticipate on this increased use a National Technology Programme (NTP N04/27 funded by NL MoD) was initiated in The Netherlands on the in-service non-destructive inspection (NDI) and repair of composite structures. A range of NDI methods were evaluated such as visual inspection, vibration analysis, phased array ultrasonic inspection, shearography and thermography inspection. The evaluation made use of carbon fibre reinforced specimens representative for primary composite aerospace structures, including relevant damage types such as impact damage, delaminations and disbonds. Important aspects of the evaluation were the capability for defect detection and characterization, portability of equipment, field of view, couplant requirements, speed of inspection, level of training required and the cost of equipment. This paper reviews the NDI results of the NTP. Furthermore, the results of a separate study on the detectability of impact damage due to runway debris on thick composite specimens are discussed (SRP project 59902N funded by NL Agency). General guidelines for the in-service inspection of composite aerospace structures are given. Visual inspection is regarded as a primary method for the detection of impact damage and other surface irregularities. As long as damage occurring in-service cannot be detected visually, it should not be structurally significant in the sense that is does not affect the safety during the aircraft life. More advanced NDI is needed in case of suspected damage during visual inspection. The recommended in-service NDI method then is ultrasonic inspection, and preferably phased array inspection, for the detection and characterization (size, depth) of relevant impact damage, delaminations and disbonds. Shearography and thermography are considered to be less applicable but may be considered as non-contact techniques for specific inspection configurations (e.g. repaired structures and honeycomb structures with water ingress). The statement about visual inspection as a primary inspection method should also be the basis for implementation of a structural health monitoring (SHM) program for composite aerospace structures, especially for the global monitoring of large surface areas.

Contents

Abbreviations

AC	Advisory Circular
AMC	Acceptable Means of Compliance
BVID	Barely Visible Impact Damage
CBM	Condition Based Maintenance
CFRP	Carbon Fibre Reinforced Plastic
CVID	Clearly Visible Impact Damage
CVM	Comparative Vacuum Monitoring
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
HTA	High Strength Aerospace grade
LL	Limit Load
MoD	Ministry of Defence
NDI	Non-Destructive Inspection
NTP	National Technology Programme
PA	Phased Array
PC	Pitch Catch
PHM	Prognostic Health Monitoring
PTFE	Polytetrafluoroethylene
RF	Radio Frequency
RTM	Resin Transfer Moulding
SHM	Structural Health Monitoring
SL	Safety Limit
SRP	Strategic Research Programme
UL	Ultimate Load
UT	Ultrasonic Testing

This page is intentionally left blank.

1 Introduction

The use of composites in military primary aircraft and helicopter structures has increased significantly in the last ten years 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. An example of the application of composites is the NH90 helicopter which already has an all-composite fuselage. To anticipate on the increased use of composites a National Technology Programme (NTP N04/27) was initiated in The Netherlands 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. This paper will describe the NDI relevant aspects of the NTP. Furthermore, the results of a separate study on the detectability of impact damage due to runway debris on thick composite specimens are discussed (SRP project 59902N funded by NL Agency). Whether in-service damage has to be detected depends on the design philosophy of the aircraft structure. This paper will discuss the main design philosophies and in more detail the damage tolerance approach. Finally, an alternative to NDI at regular intervals (scheduled maintenance) will be treated, so-called structural health monitoring (SHM) techniques that are being developed to assess the real-time condition of a structure using on-board systems with advanced sensors that are permanently attached to the structure. The paper will conclude with general guidelines for the in-service inspection and monitoring of composite aerospace structures.

2 In-service damage

During the in-service use of composite aerospace structures, defects can be caused by a number of factors such as maintenance damage (e.g. low-velocity impact by a dropped tool), ground handling (e.g. collision with a truck), foreign objects thrown up from the runway and severe operating conditions and environmental factors. Examples of the last two are high-velocity impact (bird strike, hail), static overload (over-G loads, hard landings), fatigue, moisture ingression, overheating, lightning strike, erosion, etc. These factors can result in a variety of defects such as surface damage (dents, cracks, lightning strike and overheating damage, etc.), sub-surface damage such as delaminations and matrix cracks in laminates, debonding in adhesive bond lines (e.g. skin-to-stringer or skin-to-honeycomb), moisture ingression and honeycomb core defects in sandwich structures. Of most importance is the occurrence of impact damage that can result in sub-surface damage that is only barely visible (BVID) or even without any visible mark on the surface (hidden damage). Impact damage is the type of in-service damage most significantly affecting the structural strength. The delaminations in the impact area have a negative influence especially on the compression strength. For example, a laminate can lose 60 to 65 percent of its undamaged static strength by impact damage that is essentially non-visible [1]. Furthermore, it is possible that delaminated areas grow in-service because of moisture uptake that undergoes a repeated freezing-thawing cycle (causing expansion-contraction of the laminate layers) during subsequent flight cycles. This can lead to long-term degradation of the composite structure. Moisture ingression in undamaged parts can also not be ignored because of its degrading effect on those strength properties that are matrix dependent.

Whether in-service damage has to be detected depends on the design philosophy of the aircraft structure. In earlier days (metallic) aircraft were generally designed according to the 'safe-life' (safety by retirement) or 'fail-safe' (safety through redundancies) approach. Because of safety shortcomings of these two approaches, however, the 'damage tolerance' concept was developed since the 1970's [1]. Key points of the damage tolerance approach are that flaws are assumed to already exist in the structure as manufactured, and that the structure may be inspectable or non-inspectable in service. Non-inspectable structures must be designed in such a way that the initial damage will not propagate to a critical size (causing failure) during the design service life. For inspectable structures the initial damage must grow slowly and not reach a critical size in some predetermined inspection interval. The initial inspection time is generally taken as the flaw propagation period from the initial flaw size to critical flaw size ('safety limit') divided by a safety factor, and the inspection interval as the flaw propagation period from the reliably detectable flaw size to critical flaw size divided by a safety factor. This procedure is illustrated in figure 1 [2].

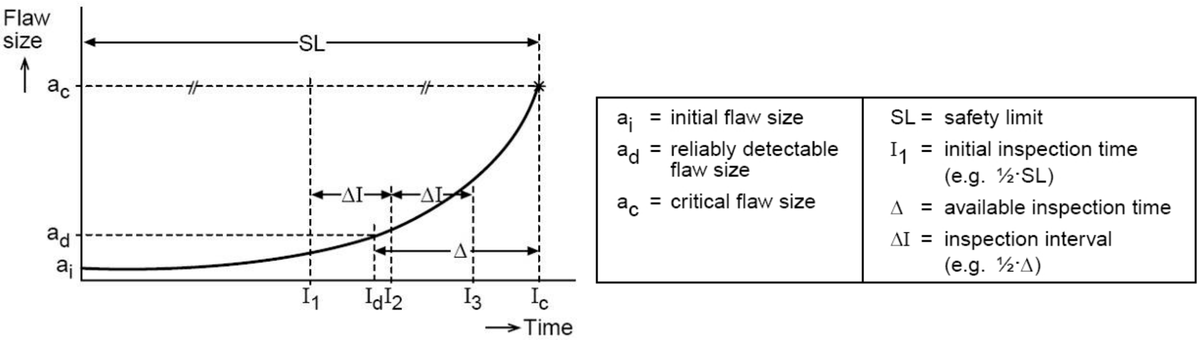


Fig. 1 Damage tolerance approach for inspectable structures (Fig. 1 from [2])

This approach works well for metallic structures under fatigue. The structural strength may temporarily decrease below the design Ultimate Load level (UL, equal to LL multiplied with a safety factor of e.g. 1½) but the damage should be detected (and then repaired) well before the strength falls below the design Limit Load level (LL – maximum load per fleet lifetime), see figure 2. Composites, on the other hand, do not gradually degrade in strength (even with damage there is generally no damage growth) but an impact can suddenly drop the strength to an undesired level (below UL). The requirement then is that as long as damage cannot be detected visually, it should never reduce the structural strength below UL. Only detectable damage may cause structural degradation below UL (but never below LL) and should be timely detected by visual inspection or more advanced NDI methods. The inspection interval should be related to the probability of damage occurrence, depending e.g. on the structure type. In the period before detection, any damage should not show significant growth. After detection, the damage should be repaired to restore UL capability or the component should be replaced.

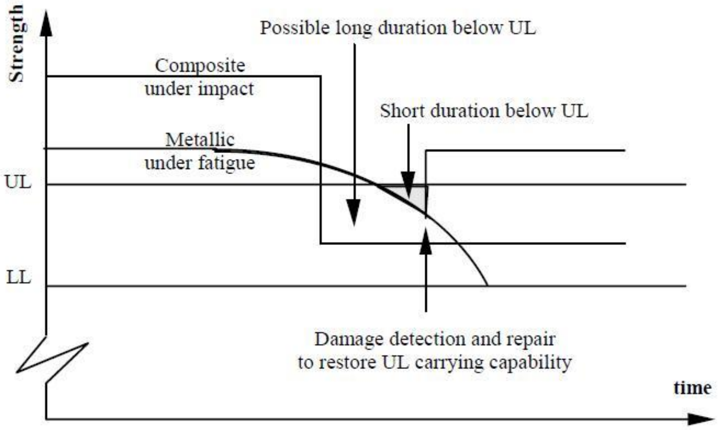


Fig. 2 Comparison of composite non-growing damage and metal fatigue crack damage (Ultimate Load, UL, and Limit Load, LL) (Fig. 7.2.2.2c from [1])

Important is the definition of detectable damage. For impact damage often the term BVID value is exercised, standing for 'barely visible impact damage'. BVID should be considered to be the upper limit of visually undetectable damage and associated with the damage level that does not reduce the strength of a structure below the design UL level. BVID corresponds with the Category 1 Damage as defined in the FAA Advisory Circular no. 20-107B [3] or its EASA equivalent AMC 20-29. More relevant for in-service inspection, however, are the Category 2 and 3 Damage types. Category 2 Damage is defined as the 'damage that can be reliably detected by scheduled or directed field inspections performed at specified intervals, and structural substantiation for this damage type includes demonstration of a reliable inspection method and interval while retaining loads above LL capability' [3]. Reliable detection of damage may be done visually or with more advanced NDI methods. Category 3 Damage is similar to Category 2 damage in the sense that limit or near limit load capability should always be retained but the damage is considered to be obvious damage that can be reliably detected within a few flights of occurrence by maintenance personnel without special skills in composite inspection [3]. Category 3 Damage is readily detectable damage and is typically found during walk-around inspection; the associated impact damage can be considered as CVID or 'clearly visible impact damage'.

Evidently, in-service use of composite aerospace structures implies the availability of a maintenance program including a selection of inspection methods. Visual inspection will always be a primary damage detection method but more advanced NDI methods will also be needed depending on the structural configuration and application purpose. To anticipate on the increased use of composites in military aircraft and helicopters (with spin-off to naval applications) a National Technology Programme (NTP N04/27 funded by NL MoD) was initiated in The Netherlands on the in-service NDI and repair of composite structures. In the following chapter the NDI relevant aspects of the NTP are described. A detailed description of the NDI results is given in reference 4.

3 Evaluation of in-service NDI methods

3.1 Composite benchmark

A composite benchmark was defined in the NTP to serve as reference for the evaluation of in-service NDI methods [4]. First, a selection of structural details in primary composites being relevant for military aircraft and helicopters was made. This resulted in the following four structural details: a solid laminate, a solid laminate with T-shaped stiffeners, a plain sandwich structure, and a 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 3 gives a depiction of the most complex structural detail, viz. a chamfered sandwich structure with L-shaped ribs/frames (dimensions 905 x 800 m).

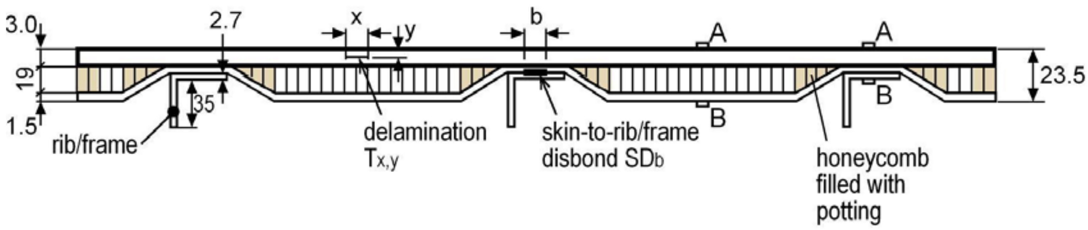


Fig. 3 Chamfered sandwich structure with 3 L-shaped ribs/frames

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 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 (Fothergill Tygaflor Ltd.). This material 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).

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. Ultrasonic C-scan is currently the primary *production* inspection technique for composite structures after manufacturing. Both the immersion and water-jet method (for the sandwich structures) were used for the base-line inspection.

3.2 Evaluation 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 3.1.
- 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, phased array UT, dry-coupling roller probe).

- Shearography inspection.
- Thermography inspection.

Figure 4 gives a depiction of the selected NDI methods.

Fig. 4 Selected in-service NDI methods for inclusion in the NTP inspection programme

A detailed description of the NDI results is given in reference 4. 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 project [4]

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

Table 1 shows that, as can be expected, 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* is a primary method for the in-service inspection of composite structures. It is relatively fast and capable of detecting relevant impact damages and other surface irregularities.
- The *automated tap tester Woodpecker* is a low-cost, couplant-free inspection unit for smaller areas where impact damage is suspected. The detectability for delaminations and disbonds, however, is varying and not always consistent.
- The *BondMaster*^{TM} is a relatively low-cost, couplant-free instrument for local inspection of structures with the pitch-catch technique. It has, however, a limited detection performance for in-service defects.
- *Ultrasonic inspection* is a 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 also relatively fast. A limitation can be the requirement to use a couplant between probe and test part.
  - The *AcoustoCam*^{TM} is a handheld, ultrasonic imaging camera for fast and real-time inspection but with a limited field of view (about 1 square inch).
  - *Ultrasonic phased array* (UT-PA) inspection provides the best capabilities for in-service inspection and characterization. A position encoder is required in order to produce a C-scan image.
  - The *RapidScan*^{TM} 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.

4 In-service inspection guidelines for composites

Review of the NTP results summarized in Table 1 and the damage tolerance aspects discussed in chapter 2 leads to the formulation of the following guidelines for the in-service inspection of composite structures:

- Visual inspection as a primary method for the detection of impact damage and other surface irregularities. The inspection will be in first instance walk around or general visual inspection depending on the type of service check. If necessary or required, detailed visual inspection can be carried out (close-proximity, intense visual examination of relatively localised areas of internal and/or external structure).
- More advanced NDI in case of suspected damage during visual inspection. The following methods are recommended:
  - Ultrasonic conventional or, preferably, phased array (PA) inspection for the detection and characterization (size, depth) of relevant impact damage, delaminations and disbonds. The ultrasonic PA inspection is preferably done with a handheld roller probe that works almost couplant-free (e.g. RapidScan equipment). It is possible that limited access prevents the use of large PA and roller probes, and then the use of smaller PA probes or conventional ultrasonic inspection with small, single crystal probes is required.
  - Automated tap test may be considered for low-cost, couplant-free detection of relevant impact damage.

Some NDI methods evaluated in Chapter 3 are absent in these guidelines: the BondMaster™ because of its limited detection performance and the AcoustoCam™ because of its limited field of view (about 1 square inch). Furthermore, shearography and thermography were not included because of their poor to moderate detectability for delaminations and disbonds (when compared with UT), their unsuitability for defect depth estimation, and the relatively high costs involved. However, it is noted that some inspection configurations have not been considered in the NTP 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). Also, the in-service inspection of repaired composite structures has not been considered in the NTP. For these items an NDI method that does not require a couplant would be highly beneficial. From the NDI methods evaluated it is probable that thermography could be an option then. Thermography is truly non-contact and is capable of inspecting surface areas up to 1 m^2 with a single exposure technique. Shearography is considered somewhat less applicable because it is not a truly non-contact method when using the mobile system with a vacuum hood (and with a limited field of view) and because of its surface requirements (surface not too shiny). It is finally remarked that the implementation of the guidelines given above may depend on specific requirements for different aircraft and helicopter types.

5 Visual inspection for impact damage

Visual inspection is a primary method for the detection of impact damage and other surface irregularities. In the NTP project the specimens were subjected to low-velocity impact with an instrumented impact tester (guided drop weight device) using impactors with hemispherical steel tup of diameter 0.5 or 1.0 inch. Also the location of impact was varied, for example for the stiffened panels relative to the location of the stiffened areas. Impacts in the bay area create a larger damage area with delaminations that become larger towards the back face, while impacts near the stiffened areas create a smaller damage area which is more near the front face and which comprises of crushing and fibre fracture [5]. The dent depth was measured immediately after impact and after 10 months to observe any decay of the dent depths. The results showed that a relaxation of the dent depth of 10 to 20% can easily occur, for some impacts on thin laminates even a relaxation up to 65% occurred [4]. The specimens in the NTP project, with in total 43 impacts (impact energy 12 to 70 J), were visually inspected for impact damage 10 months after impact by an experienced NLR technician according to the definition of 'general visual inspection' [1]. Figure 5 gives an overview of the results and shows that all impacts with an actual dent depth exceeding 0.35 mm were detected. All missed impacts or suspect impact areas (not identified as a clear defect area but worthy of further check with more advanced NDI) had an impact dent depth less than 0.35 mm. When the relaxation of dent depths is considered then all impacts with an initial dent depth larger than 0.5 mm were detected.

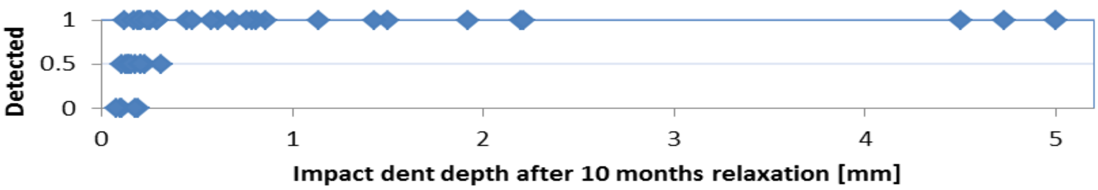


Fig. 5 Visual inspection of 43 low-velocity impacts on the composite specimens of the NTP project [4] (1: 28 impacts detected, 0.5: 10 impact areas marked as suspect, 0: 5 impacts not detected)

Most specimens in the NTP project can be considered as relatively thin, with a maximum skin thickness of about 6 mm (excluding stiffeners). For thin composite structures the detection method using dent depths is suitable because the material is relatively flexible and the impact leads to fibre outbreak at the back of the laminate due to the bending stress, and a significant dent at the front side. Figure 6 gives an illustration of this mechanism.

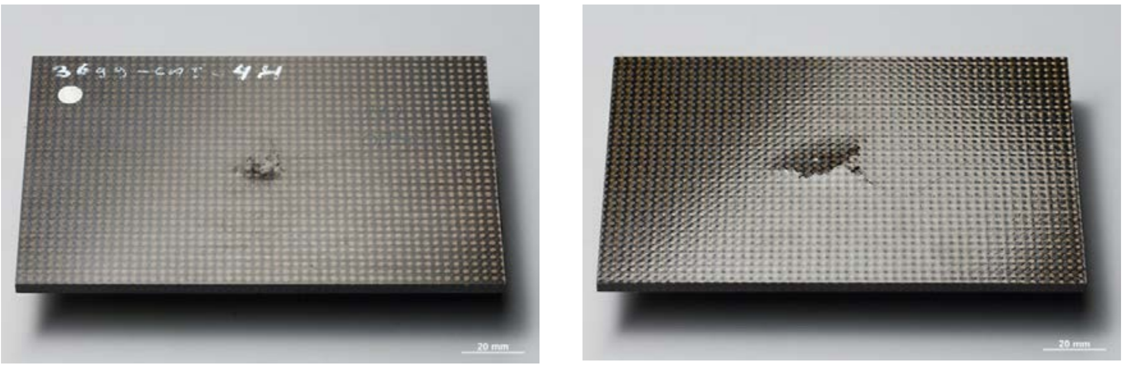


Fig. 6 Impact on a thin laminate. Left: dent caused by a 16 mm spherical impactor at 21 J. Right: outbreak at the back of the same sample (Fig. 2 from Ref. 6)

Thick composites as used in e.g. landing gear components, however, do not exhibit such flexibility and require a different method to assess the presence of an impact and link this to the related damage. In thick composites, fibre outbreak at the backside does generally not occur, not even for energy levels exceeding 100 J. As a consequence, only very shallow dents are created or, alternatively, the impactor penetrates the surface (especially for smaller impactors) which creates a pit or hole. This is a distinctly different damage mode than a dent, and is accompanied by broken fibres at the impact side due to high contact stresses (and not at the backside due to bending stresses). The difference between relatively 'thin' and 'thick' composites is also addressed in [1] regarding damage detectability thresholds and impact energy cut-off levels, see figure 7.

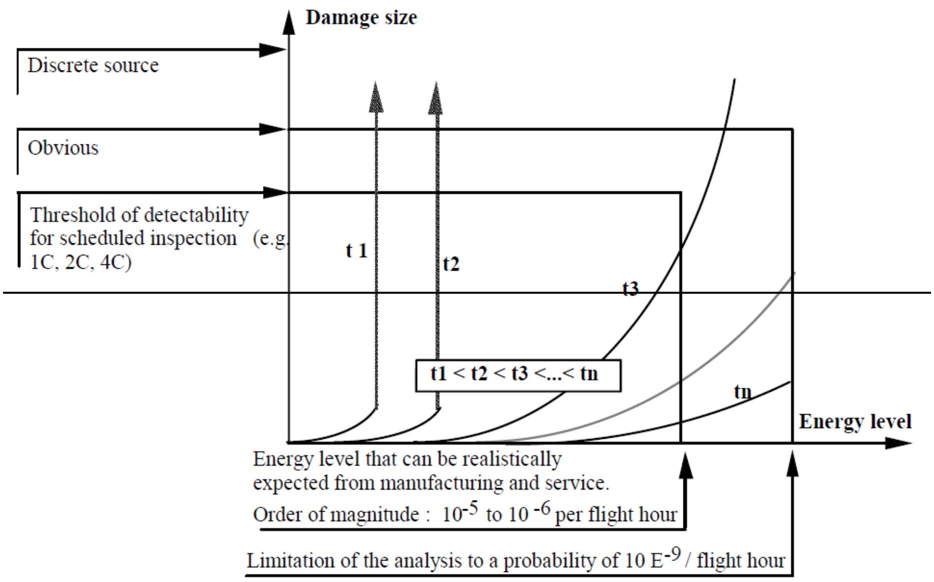
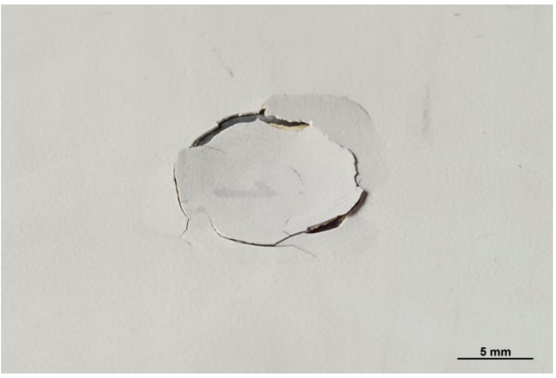


Fig. 7 Damage size versus impact energy level for composite structures of different thickness t (Fig. 7.2.2.2(b) from [1])

The NLR conducted a separate study on the detectability of impact damage due to runway debris on thick composite specimens (SRP project 59902N funded by NL Agency, [6]). The carbon fibre specimens, with dimensions 190 mm x 100 mm and thickness 20 mm (76 plies), were cut from composite panels manufactured using Resin Transfer Moulding (RTM). The specimens were painted white using the same coating as for current metal landing gear components. Four different types of impactors were used: two hemispherical impactors with diameter of 0.5 and 1 inch, and two conical nose profiles with a total angle of 60 and 120 degrees. Both high-velocity impacts using an impact gun and low-velocity impacts using a guided drop weight device were performed with impact energy levels in the range of 12 to 148 J. The impacts resulted in a range of specimens with damage that was non-visible to clearly visible. Examples of the more readily detectable impact damages are given in figure 8.

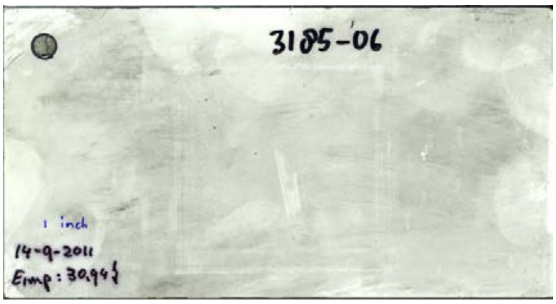


cracked paint, 1 inch impactor, 76 J

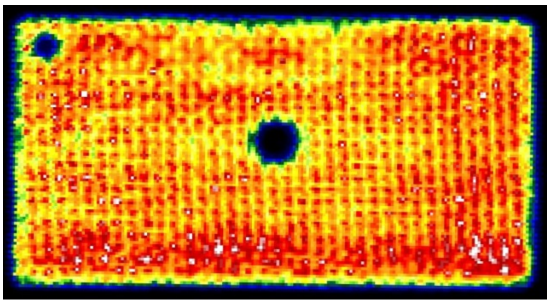
pit/hole, 0.5 inch impactor, 148 J

Fig. 8 Readily detectable high-velocity impact damages on 20 mm thick, painted RTM specimens [6]

On the other hand, also impacts resulting in internal damage but with no visible dents or surface damage occurred, see for example figure 9.



impact with 1 inch impactor, 31 J



ultrasonic C-scan

Fig. 9 Non-detectable high-velocity impact damage on a 20 mm thick, painted RTM specimen [6]

The impacted specimens were visually inspected by 36 persons in a simulated 'walk-around' inspection and in more detail by an experienced inspector according to the definition of 'detailed visual inspection' [1]. The walk-around inspection made use of a special test set-up being representative of a less favourable inspection setting (low light conditions). Figure 10 gives an overview of the detection rate for the different impactors.

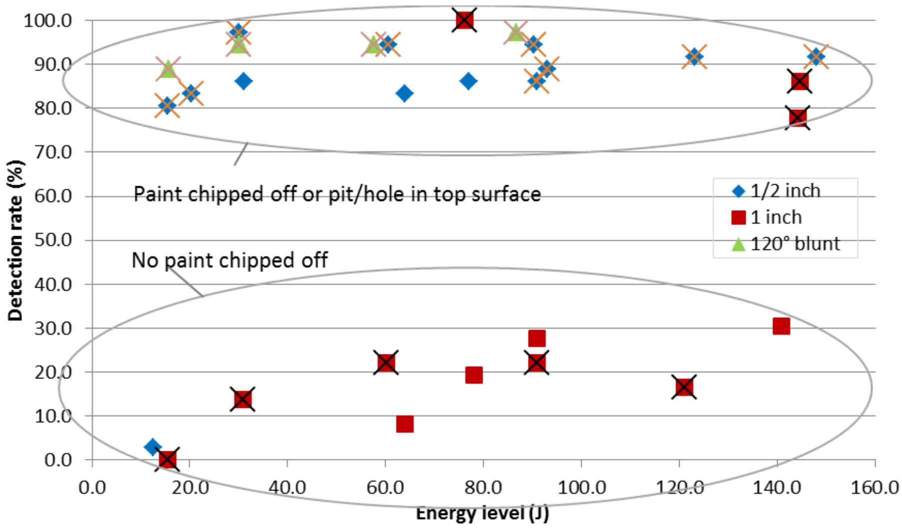


Fig. 10 Overview of the detection rate for different impactors used on 20 mm thick, painted RTM specimens. An X through a point denotes a high speed impact (Fig. 16 from [6])

Various relations were discussed in [6] such as the detection rate versus dent depth, detection rate versus chipped paint (creating a distinct black area on a white background) and dent depth versus impact energy. There appeared to be little difference in the detection rate between high and low speed impacts. On the other hand, a significant difference in impact damage was observed between the 1 inch and 0.5 inch impactors. Impacts with a 0.5 inch impactor caused paint damage (cracking or chipping and/or a pit) in all cases but one, while impacts with a 1 inch impactor only showed chipped paint at higher impact energy levels. It was concluded that dent depth is not a suitable criterion to assess damage in thick composite specimens (too thick/stiff to cause sufficient bending) as the impact energy necessary to create a visible damage is very high. Instead, the detection of an impact on thick painted specimens is more related to the size and amount of paint that is chipped off the surface.

The study in [6] was followed by a study on the static strength and strength after fatigue (compression loading) of the 20 mm thick, impacted RTM specimens [7], also within the framework of SRP 59902N. Damage growth was monitored during the fatigue testing by ultrasonic C-scanning at regular inspection intervals. The fatigue tests were followed by destructive verification of internal damage. A remarkable outcome of the study was that the amount of surface damage is not at all representative for the amount of internal damage. For example, a high speed low mass impact of 15 J with the hemispherical 0.5 inch diameter impactor led to paint being chipped off, but the surface of the specimen itself did not show any visual damage nor did the C-scan reveal any internal damage. On the other hand, high speed low mass impacts with the hemispherical 1 inch impactor did not lead to distinct visual damage for energy levels up to 80 J, while the C-scans revealed significant internal damage (delaminations) which already started to develop for energy levels from 30 J. Further, the effect of impact damage on the residual static strength and on the fatigue strength is described in detail in [7], together with a description of the failure mechanisms. The most critical impact configuration turned out to be the high speed impact with a 1 inch impactor; this impact resulted in low detectability of the damage and the largest strength reduction. The results of the study are used for the design and analysis of any thick composite aerospace component to which damage tolerance requirements apply. A basic guideline remains, for the time being, that as long as damage occurring in-service cannot be detected visually, it should not be structurally significant.

6 Structural health monitoring

Structural health monitoring (SHM) techniques are special inspection techniques employing on-board sensors to assess the real-time condition of a structure [8]. Typical examples of SHM techniques are piezoelectric sensors in the passive mode (acoustic emission) or in the active mode (e.g. Lamb waves), fibre optic sensors, eddy current sensors and the comparative vacuum monitoring (CVM) technique [9]. The SHM techniques are aimed at the detection, localisation and characterisation of structural damage. In a far-term SHM system application also the effect of the damage (e.g. on the residual life) may be determined using failure progress prediction. This is sometimes referred to as prognostic health monitoring (PHM). In contrast to conventional NDI techniques that are usually operated off-board during scheduled maintenance on the ground, SHM techniques are part of on-board systems (centralised or distributed) with low-profile sensors that are permanently attached to the structure. The SHM techniques can be operated on-line during the flight (so with the vehicle in operation) or off-line on the ground. In the on-line operation mode we can distinguish static systems that interrogate the structure at predetermined intervals (active measurements) and dynamic systems that require continuous, reliable monitoring (passive measurements). The main objectives of SHM are to introduce condition-based structural maintenance (CBM) replacing maintenance based on an inspection schedule, to reduce the cost of ownership (inspection and maintenance costs) and to improve the system operational availability (downtime reduction and service life extension) while maintaining current safety levels.

Additional objectives for integrated automated damage detection systems are to solve problems of poor accessibility and to remove the human factor of inspector fatigue.

A main distinction with SHM techniques is whether they are focused on global inspection of large surface areas or on local inspection of highly critical areas (hot spots). Most SHM research and applications are currently focused on local monitoring of critical areas. A good example of that is the SMART Layer® of Acellent Technologies using a thin dielectric film with an embedded network of piezoelectric sensors [10]. Global monitoring applications are also widely studied, employing for example guided ultrasonic waves or acoustic emission sensors. Current work at NLR on SHM techniques for large surface areas, however, questions the reliability for defect detection in all areas. Also here it is thought that composite structures should be designed such that damage occurring in-service that cannot be detected visually, should not be structurally significant. Global SHM application should then imply just visual inspection. On the other hand, local SHM application is thought to have potential for composite structures, especially for the monitoring of local, critical areas or areas that are poorly accessible.

7 Conclusions

1. Damage tolerance requirements for composite aerospace structures should be interpreted so that as long as damage occurring in-service cannot be detected visually, it should not be structurally significant in the sense that is does not affect the safety during the aircraft life. In terms of load capability this implies that the damage should never reduce the structural strength below ultimate load (UL) capability.

2. Only detectable damage may cause structural degradation below UL (but never below LL, limit load – the maximum load per fleet lifetime) and should be timely detected by visual inspection or more advanced NDI methods. The inspection interval should be related to the probability of damage occurrence, depending e.g. on the structure type. In the period before detection, any damage should not show significant growth. After detection, the damage should be repaired to restore UL capability or the component should be replaced.

3. The recommended in-service NDI method is ultrasonic conventional or, preferably, ultrasonic phased array inspection for the detection and characterization (size, depth) of relevant impact damage, delaminations and disbonds. Automated tap test may be considered for low-cost, couplant-free detection of relevant impact damage.

4. Shearography and thermography are considered to be less applicable because of their poor to moderate defect characterization capabilities, when compared to ultrasonic inspection. But, thermography and shearography may be optional, non-contact techniques (especially thermography) for specific inspection configurations such as curved panels and repaired structures, and for the inspection of specific defect types such as water ingress in honeycomb structures.

5. The statement about visual inspection as a primary inspection method should also be the basis for implementation of an SHM program for composite aerospace structures, especially for the global monitoring of large surface areas. Local SHM application employing on-board sensors, on the other hand, is thought to have potential for composite structures, especially for the monitoring of local, critical areas or areas that are poorly accessible.

8 References

[1] U.S. Department of Defense Handbook, *Composite Materials Handbook, Volume 3: Polymer matrix composites – Materials usage, design and analysis*, MIL-HDBK-17-3F, Volume 3, 17 June 2002. Currently available as Composite Materials Handbook CMH-17, http://www.CMH17.org.

[2] J.H. Heida and F.P. Grooteman, *Airframe inspection reliability using field inspection data*, NLR-TP-98144, March 1998.

[3] U.S. Department of Transportation, Federal Aviation Administration, *Composite aircraft structure*, Advisory Circular AC No: 20-107B, Change 1, 24 August 2010.

[4] J.H. Heida and D.J. Platenkamp, *Evaluation of non-destructive inspection methods – NTP N04/27, WP 2.3*, NLR-CR-2010-076, September 2010.

[5] G.A.O. Davies and R. Olsson, *Impact on composite structures*, The Aeronautical Journal, November 2004, pp. 541-563.

[6] J.M. Müller, *Impact damage detectability for thick composites*, NLR-CR-2013-029-PT-1, May 2013.

[7] R.J.C. Creemers, *Static and fatigue test results on thick composites with different types of impact damage*, NLR-CR-2013-191-PT1, June 2013.

[8] W.J. Staszewski, C. Boller and G.R. Tomlinson, Editors of: *Health Monitoring of Aerospace Structures – Smart Sensor Technologies and Signal Processing*, John Wiley & Sons Ltd., Chichester, England, 2004.

[9] J.H. Heida, *Structural health monitoring – Sensors for damage detection and usage monitoring*, NLR-CR-2008-441, August 2008.

[10] Acellent Technologies Inc., Sunnyvale (CA), USA, http://www.acellentsensors.com.