European Aviation Safety Agency

Research Project EASA.2007/3

Study on visual inspection of composite structures

Disclaimer

Visual Inspection of Composite Structures

EASA-Research Project/2007/3

Final Report

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Executive Summary

The study focuses on the visual inspection of composite structures, which are relevant for aeroplanes to be certified to CS 25. Of special interest are composite damage metrics and variables that influence damage detection, such as colour, finish, lighting, cleanliness and the angle at which the inspection is conducted relative to the surface.

The intent was to investigate the basic detectability of damages to composite structures as they may be caused by ground vehicles, baggage load belt vehicles and others.

A survey of the literature related to visual inspection of composite structures formed the basis on which the present work has been carried out. A methodology for the conduction of a visual inspection study for composite structures has been developed, which comprises a plan for the introduction of damages of different sizes, an inspection plan, questionnaires and evaluation guidelines.

Two nominally equal structures, with nominally equal impact damages have been manufactured, so inspection results for both structures could be compared to each other. The structures were painted according to aeronautic standards. Twenty damages were introduced into each of the panels. Both structures were exposed to different inspection conditions, thus enabling the determination of influences of single inspection parameters on detectability of damages.

A total of ten visual inspections have been carried out. Inspection results of ten visual inspections with a total of 112 inspectors were generated and recorded. These records have been transferred to a database to facilitate their evaluation.

The visual inspections showed that variation of a single inspection parameter such as cleanliness, inspection angle and colour / finish combination did not have a large effect on inspection results. Illumination was the parameter with the greatest effect on damage detectability. Influences of colour / finish, inspection angle and lighting are closely related to each other.

By evaluating questionnaires filled out by each inspector it was also possible to investigate the influence of certain person-related parameters such as visual capability, age, gender and professional qualification on inspection results.

Implications for subsequent research and recommendations for carrying out visual inspections have developed based on the findings of this study.

1 Background

Two excerpts from FAA reports summarize the damage tolerance design concept and state the significance of visual inspection in the damage tolerance philosophy:

> "Damage tolerance maintains that an aircraft remain airworthy despite the possibility of containing subcritical cracks and flaws. This philosophy recognizes the impossibility of establishing complete structural redundancy throughout the aircraft. Accordingly, continued airworthiness of damage tolerant aircraft strongly depends upon the implementation of inspection programs capable of detecting cracks and flaws prior to reaching their critical size." [1]:
>
> "Over 80 percent of inspections on large transport category aircraft are visual inspections. Small transport and general aviation aircraft rely on visual inspection techniques even more heavily than do large transport aircraft. Visual inspection, then, is the first line of defense for safety-related failures on aircraft and provides the least expensive and quickest method of assessing the condition of an aircraft and its parts. Therefore, accurate and proficient visual inspection is crucial to the continued safe operation of the air fleet." [2].

As the use of composite materials in transport aircraft is rapidly expanding, damage tolerance maintenance practices for composites need to be standardized. Composites have some substantially different attributes than metal and therefore require unique considerations and procedures [3].

Previous research on visual inspection of aircraft structures with a focus on human factors has been conducted during the 1990s in the USA [2]. Airbus has recently carried out general visual inspections as well as detailed visual inspection and has statistically processed the inspection results. Impacts with impactor diameters from 6 to 120 mm were investigated on composite panels with different colours and finishes. The University of Wichita conducted an initial study on the detectability of dents on composite fuselage structures and identified important parameters influencing the detectability [18].

At the 2006 Composite Damage Tolerance and Maintenance Workshop in Chicago Waite [5] stated some research needs. An important aspect is the influence of colour / finish on damage detection. For example new gloss dark blue from British Airways lead to many visual indications, whereas old matt blue gave fewer visual indications. On the other hand there is contrary evidence regarding damage detectability on matt white and glossy white surfaces. Furthermore there is some (surprising) evidence that it is easier to find damage on green surface than white surface [5]. It is assumed that as a product of the visual search further investigation is required. Subsequent inspection/tactile tests strengthen the 'signal' (damage) component and filter the 'noise' component. This could be done by changing the visual distance, angle, lighting, cleanliness etc. Also tactile tests (tap test, scratch test, poke test) could be used to confirm visual indication of damage [5].

2 Aims and Objectives

The study focuses on the visual inspection of composite structures, which are relevant for aeroplanes to be certified to CS 25. Of special interest are

- composite damage metrics
- variables that influence damage detection
    - colour, finish
    - lighting
    - cleanliness
    - angle at which the inspection is conducted relative to the surface.

The intent is to investigate the basic detectability of damages to composite structures as they may be caused by ground vehicles, baggage load belt vehicles and others. Therefore other impact diameter than the standard 1 inch have to be investigated. The project is to be seen in the context of other projects currently being carried out by the University of Cranfield / CAA-UK (work on dent) and Stanford University California / FAA (crash dynamics approach).

3 Literature Review

3.1 Damage in composite structures

3.1.1 Damage categories

According to FAA (L. Ilcewicz, [6]) damage is categorized according to its severity as follows.

- Category 1

  Allowable damage that may go undetected by scheduled or direct field inspection, allowable manufacturing defects; damage below Allowable Damage Limit (ADL), e.g. barely visible impact damage (BVID).

- Category 2

  Damage detected by scheduled or directed field inspection at specified intervals, e.g. exterior skin damage, interior stringer blade damage.

- Category 3

  Obvious damage detected within a few flights, e.g. accidental damage to lower fuselage or lost bonded repair patch.

- Category 4

  Discrete source damage immediately known by pilot to limit flight maneuvers, e.g. rotor disk cut through fuselage or severe rudder lightning damage.

- Category 5

  Severe damage created by anomalous ground or flight events. Such damage represents damage/manufacturing events that are outside of design considerations. It does not drive stress analysis, it rather relates to a feedback loop from maintenance/operations to the authorities. Analogous to an automobile accident special directed inspections are needed for category 5 damage [7].

Damage of categories 1 to 4 has to be taken into account during aircraft design. For damages of category 2 to 5 repair scenarios are required.

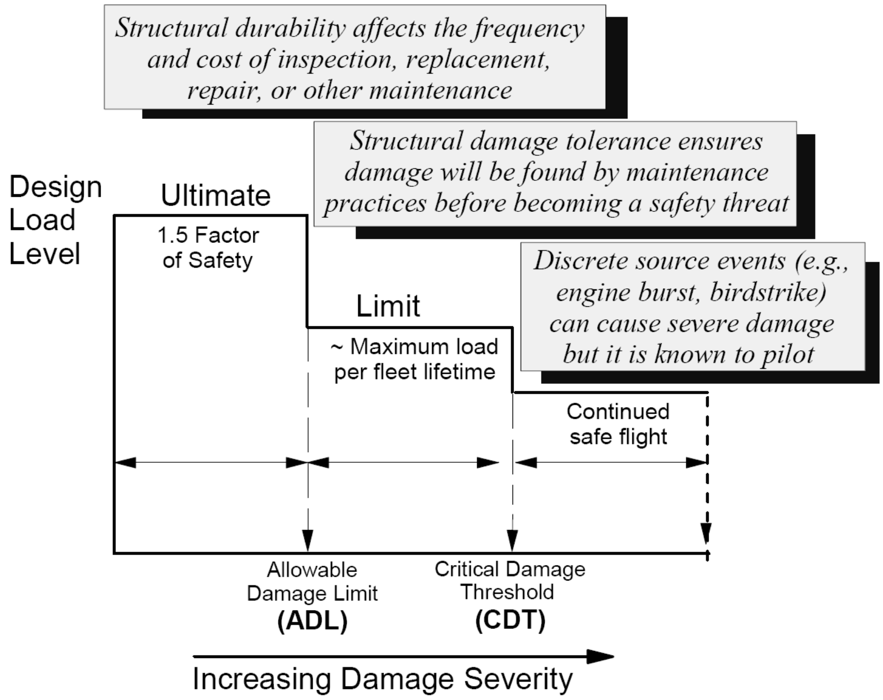


Figure 1: Design load and damage considerations for durability & damage tolerance (Figure 7.2.1(a) in [8].

3.1.2 Origins of damage

ATA MSG3 [9] specifies requirements for detection of

- accidental damage
- fatigue damage
- environmental damage.

Inspections of fatigue damage are often not required for composites, since designs are usually based on the no-damage-growth philosophy [10], [11]. Also environmental damage is much less of a problem for non-metals, if proper design precautions are taken. This study is therefore focussed on inspection for accidental damage.

Large size accidental damage, such as that caused by engine disintegration, bird strike or major collision with ground equipment, will be readily detectable and no maintenance task assessment is required [9]. However, low-velocity large-mass impact (e.g. by ground vehicle) may lead to large internal damage in composite structures (delaminations) without much indication on the surface of the structure. This may show different behaviour compared to metals, and requires further research efforts [12].

Low-energy impact usually causes small size accidental damage, namely non-visible impact damage (NVID) or barely visible impact damage (BVID). Design of composite aircraft structures often uses a BVID threshold: Structures containing BVID must sustain ultimate load (UL) for the life of the aircraft. Presently, the dent depth is normally used as the damage metric to define BVID.

Schoeppner and Abrate describe the low-velocity impact threat for composite structures [13]:

> “Low velocity impact damage to aircraft is due to both operational and maintenance activities. In the operational environment, there are typically few incidents of low velocity impact damage and most can be attributed to hailstone strikes and foreign object damage (FOD) such as

runway debris. The major source of low velocity impact damage for aircraft structures is due to mishandling and maintenance mishaps that include off aircraft part transportation, handling and storage, and incidental tool drops. Impact induced damage, which may be undetectable by visual inspection, can have a significant effect on the strength, durability and stability of the structure."

Hailstones are not necessarily low velocity, e.g. in-flight hail.

3.1.3 Damage morphology

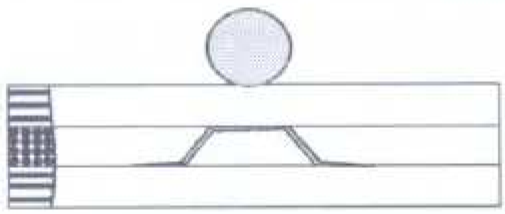
Impact on composite structures typically causes a permanent indentation. This indentation depth diminishes over time, so the impact becomes harder to detect. In addition to the permanent indentation internal cracks can develop, leading to a complex damage state. This internal damage has a much stronger influence on the remaining load bearing capability than the visible indentation. Abrate describes impact damage in composite structures as follows [13][14].

Damage types in composite laminates are delaminations, matrix cracking and fibre breakage. Delaminations due to impact are typically peanut shaped with the longer axis oriented in the direction of the lower ply. They only occur between plies of different orientation and are dangerous in combination with compressive loading. They greatly reduce the bending stiffness of the laminate. Buckling of delaminated sublaminates can lead to damage growth and to a significant reduction of compressive strength [14].

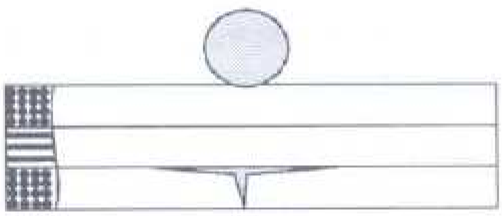
Matrix cracks typically occur in a complex pattern in the vicinity of the impact location. Matrix cracks by itself do not affect the laminate strength significantly, but they are usually first failure mode to occur. Delaminations often are induced by matrix cracks in the adjacent plies [14].

For thick laminates damage progresses from top to the bottom of the laminate. Delaminations are arranged in a pine tree pattern with increasing size from top to the bottom of the laminate. The first occurrence of damage is due to the highly concentrated stresses below the impact point. For thin laminates, the damage starts from tensile cracks in the bottom ply and develops upwards in a reversed pine tree pattern [14].

There is not much known about the amount of fibre damage introduced by impact [14].



(a)



(b)

Figure 2: Two types of matrix cracks: a) shear crack, b) tensile crack [source: [14]].

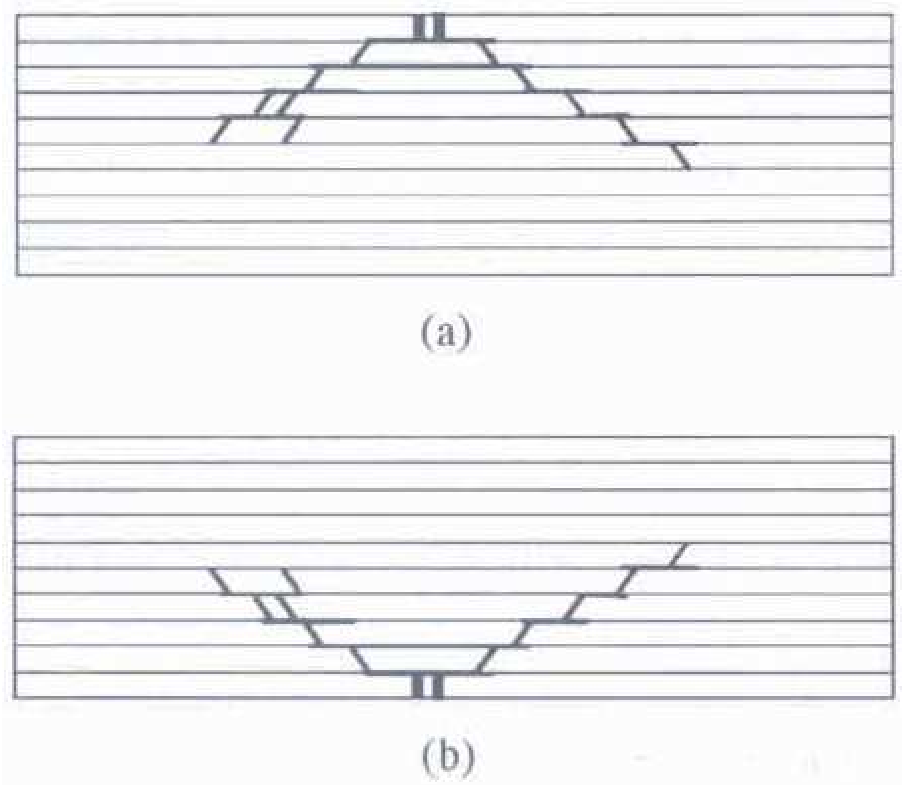


Figure 3: Pine tree (a) and reversed pine tree (b) damage patterns [source: [14]].”

Material qualification and research on low velocity impact typically uses a standard steel tup with a diameter of one inch. Such impacts may not be conservative for the detection of large-mass low velocity impacts cause by ground vehicles (ground vehicle impact), which may cause large indentations at relatively low contact forces. Such blunt impactors could cause little permanent indentations (BVID), which may be accompanied by large delaminations. Investigations are under way at the University of California, San Diego [12].

Airframe structures used in wing or fuselage are typically thin shells stiffened by stringers. The stringers mainly provide bending stiffness and strength for out-of-plane loads. In metallic design skin and stringer are usually connected by bolted joints, whereas composite design favours adhesive bonding or co-curing / co-bonding. Impacts near the stringers can lead to skin-stringer separation. This is a dangerous failure mode, since a missing bond can be invisible from the outer surface and may also escape a visual inspection from the inside.

3.1.4 Damage metrics

Airbus damage definition

BVID is the minimum impact damage surely detectable by scheduled inspection. BVID corresponds to a probability of detection of 90% with an interval of confidence of 95%. The aim is to sustain UL with BVID. Two values for the BVID criterion are typically established dependent on the visual inspection type: Detailed visual inspection (DET) and general visual inspection (GVI) [15].

Dent depth is the damage metric for transverse impact. For an edge impact, where internal cracks and delaminations become visible, the damage metric is the dent depth and/or the crack length [15].

Boeing damage definitions

BVID are small damages, which may not to be found during heavy maintenance general visual inspections using typical lighting conditions from a distance of five feet. Damage metric is typically a dent depth of 0.01 to 0.02 inches (OML). Dent depth relaxation must be accounted for [16].

Other damage metrics

Presently there are no damage metrics in use that could replace the permanent indentation for the visual inspection. The requirement on such damage metrics would be that it be easily and quickly detectable with a minimum of equipment. A promising alternative for visual inspections of future aircraft are Structural Health Monitoring (SHM) technologies, which are presently being investigated in a number of international research projects. More information about these projects is included in section 3.7.2 of this document.

There are a few damage metrics in use that can complement the “classic dent”. These metrics are associated to NDI methods described in section 3.7.1, such as the acoustic response to a tap with a tap hammer or narrow surface cracks detectable by the penetrant method. One activity of this project is to look for further damage metrics, which could indicate internal damage in composites.

In aircraft applications, scheduled inspections are the basis for initially detecting damage that does not result in an obvious malfunction. Aircraft structures have historically relied heavily on visual methods in this process [9].

3.2 Types of visual inspection

There are a few sources for definitions of visual inspection. The most widely used seems to be the one from the FAA advisory circular AC 43-204 [17]:

> “Visual inspection is defined as the process of using the eye, alone or in conjunction with various aids, as the sensing mechanism from which judgment may be made about the condition of a unit to be inspected.”

In the 1990s an extensive research program was conducted to investigate the influence of human factors on visual inspection in aircraft maintenance (Visual Inspection Research Project, VIRP). In this project visual inspection was defined as follows [2]:

> “For the Visual Inspection Research Program, we expand the definition of “Visual Inspection” to include other sensory and cognitive processes that are used by inspectors. We feel that neglect of these other systems provides an artificially narrow picture of the rich range of behaviors involved in visual inspection. Thus, the Visual Inspection Research Program uses the following definition of Visual Inspection:
>
> *Visual inspection is the process of examination and evaluation of systems and components by use of human sensory systems aided only by such mechanical enhancements to sensory input as magnifiers, dental picks, stethoscopes, and the like. The inspection process may be done using such behaviors as looking, listening, feeling, smelling, shaking, and twisting. It includes a cognitive component wherein observations are correlated with knowledge of structure and with descriptions and diagrams from service literature.*”

There are four categories of visual inspection relating to their difficulty and degree of effectiveness [17]:

- Walkaround Inspection: The walkaround inspection can be performed by aircraft maintenance personnel and also aircraft operating personnel. It usually serves as a quick check for obvious damage and most maintenance instructions require them to be performed on a periodic basis. Aircraft history should be taken into account (e.g. recurring problems or hard landings).

- General Visual Inspection (GVI): GVI is often required on a periodic basis, but may also be scheduled, when a specific problem is suspected.
- Detailed Visual Inspection (DET): A detailed visual inspection is carried out, when a specific problem is suspected and the general visual inspection dictates additional inspection. Detailed visual inspections are also periodically called for to ensure airworthiness of damage tolerant aircraft.
- Special Detailed Visual Inspection: Special detailed visual inspections are likely to involve specialized inspection aids. Special detailed inspections are periodically called for on damage-tolerant aircraft to ensure the airworthiness of the critical structure. They may also be invoked based on recommendations from a lower level.

Detailed descriptions of each of these inspection types is provided in the Advisory Circular 43-207 [17] and in Appendix C.

3.3 The visual inspection process.

It is considered good practice to pre-inspect the general inspection area for cleanliness, foreign objects, deformed of missing fasteners, security of parts, corrosion and damage before a visual inspection. Areas to be inspected should be carefully pre-cleaned without removing indication of damage and without damaging any surface treatment [17].

In [17] inspection procedures applying to painted composite airframe structures are described for identification of

- surface cracks, using a flashlight (see Figure 4)
- disbonds
- chipped, missing, loose or blistered paint.

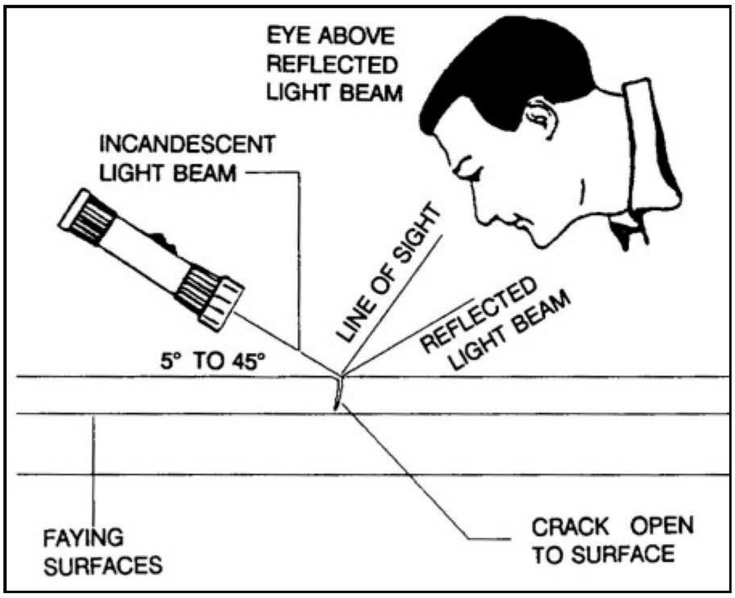


Figure 4: Using a flashlight to inspect for surface cracks (source: [15]).

The standard visual inspection aids are flashlight, mirror and magnification glass. For special inspection tasks further inspection aids may be necessary. For a detailed description of such equipment see AC 43-204 [17].

All defects found should be documented. Specifically defect type, location and approximate size should be reported. In addition to textual information it is encouraged to use illustrations such as sketches, photographs or video recordings [17].

Disbonds are typically difficult to see. The advisory circular [17] states, that often mechanical distortion is the only means to determine whether any bonding exists.

3.4 Research on visual inspection of composite structures

3.4.1 Airbus study

Two types of visual inspection were investigated: Detailed Visual Inspection (DET) and General Visual Inspection (GVI) [15].

- DET: Detection of damages on different composite panels (size: from 100*100mm to 0.8m², painted or not, glossy or mat, white, grey, blue or green paint, primer). Duration of inspection: not limited. Distance of inspection: 50 cm. Lighting condition: available lighting + grazing light (if required). Several impactor diameters: 6mm and 16mm. A total of 902 inspections.
- GVI: Inspection on large panel (8m * 1.2m). Two configurations: horizontal or vertical panels. Distance of inspection: 1m. Duration of inspection: 30sec/panel. Artificial lighting representative of natural daylight. Several impacts on painted panel: from 0.3mm deep to perforation. Several impactor diameter: from 6 to 120mm. A total of 240 inspections.

Results of DET and GVI inspections were statistically processed, POD was determined as a function of the damage size; BVID is associated to POD of 90%. The result of the study was consistent with GVI in-service survey of European airlines [15].

3.4.2 HFAMI / VIRP

The Aging Aircraft Nondestructive Inspection Validation Center (AANC) at Sandia Labs carried out the Visual Inspection Research Project (VIRP). The VIRP was conducted in the framework of the Human Factors in Aviation Maintenance & Inspection Research Program (HFAMI research program 1989-1998). Documentation of this research is available online at at the website of the HFAMI research program http://amelia.db.erau.edu/hfami/, particularly in the Phase V progress report. Furthermore, Spencer published a report on benchmark inspections of the VIRP [2].

3.4.3 Visual detectability of dents

In an initial study, the visual detectability of 0.05 inch deep dents was investigated [18]. Two specimens made of composite material were used with different surface condition (dirty / clean), different lighting (only ambient lighting / additional directed artificial lighting), different inspection angle (30° / 45°). Dents were produced by dropping a lead ball and a lead weight onto the structure at different locations and from different heights. A grid pattern was laid out on the specimens and was repeated on the inspection forms, where the inspectors recorded their findings.

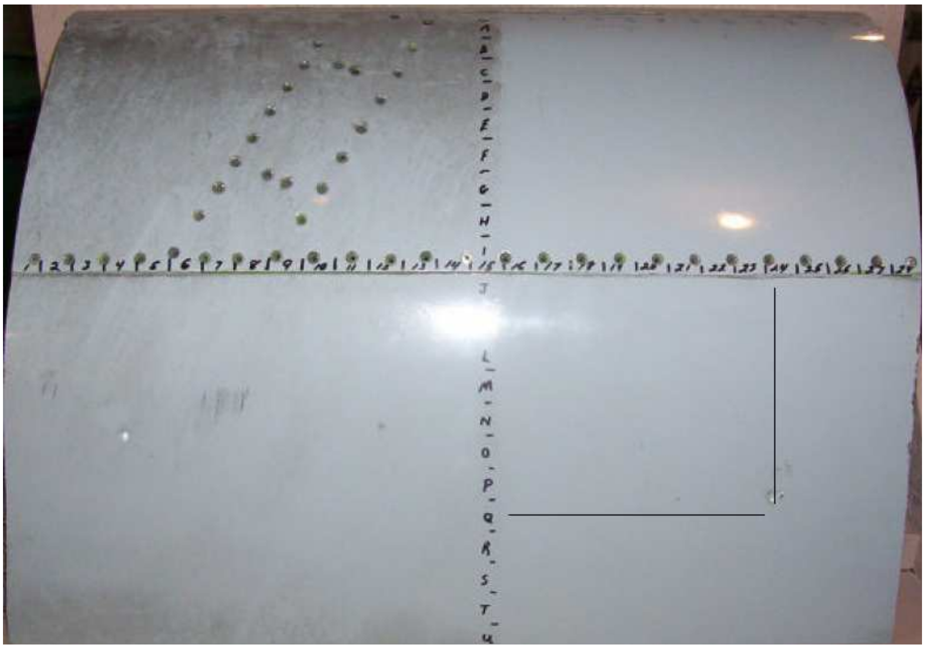


Figure 5: Inspection specimen A with dent at grid point Q24. Left side of the panel was left dirty, the other side was cleaned. The horizontal marks (presumably) define the border between the upper side and the lower side of the panel.

73 persons participated in the study. Sex and age of the participants were captured. The average time spent by one participant to examine the two specimens was 15-20 minutes.

It was found, that there was a difference in the POD of dents on the upper side and lower side of the panel. Whether age versus dexterity of the participants was a factor in the POD could not be answered. The captured data did not suggest that the chosen lighting and surface conditions played a role for the POD of the dents.

In summary, an average of 93.2% of untrained adults was able to find 0.05 inch deep dents. The study concluded that there may be a problem with people being able to see small dents and recommended more detailed and specific studies. Variables of most interest to aircraft industries were identified for further work in this area. These variables are

- Clean vs dirty surfaces
- Dull vs glossy finishes
- Lighting
- Viewing distance
- Visual angle
- Correlation of identified interior damage with a surface defect
- Experience and training
- Combination of visual and tactile inspections.

3.4.4 Automated visual NDT

As a step towards the automation of visual inspection tasks systems have been developed consisting of an optical system, a CCD-camera, a light source, a data processing unit and the necessary software, which can be used to automatically scan the surface of an aircraft and store images of the sources on a medium for later evaluation by maintenance staff. This method is called “enhanced visual inspection” [27].

3.5 Parameters affecting visual inspection

The FAA AC 43.204 “Visual inspection for aircraft”, first published in 1994 and updated in 1997 [17], contains detailed specifications regarding all aspects of visual inspection. Parameters relevant to this study are

1. inspection personnel qualifications and training
2. inspection area access
3. lighting
4. pre-cleaning
5. working environment factors, such as excessive climatic factors and noise.

A preliminary visual inspection study carried out at the University of Idaho on two composite panels identified variables of most interest to aircraft industries (see section 3.4.3 and [18]). These variables are

1. surface finish and cleanliness
2. lighting
3. viewing distance and visual angle
4. correlation of identified interior damage with a surface defect
5. experience and training of the inspector
6. combination of visual and tactile inspections.

3.6 Colour / lighting / vision aspects

3.6.1 Light characteristics

CAA, Safety Regulation Group, Aviation maintenance and human factors, 2003 [20], identified four fundamental light characteristics, which need to be considered for maintenance tasks. These are

1. Light Level: Generally, most maintenance tasks require between 750 lux and 1000 lux, although more detailed maintenance tasks may require additional illumination. General line inspections (e.g., easily noticeable dents) may only require 500 lux. Based upon IES standards [22], [23], it is recommended that the ambient light level in a maintenance hangar be at least 750 lux in order to perform pre- and post-maintenance/inspection operations and some general maintenance/inspection tasks without the necessity for additional task lighting. Furthermore, adequate illumination levels may be obtained in a majority of inspection tasks and many maintenance tasks through the utilisation of task lighting.

2. Colour Rendering: Colour rendering measures the degree, to which the perceived colours of an object illuminated by various artificial light sources match the perceived colours of the same object when illuminated by a standard light source (i.e. daylight). The difference in the spectral characteristics of daylight, incandescent lamps, fluorescent lamps, etc., has a large effect on colour rendering. Such effects are described in detail in [23].

3. Glare: Glare is caused by excessive lighting within the visual field. It obscures the visual impression of details and thus has an adverse effect on damage detectability. The existence of direct light sources in the visual field, reflecting

surfaces and even reflections from light objects can produce glare. Glare can be reduced by resorting to indirect lighting.

4. Reflectance: The lighting conditions are largely influenced by the reflectance of nearby surfaces. While high reflectance surfaces increase the effectiveness of luminaires, they can produce glare and should be avoided. Diffuse reflectance from a semi-matte surface is preferred. The IES recommends a diffuse reflectance of 80-90% for ceilings, 40-60% for walls and not less than 40% for floors of aircraft hangars, where maintenance is performed.

Since it is possible that different types of damage on the same structure require different types of lighting, some visual inspection tasks may need more than one specialized lighting condition for best inspection results. For example, ripples in an aircraft fuselage are best detected with grazing light, while colour differences require normal-incidence lighting.

In the automotive industry it is important to inspect painted surfaces for paint defects, which are often of topographical nature. When it comes to the detection of small topographical defects (small meaning a size of less than a few mm^2) on glossy surfaces there are several measures which can be taken to optimise lighting conditions [26]. However, the typical small paint defect is topographically different from an impact dent on a composite surface and automotive parts to be inspected for paint defects are much smaller than a whole CS 25 aircraft. Further studies are necessary to investigate the transferability of recommendations mentioned in [26] to the inspection of composite aircraft structures.

Details about aspects of light characteristics in the context of visual inspections can be found in Appendix D.

3.6.2 Airline colours

A survey among European airlines yielded the following table of colours used for their aircraft. The colour specifications (Pantone, RAL or BAC identification number) have been approximated by an RGB code and a coloured rectangle for illustration purposes.

	Name	Pantone	RAL	BAC	RGB-Code
Alitalia	green	3425			000 / 104 / 071
	red	200			135 / 031 / 054
	white				
	blue	280			000 / 043 / 127
LTU / Air Berlin	red		3020		190 / 017 / 016
	grey		7042		141 / 145 / 145
	white		9003	7309	237 / 237 / 231
	grey		7035	707	193 / 197 / 192
Lufthansa	white		9016	7945	237 / 238 / 232
	blue		5022		034 / 040 / 086
	red		3000		169 / 030 / 031
	yellow		1028		255 / 162 / 000
	grey		7035	707	193 / 197 / 192
	grey		7048	708	
		11c			
		7c			
		3c			
DHL	yellow				252 / 209 / 022
	red				135 / 031 / 054
	yellow				255 / 190 / 000
	red				186 / 021 / 054
TNT	white		9016		237 / 238 / 232
	orange		2009		225 / 081 / 005
	black		9005		018 / 019 / 020
	grey				
	blue	275		5926	038 / 015 / 084
	red	485		1883	204 / 012 / 000
	orange	021		2569	215 / 130 / 057
Iberia	white		9003	7067	237 / 237 / 231
	yellow		1033	3259	246 / 156 / 000
	orange		2002	1001	194 / 051 / 028
	red		3002	134	159 / 022 / 028

Table 1: Airline colours used by airlines

According to Lufthansa Technik (phone conversation with paint shop manager) 90% of their customers prefer glossy over matt surface finish.

3.6.3 Human vision

Human eyesight can be characterised by its colour vision capability and its visual acuity.

Visual acuity is a quantitative measure of the ability to identify black symbols on a white background at a standardized distance as the size of the symbols is varied. It is the most common clinical measurement of visual function. Visual acuity can be expressed as a fraction, i.e. 6/5, where the numerator defines the distance between the test person and the symbol, so that the test person can just barely identify the symbol. The denominator is the distance, from which a person with a standard value of visual acuity would be able to distinguish the symbol. Visual acuity can also be expressed as the decimal value, which is obtained by evaluating the above mentioned fraction. A person with normal eyesight has a visual acuity of 1.0. Visual acuity can be determined using an eye chart.

The human eye contains three types of cone cells with different sensitivities to the colour spectrum of light. The combination of the signals of these three types of cells is interpreted by the human brain, thus constructing a colour impression. Since many of the genes involving colour vision are located in the X-chromosome, colour vision deficiency is more common among males than females. So-called “Ishihara colour plates” [28] can be used for testing colour vision.

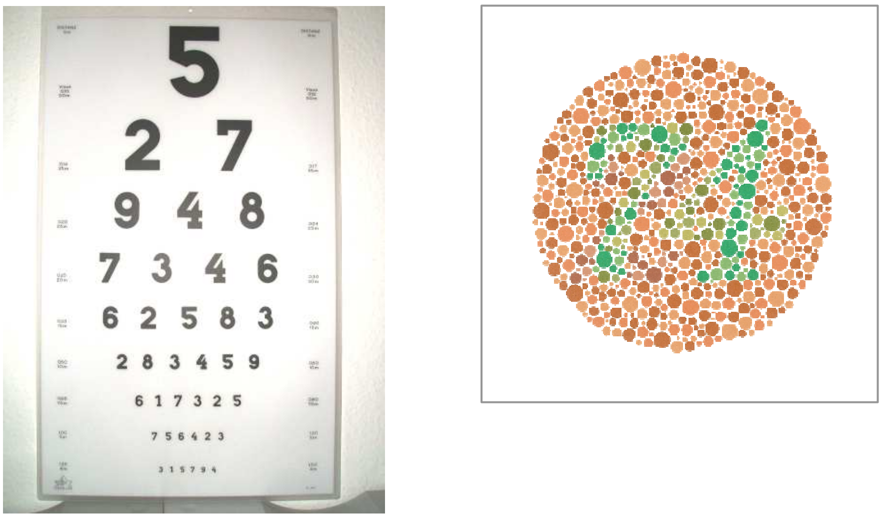


Figure 6: Eye chart for determination of the test persons’ visual acuity and Ishihara colour plate for colour vision testing.

3.7 Alternative inspection methods

3.7.1 Non-destructive testing

The advisory circular AC 43.13-1b, published in 1998, gives an overview of acceptable means for the inspection of airframe structures [24]. The most important ones are

- Penetrants
- Radiography (X-ray)
- Ultrasonic
- Acoustic emission
- Thermography
- Holography
- Shearography
- Tap testing.

Most relevant for inspection of composite structures are tap testing and ultrasonic scanning. Penetrants are reported not to be effective for composites. X-ray inspection is being used for the inspection of helicopter rotor blades, but requires a large instrumental effort and is presently not available for standard maintenance practices, at least up to detailed visual inspection level. The same applies for thermography, shearography, acoustic emission and holography.

A brief summary of methods, which are applicable to composite structures, is given in Appendix E.

3.7.2 Structural Health Monitoring

With present damage tolerance philosophy

- non-visible damage must not lower the residual strength below ultimate load.
- non-visible damage must not grow under limit loading conditions.

This leads to conservative designs, since non-visible damage can become quite large in composites. Recently more and more effort is being spent on structural health monitoring (SHM) systems. These typically rely on sensors embedded within the composite structure. These sensors could be used to

- monitor loads during operation, e.g. record strain cycles for fatigue monitoring as in the Eurofighter, and/or
- monitor structural integrity (e.g. detect non-visible damage) and thus complement or replace a visual inspection.

There are a number of projects presently running in the European aeronautic research community, dealing with development of sensor technology, reliability issues, sensor integration aspects, etc. While for certain military aeronautic applications SHM systems are already being used, there is currently no approved SHM technology available for monitoring the structural integrity of composite parts. A brief overview of recent and presently running projects is given in Appendix F.

4 Methodology

Major work packages which also mark the milestones of the project are

- literature survey
- design and manufacturing of composite structure for tests
- introduction of damages
- visual inspection under different conditions
- investigation of alternative damage metrics.

4.1 Survey

At the beginning of the study a survey has been carried out, in order to review previous research about visual inspection of composite aircraft structures. The survey particularly addresses the following topics.

- Identification of parameters influencing the detectability of defects.
- Definition of a realistic inspection environment.
- Definition of a realistic design of the test structures.

This survey can be found in section 3 of this document. Furthermore, results of the survey determined the methodologies, which are described in the following chapters.

4.2 Panel manufacturing and preparation for visual inspections

Two identical CFRP structures have been designed and manufactured: stringer-stiffened panels of 600 mm x 800 mm size with four T-stringers attached to the inside of the panel. The structure is slightly curved with a radius of approximately 2m. Such structures are considered typical for composite fuselage and composite wing applications. A statement from Airbus confirmed that the chosen design could resemble a typical substructure for the A350.

The structures were large enough to be impacted 20 times with energies between 10 and 75 Joule causing barely visible damage. Impacts in the skin region and impacts near a stiffener caused different typical sorts of impact damages with a high relevance for composite structures.

Material system, skin thickness, stacking sequences, stringer spacing and geometry were chosen to be comparable to a possible lower CFRP fuselage of a typical aircraft (e.g. A350) to be certificated to CS 25. Skin and stringers are co-cured, as secondary bonding is not acceptable at the moment for such primary fuselage structures.

The structures do not contain frames, as this would have increased manufacturing effort too much. During introduction of impacts the structures were placed on wooden supports with a typical frame spacing.

The outside surface of the panels was coloured and finished like a typical composite aircraft structure. Three different colours with relevance for today's airline liveries were used for the visual inspection.

Next the panels were impacted in order to create typical damages. Impact energies were chosen to produce damages with different degrees of visibility. Previous research indicated that impactor geometry has a large influence on damage visibility. For this study the typical 1-inch diameter hemisphere and a 320 mm diameter spherical sector were used. In between impacts ultrasonic scanning was used to detect internal damages. The overall goal was to produce a maximum of internal damage at a minimum of damage visibility.

When choosing impact locations, care was taken that impact damages did not influence each other and were not too close to the free boundary or the wooden supports, in order to ensure the creation of realistic damages.

After impacting the panel surfaces were covered with a thin film of soot and oil to resemble typical airplane dirtiness.

4.3 Carry out inspections

The visual inspections were carried out under 3 different conditions for all parameters to be investigated: average, poor and very poor. The definition of these conditions was to be derived from the literature survey and from answers to questionnaires, which were sent out to aircraft operators participating in the study.

Originally it was planned to involve two groups of people during the inspections:

- Persons with good experience in composite structures and / or aircraft maintenance and inspection, and
- Persons with minor experience in composite structures and aircraft maintenance and inspection.

It was originally planned to recruit the test persons only from DLR Braunschweig, where aircraft operating and maintenance personnel are available. This has been changed during the project. Professional aircraft maintenance and inspection personnel were also recruited from nearby aircraft operators Lufthansa Technik and TUIfly. Involving two airlines had several benefits. A questionnaire (see Appendix B) was filled out by airline personnel, which greatly contributed to the definition of realistic inspection conditions. Average illumination conditions were redefined after the first visit at Lufthansa Technik, see section 5.6.1. Furthermore the experience / background of the inspectors involved in the study was broadened.

Additionally it was planned to only recruit people with normal eyesight. However, there were participants from aircraft operators with vision defects regarding contrast vision and also colour vision, so it was decided to include such persons in the survey as well.

In order to define realistic inspection conditions a questionnaire for aircraft operators was prepared (see Appendix B). A detailed planning of the inspections ensured reproducible conditions for each inspection. This includes the time available for the inspection, lighting, the surrounding environment and the distance between inspector and structure. Another questionnaire (see Appendix A) was handed out to the inspectors. The observations including damage locations and damage severities were recorded in the questionnaire as well as the experience of the individual inspector concerning damage detection and composite structures.

The two panels with equal damages (but at different locations) were put into conditions with different influence on the detectability of damage, according to Table 2. An “Inspection type” (first row in Table 2) is defined by a certain set of inspection conditions described by the last four rows in Table 2. The second row, “Inspection No.” lists the consecutive order, in which inspections were carried out. Two inspection types were carried out twice. For example, inspection type 1 was conducted with average conditions throughout. Such conditions were present at the second inspection carried out in November 2008 at Lufthansa Technik with professional aircraft maintenance personnel and also at the 5th inspection, carried out in December 2008 at DLR Braunschweig. Further details regarding each of the nine inspections listed in the second row of Table 2 can be found in Table 16.

The first inspection (inspection No. 1) was carried out at an illumination of 1100 lux at DLR Braunschweig in November 2008. At this time an average amount of lighting was thought to be between 1000 and 1200 lux. However the second inspection (inspection No. 2) at Lufthansa Technik showed that the average amount of lighting in an aircraft hangar is 350 to 400 lux. Therefore the inspection for generally average conditions had to be repeated later with less illumination (inspection No. 5). This resulted in an additional inspection type with very good lighting conditions (inspection type 2), which was not planned originally.

The literature survey and interviews with airline personnel revealed, what constitutes average, poor and very poor inspection conditions with respect to damage detectability. A worst case scenario with very poor (but still acceptable) conditions throughout has been investigated.

“O” means average condition with respect to damage detectability

“-” means poor condition with respect to damage detectability

“--” means very poor condition with respect to damage detectability

“++” means very good condition with respect to damage detectability

Inspection type	1		2		3		4		5		new colours / finishes new impacts	6		7	
Inspection No.	2, 5		1		4, 6		3		7			8		9	
Panel	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2		P1	P2	P1	P2
Colour / finish	o	o	o	o	o	o	o	o	o	o		-	--	-	--
Lighting	o	o	++	++	-	--	o	o	o	o		o	o	-	--
Inspection angle	o	o	o	o	o	o	-	--	o	o		o	o	-	--
Cleanliness	o	o	o	o	o	o	o	o	-	--		o	o	-	--

Table 2: Investigation of variables influencing detectability for colour finishing with average properties concerning damage detection, inspections 0 to 5.

Each inspection type in Table 2 was carried out by nine to eighteen persons. The inspectors for the inspection types 1 to 5 in Table 2 were all different, in order to make sure that the inspectors didn’t know locations of damages from previous inspections.

Originally it was planned to repeat the inspections 3 to 5 in Table 2 for colour and finish combinations with poor and very poor influence on damage detectability. During the project it was decided to perform a reference inspection instead with average conditions throughout (inspection 1 in Table 2), to serve as a reference. This was useful to make sure, that under equal average conditions the damage detectability was comparable for both panels. Additionally, this provided three data points for each inspection variable: average, poor, and very poor conditions for one variable, while all the other variables were of average condition. After application of new colours and finishes inspection type 6 in Table 2 could be performed. Before this inspection, new damages were introduced, because in the process of applying a new coating some damages were obscured. Finally, in inspection type 7 all variables will be chosen as "poor" and "very poor" with respect to damage detectability.

The distance between inspector and panel was chosen to be within a typical range for visual inspection and at the same time close enough, so that relevant damage metrics could be identified by persons with good eyesight and good experience in visual inspection. The inspection time for each structure was set to 10 minutes maximum. This time allowance permitted barely visible damages to be detected. There should not be any time pressure on the inspectors, but inspection time should be limited and should not be extended too long in order to provide realistic inspection conditions.

After completion of the visual inspections No. 1 - 9, each of the two panels was damaged by 20 damages of different severities. These damages were then subjected to further tests in order to establish additional / alternative damage metrics. The investigations of damage metrics were performed by experienced maintenance personnel (6 persons from Lufthansa Technik) and included tactile methods and tap tests. Since the alternative inspection methods required contact with the panel (tap hammer), they could have influenced damage sizes and damage appearance. Therefore these investigations were carried out after the other visual inspections were completed.

4.4 Evaluation

The careful preparation of the visual inspections ensured, that all relevant data was captured, including relevant data of the test persons (eyesight, experience in inspection / maintenance), relevant data of the inspection conditions and inspection results. The recorded data allowed a detailed evaluation of the variables influencing damage detectability.

New damage metrics were evaluated on 20 damages in two composite panels. The results of this study were compared to the standard metric (the permanent indentation) and to NDI results for damage sizes obtained by ultrasonic scanning.

5 Implementation

5.1 Panel manufacturing and preparation

5.1.1 Panel design

The structures resemble a fuselage structure, as it could come into consideration for a future large aeroplane, such as the A350, because damages and inspection conditions should be as realistic as possible. The results of this study is also valid for Boeing 787 structures and the composite fuselage of the Hawker 4000 introduced in 2001 by the Raytheon Aircraft Company. Based on the experience of past research projects together with European aeronautic industry a panel design has been proposed (Figure 7). A statement from the Airbus A350 team in Toulouse confirmed that the proposed design is comparable to a possible A350 fuselage structure.

Since the curvature of the fuselage could influence the appearance of damage, it was decided to build a slightly curved structure with 1975 mm radius. This was possible, because a tooling with this radius was already available at DLR. A typical stringer spacing in a metallic fuselage is around 150 mm, so the composite panel is stiffened by four T-stringers like shown in Figure 7. Omega stringers were another option for stringer geometry, they are even more relevant for the fuselage area, but the opinion of Airbus was, that the stringer geometry would not make a substantial difference for damage detectability.

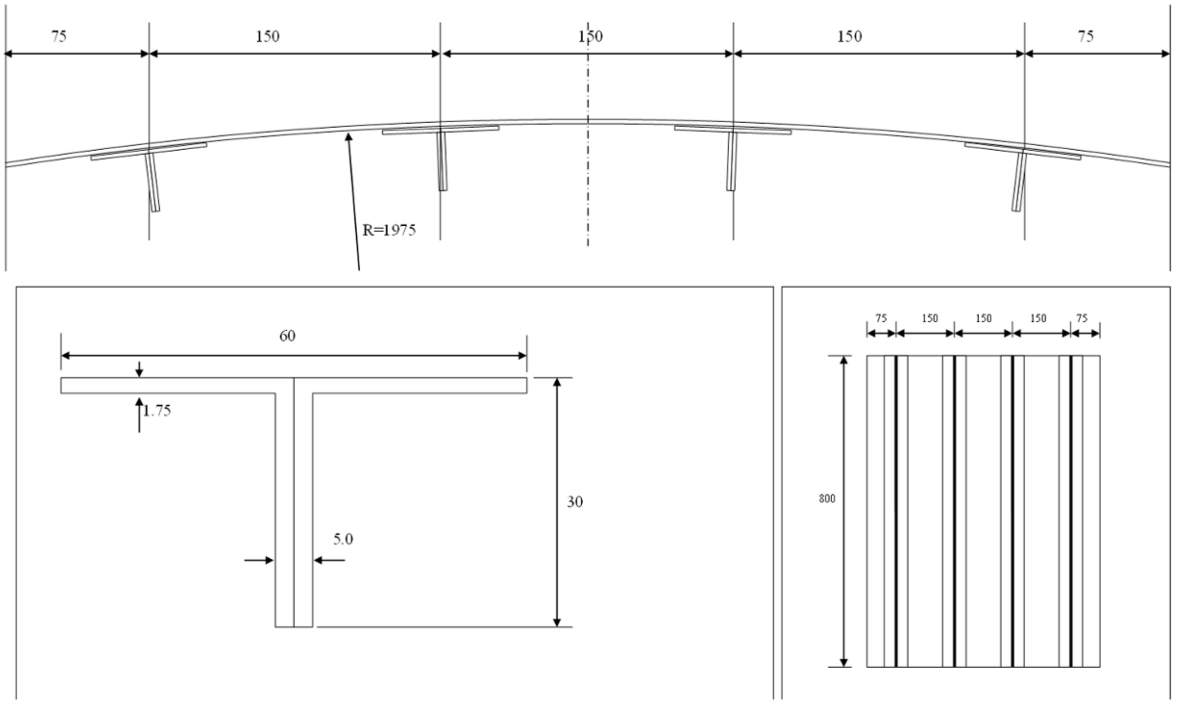


Figure 7: Design of the test structure

5.1.2 Panel manufacturing

Manufacturing test

A manufacturing test was performed with left over Prepreg material from previous projects. This manufacturing test helped to ensure proper quality of the real test structures. Different ways for producing the stringers were tried out.

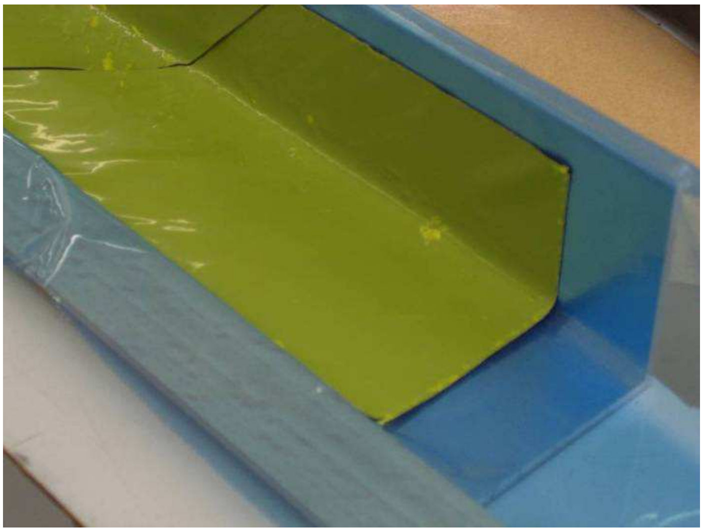


Figure 8: Lay-up of T-stringer

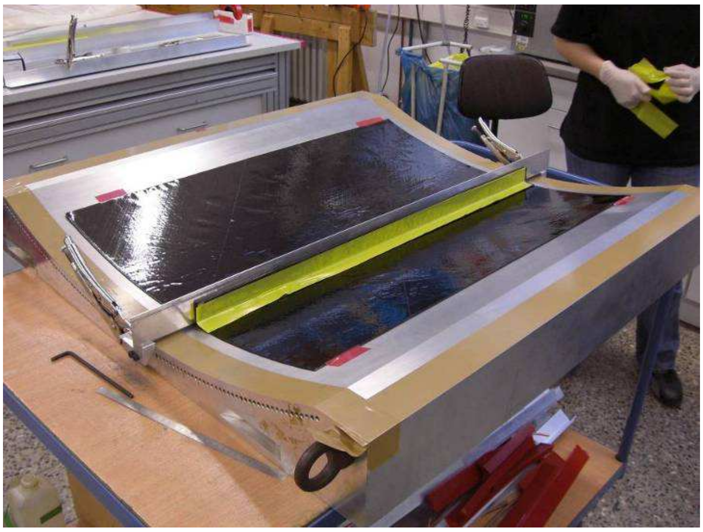


Figure 9: Placement of stringer on skin laminate. A tool with 1 m radius was used for the manufacturing test.

Figure 10: Stringers are supported by silicone cores (red pieces) with triangular cross sections to prevent the from collapsing during curing.

Manufacturing of the test structures

For the final test structures 0.25 mm Prepreg was delivered instead of the 0.125 mm Prepreg that was ordered. A new design was worked out with symmetrical and balanced laminates for skin, stiffener blade, and skin + stiffener foot, which make less problems for the co-curing process. DLR design experts took care that the laminates have a stiffness distribution typical for a fuselage design.

There was also a slight change in the thicknesses of the laminates with respect to the original design. This was necessary to achieve a reasonable stiffness distribution. 2.25 mm thickness of the skin laminate is still a typical value for a fuselage skin with 2 m radius.

Different failure modes due to the impacts were not to be expected; only the size and shapes of the damage are somewhat different for impacts of the same parameters. This is not a problem, though, because the range of impact energies provides for different damage sizes and shapes.

With the experiences from the manufacturing test, the production of the two test structures did not pose any problems and went very smoothly. Ultrasonic scans carried out later during impact testing showed a good quality of the panels without manufacturing defects.

Skin laminate			
No	Orientation	Ply thickness	Material
	[°]	[mm]	
outside			
1	45	0.25	IMS / 977-2
2	0	0.25	IMS / 977-2
3	-45	0.25	IMS / 977-2
4	0	0.25	IMS / 977-2
5	90	0.25	IMS / 977-2
6	0	0.25	IMS / 977-2
7	-45	0.25	IMS / 977-2
8	0	0.25	IMS / 977-2
9	45	0.25	IMS / 977-2
inside / stiffener foot			
		2.250	

Stiffener foot laminate			
No	Orientation	Ply thickness	Material
	[°]	[mm]	
skin laminate			
1	45	0.25	IMS / 977-2
2	0	0.25	IMS / 977-2
3	-45	0.25	IMS / 977-2
4	0	0.25	IMS / 977-2
5	90	0.25	IMS / 977-2
6	0	0.25	IMS / 977-2
7	-45	0.25	IMS / 977-2
8	0	0.25	IMS / 977-2
9	45	0.25	IMS / 977-2
inside			
		2.250	

Stiffener blade laminate			
No	Orientation	Ply thickness	Material
	[°]	[mm]	
1	0	0.25	IMS / 977-2
2	45	0.25	IMS / 977-2
3	0	0.25	IMS / 977-2
4	-45	0.25	IMS / 977-2
5	0	0.25	IMS / 977-2
6	90	0.25	IMS / 977-2
7	0	0.25	IMS / 977-2
8	-45	0.25	IMS / 977-2
9	0	0.25	IMS / 977-2
10	45	0.25	IMS / 977-2
11	0	0.25	IMS / 977-2
12	0	0.25	IMS / 977-2
13	45	0.25	IMS / 977-2
14	0	0.25	IMS / 977-2
15	-45	0.25	IMS / 977-2
16	0	0.25	IMS / 977-2
17	90	0.25	IMS / 977-2
18	0	0.25	IMS / 977-2
19	-45	0.25	IMS / 977-2
20	0	0.25	IMS / 977-2
21	45	0.25	IMS / 977-2
22	0	0.25	IMS / 977-2
		5.500	

Figure 11: Stacking sequences for the test structures using 0.25 mm Prepregs from Cytec.

Specimen testing

A few test samples for tension testing have been manufactured with the stacking sequence of the skin laminate (Figure 11). Test were performed according to DIN EN 2747 using a Zwick 1484 test rig with a cross head velocity of 2 mm / min. Clamping length of the specimens was 130 mm, specimen width was 10 mm.

Stacking sequence	No. of specimens	Average modulus uniax. tension	theoretical modulus, via UD properties & CLT
[45/0/-45/0/90/0/-45/0/45]	4	94626	97300
[-45/90/45/90/0/90/45/90/-45]	4	41667	45300

Table 3: Results for uniaxial tensile tests on skin laminate specimens. Elastic modulus is given in MPa.

Considering the fact that multidirectional laminates were tested, the test results show acceptable conformity with theoretical predictions from classical laminate theory (CLT), see Table 3, using the UD 0° tensile modulus of 165 GPa as specified in the data sheet of Cytec.

Painting

Painting of the panels was performed by Lufthansa Technik in Hamburg according to the usual procedures for composite structures. Only the outer surface was coloured. The procedure is as follows.

1. Primer
2. Anti Static Lac
3. Primer
4. Top coat (colour according to customer specification)

5.2 Impacting

5.2.1 Introduction of impacts – part 1

Introduction of impacts was done with a pendulum impact device at DLR Braunschweig. In its standard configuration impact energies of up to 40 Joule can be introduced. Two impactors were available: the standard 1-inch hemisphere and a spherical sector with a diameter of 320 mm for blunt impacts.

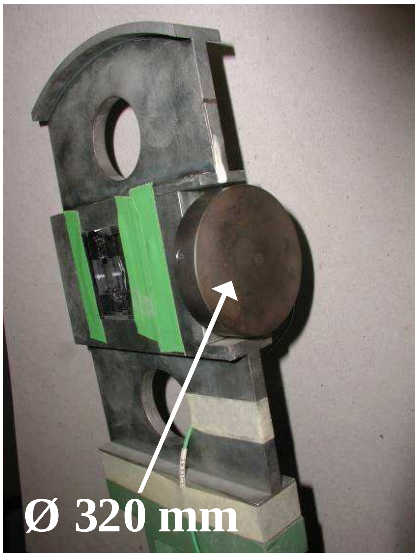


Figure 12: 320 mm impactor and one-inch impactor.

For the impact the structures are placed on wooden supports at a spacing of 530 mm. These support the structure between the stringer blades and ensure a continuous load transfer into the massive orange steel construction shown in Figure 13. It is important to prevent the panel from jumping out of the supports when the impact arm rebounds. Therefore the panel is secured at four points with screw clamps as shown in Figure 14.

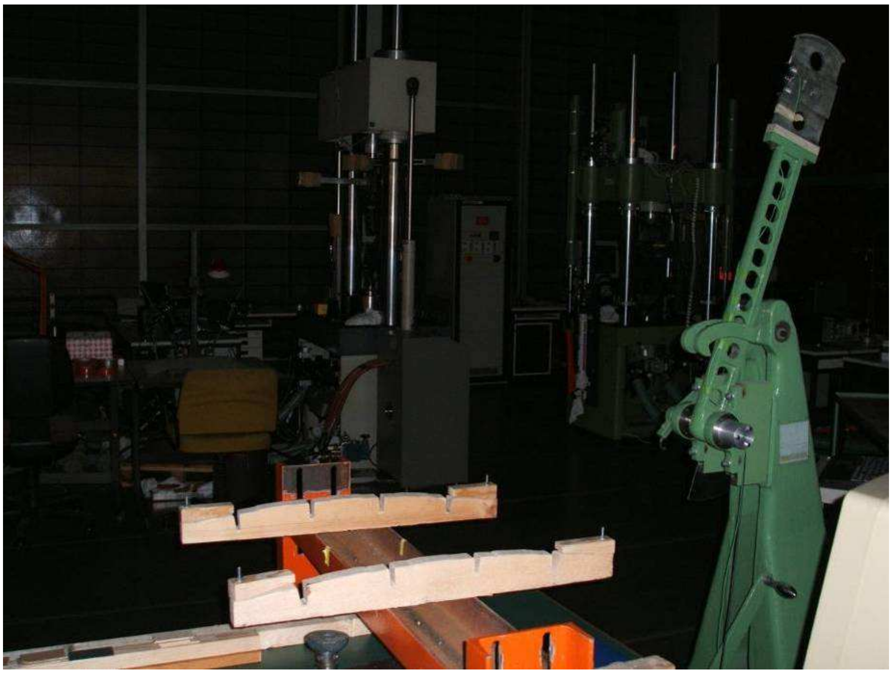


Figure 13: Pendulum impactor and wooden supports.

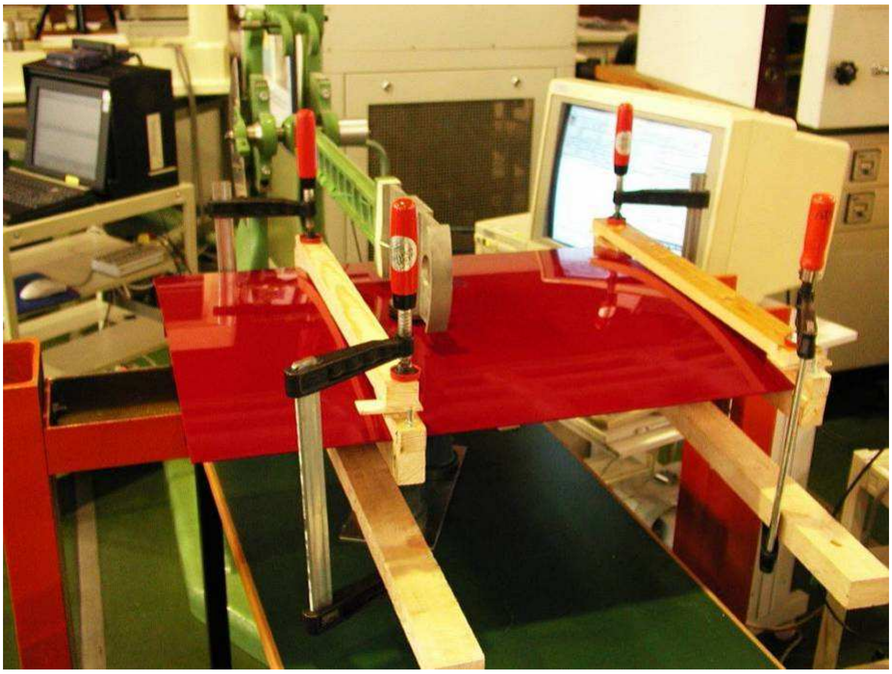


Figure 14: Panel secured against jumping out of the supports before impacting.

The overall goal was to produce a maximum of internal damage at a minimum of damage visibility. The impacts are to be introduced between the wooden supports, which represent the frames of a real aircraft structure.

Since damage severity is expected to increase with increasing impact energy and decreasing impactor diameter, the first four impacts were introduced into panel 1 with the 320 mm impactor and increasing energy from 5 Joule up to 40 Joule. Even the 40 Joule impact did not show any visible impact damage. Also, the subsequent US-scan showed no signs of internal damage.

Therefore further impacts of 30 and 40 Joule were introduced with the 320 mm impactor (impacts # 5 to 7 in Table 4), this time in more vulnerable areas in the bay area between the stringer feet and at the edge of the stiffener foot. Furthermore, three impacts from 20 Joule up to 40 Joule were applied using the 1-inch tup (impacts # 8 to 10 in Table 4). When looking at damage visibility and internal damage from US-scans it became clear, that the range of available impact energies must be expanded. Surprisingly even the 40 Joule impact with the 320 mm impactor in the skin area (impact # 6) did not produce any damage at all, while the impacts of the same energy with the smaller impactor diameter produced classical impact damage with clearly visible dents.

Chronol. impact order	Energy	Impactor diameter	Impact location	Remark	Subjective visibility	Impact No
#	Joule	mm				
1	5	320	Skin		0	
2	10	320	Skin		0	
3	20	320	Stringer foot edge		0	
4	40	320	Stringer foot		0	
US-scan 1						
5	30	320	Skin	At impact # 1 location	0	
6	40	320	Skin	At impact # 2 location	0	
7	40	320	Stringer foot edge	At impact # 3 location	1	1
8	20	2.54	Stringer foot edge		15	6
9	30	2.54	Skin		15	7
10	40	2.54	Stringer foot edge		15	8
US-scan 2						
11	60	320	Skin	At impact # 2 location	0	
12	75	320	Stringer foot edge		3	3
13	75	320	Skin		0	
14	10	2.54	Skin		10	5
15	60	2.54	Stringer foot edge		20	9
16	60	2.54	Skin		20	11
17	75	2.54	Stringer foot		20	10
18				Left out (no impact)		
US-scan 3						
19	60	320	Stringer foot edge		2	2
20	10	2.54	Stringer foot edge		1	4
US-scan 4						

Table 4: Impacts on panel 1 (red colour, glossy finish) in chronological order. The impacts, which produced damage, were given a number (last column). Impacts No. 1 to 10 (last column) were selected for impacting panel 2.

The “subjective visibility column” in Table 4 served as an aid to rate the visual appearance of an impact damage during the impact testing. The evaluation of the subjective visibility was made at the available lighting in the testing lab (around 350 – 400 lux), on the clean panel surface with the knowledge, where the impact occurred (impact locations were marked on the panel before impacting) and at arbitrary distance and angle to the damage. A value of 0 means, that no sign of damage could be seen. A value between 1 and 5 was assigned, if a sign of visible damage was noticeable, but was considered to be below the detectability threshold for a person not knowing, where the impact location is. A value of 10 corresponds to a dent, which was very easily noticeable, if one knows where to look. Values of 15 and 20 were assigned to immediately obvious damage.

Following the second US-scan after impact #10, the impacts #11 to #17 produced interesting damages. The impact of 75 Joules with the larger impactor diameter caused a skin-stringer separation and an almost invisible flat dent distributed over an area with a diameter of several centimetres. The same impact did not produce any damage when applied in the bay area between the stiffener feet. Impact #14 produced a noticeable dent, while high energy impacts with the 1-inch tup produced internal damages with clearly visible signs on the panel surface. The following tables and figures show detailed qualitative and quantitative data of the impact damages.

For completeness two more impacts #19 and #20 round off the impact programme. While impact #20 did not produce internal damage, it left a tiny mark on the painted panel surface. Impact # 19 produced a flat, spread-out dent, which is almost invisible and large internal damage.

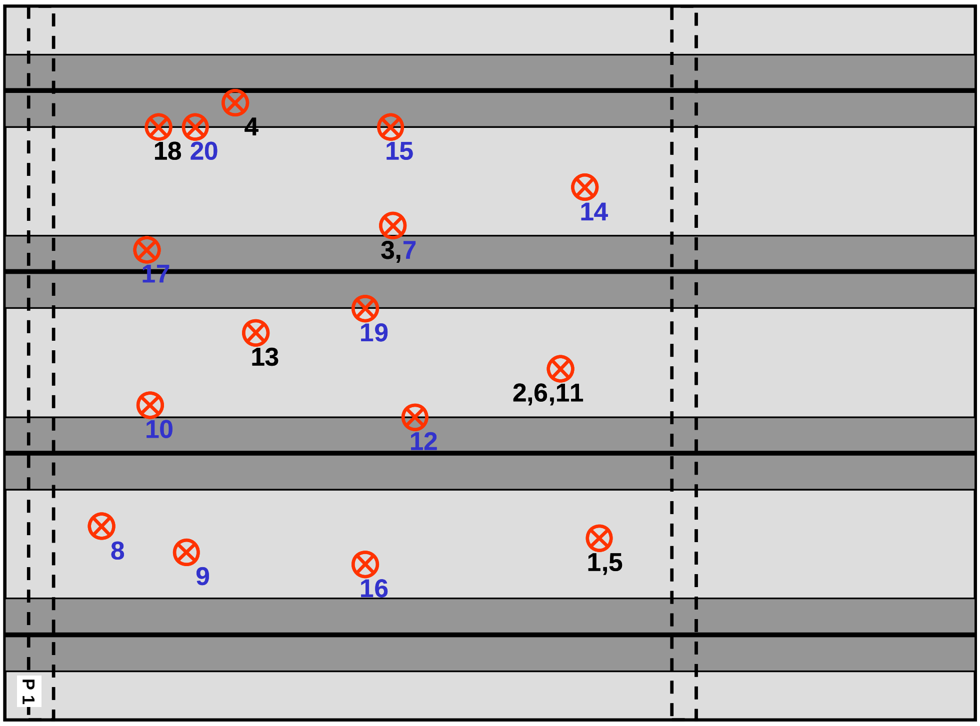


Figure 15: Impact locations, numbered in chronological order (see Table 4), for panel 1.

Ten of the 19 impacts on panel 1 were selected to be introduced into panel 2 as well. Among them were the 3 impacts with the 320 mm impactor, which were hardly visible, but produced internal damage. The seven remaining impacts with the 1-inch tup produced different sizes of internal damage at varying visibility (Table 5).

Impact No	Energy	Impactor diameter	Impact location	Subjective visibility
	Joule	mm		
1	40	320	Stringer foot edge	1
2	60	320	Stringer foot edge	2
3	75	320	Stringer foot edge	3
4	10	2.54	Stringer foot edge	1
5	10	2.54	Skin	10
6	20	2.54	Stringer foot edge	15
7	30	2.54	Skin	15
8	40	2.54	Stringer foot edge	15
9	60	2.54	Stringer foot edge	20
10	75	2.54	Stringer foot	20

Table 5: Impacts selected for further impacting in this study. First column corresponds to last column in Table 4.

5.2.2 Internal impact damage

The NDT results for both panels are shown in Figure 16 and Figure 17. In these Figures, equal impact conditions have equal numbers, corresponding to the first column in Table 5.

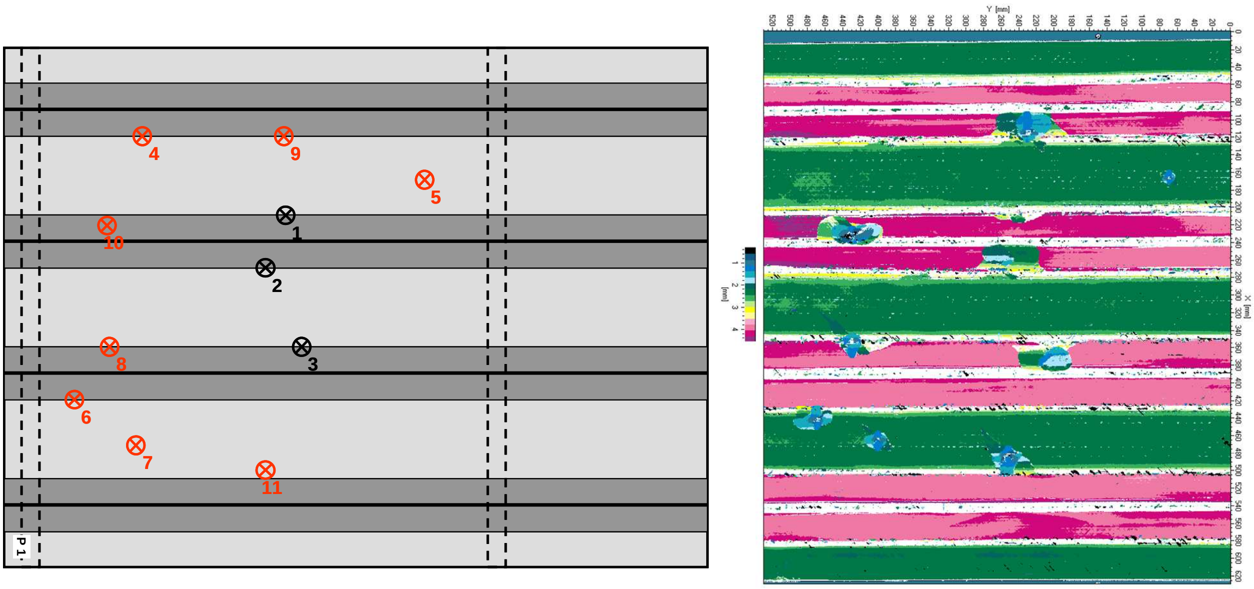


Figure 16: Impacts on panel 1 with NDT result. Impacts are numbered according to Table 5. Left border of NDT results corresponds to left edge of the panel.

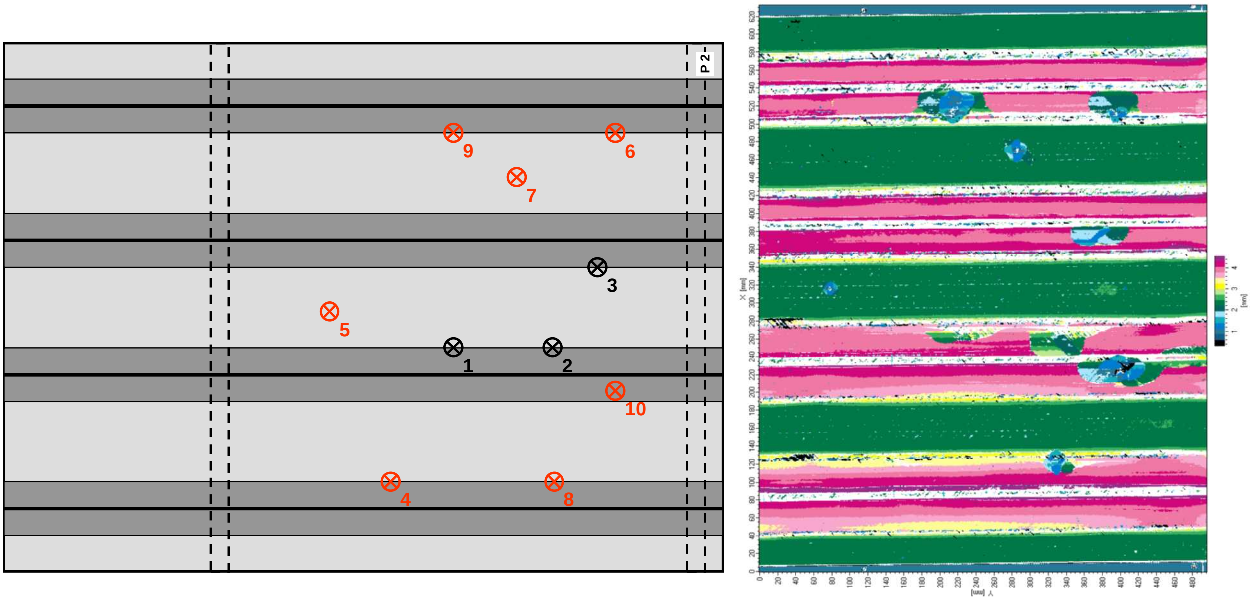


Figure 17: Impacts on panel 2 with NDT result. Impacts are numbered according to Table 5. Right border of NDT results corresponds to right edge of the panel.

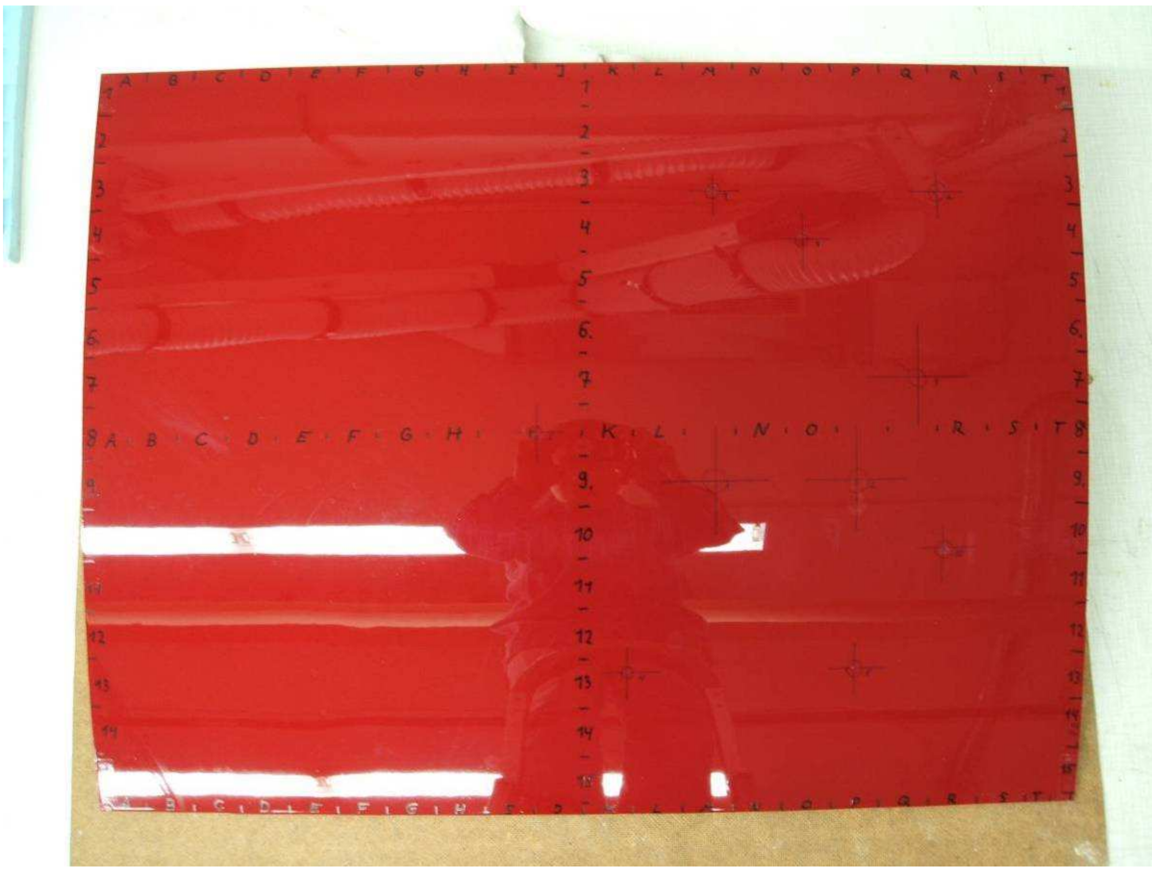


Figure 18: Panel 2 after introduction of 10 impacts and before application of dirt, with impact locations marked on the panel.

Figure 19: The ultrasonic scans were conducted with a stationary high resolution device using water coupling.

The impact damage consists of a combination of different failure modes (see section 3.1.3). The most important failure mode is delamination, i.e. the separation of two layers with different orientations. Delaminations, which occur in the interface between the stiffener foot laminate and the skin laminate are called “skin-stringer separations”. The impact damage in the stiffener foot region typically consists of both, skin-stringer separations and delaminations in the skin laminate. Delaminations in the skin laminate and skin-stringer separations can be distinguished by the US-scans, if the impulse-echo technique is used and the time of flight of the US-sound waves is recorded.

In order to categorize the impact damage, five size categories were defined (Figure 20) and applied to skin-stringer separations and ordinary delaminations in the skin laminate.

Size	Area
0	0 mm²
1	< 100 mm²
2	< 900 mm²
3	< 2500 mm²
4	> 2500 mm²

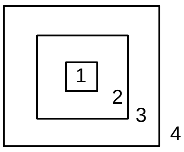


Figure 20: Categories 0 – 4 for damage sizes used in Figures below.

The figures in Table 7, Table 8 and Table 9 are all scaled equally and show the damages corresponding to the ten impacts 1-10. The scale for the damage categories is superimposed over the US-scans to facilitate the comparison of damage sizes. “Delamination size” in these figures means the overlapped size of the delaminations within the skin laminate. These are shown in blue and yellow colours in the US-scans. Delaminations in the skin-stringer foot interface (skin-stringer separations) are shown in dark green colour.

There is some scattering to be noted for the internal damage of nominally equal impacts. Reasons for this may be manufacturing tolerances, slightly varying impact locations (especially for impacts close to the stiffener foot edge) and slightly differing impact energies.

Energy	Impactor diameter	Impact location	Delamination				Skin-stringer separation			
			Panel 1		Panel 2		Panel 1		Panel 2	
Joule	mm		cat.	cat.	cat.	cat.	cat.	cat.	cat.	cat.
40	320	Stringer foot edge	1	1	1	2	2	2	3	3
60	320	Stringer foot edge	2	2	1	2	3	3	4	3
75	320	Stringer foot edge	2	2	3	3	3	3	3	3
10	2.54	Stringer foot edge	0	0	0	0	0	0	0	0
10	2.54	Skin	2	1	2	2	0	0	0	0
20	2.54	Stringer foot edge	3	0	2	2	0	2	3	0
30	2.54	Skin	2	2	2	2	0	0	0	0
40	2.54	Stringer foot edge	3	2	2	3	3	2	2	2
60	2.54	Stringer foot edge	3	3	3	2	3	2	4	2
75	2.54	Stringer foot	3	3	3	3	3	3	4	3

Table 6: Categories of damage and delamination sizes according to Figure 20 and Table 7, Table 8 and Table 9.

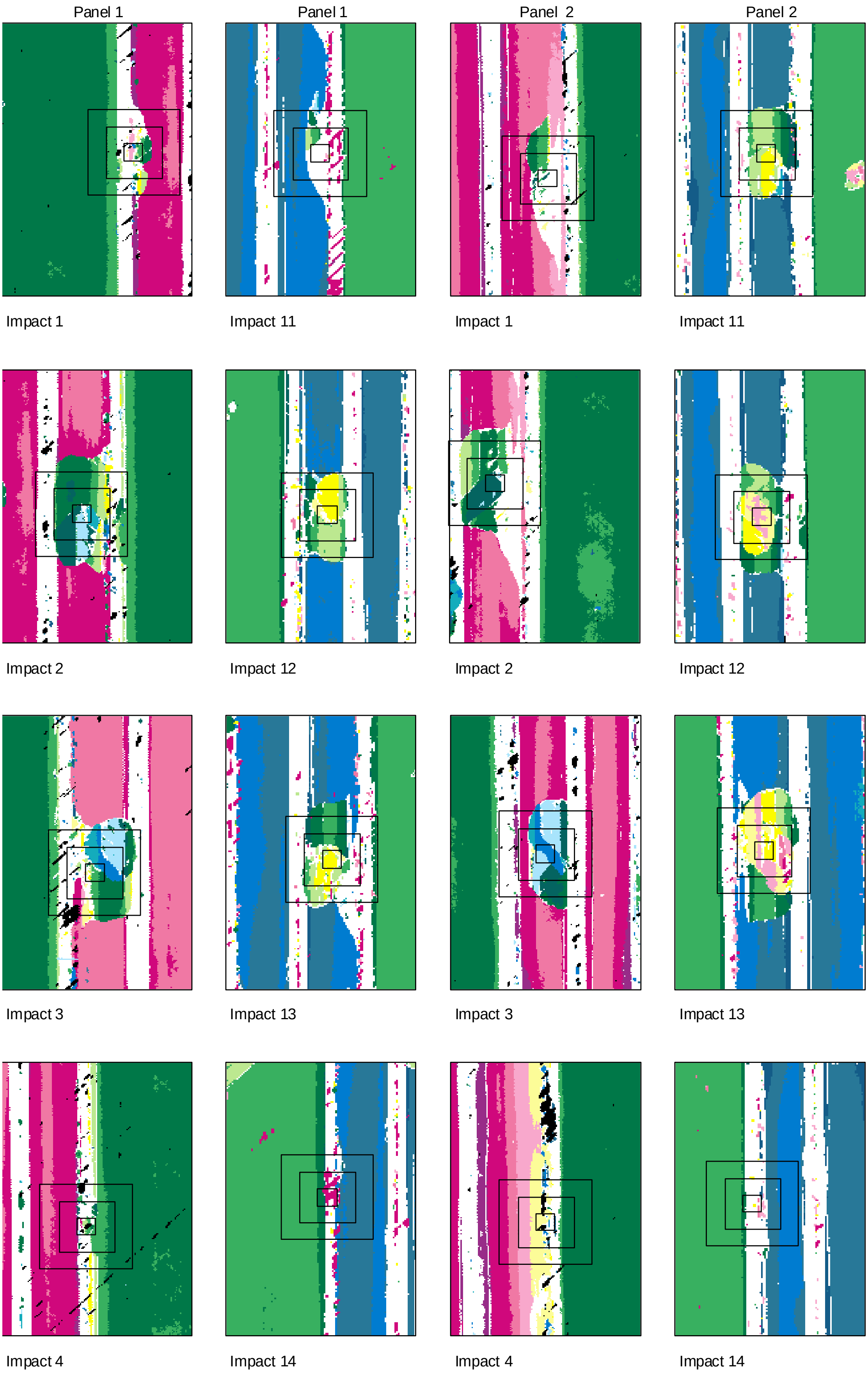


Table 7: Individual damages with superimposed damage category grid (Figure 20)

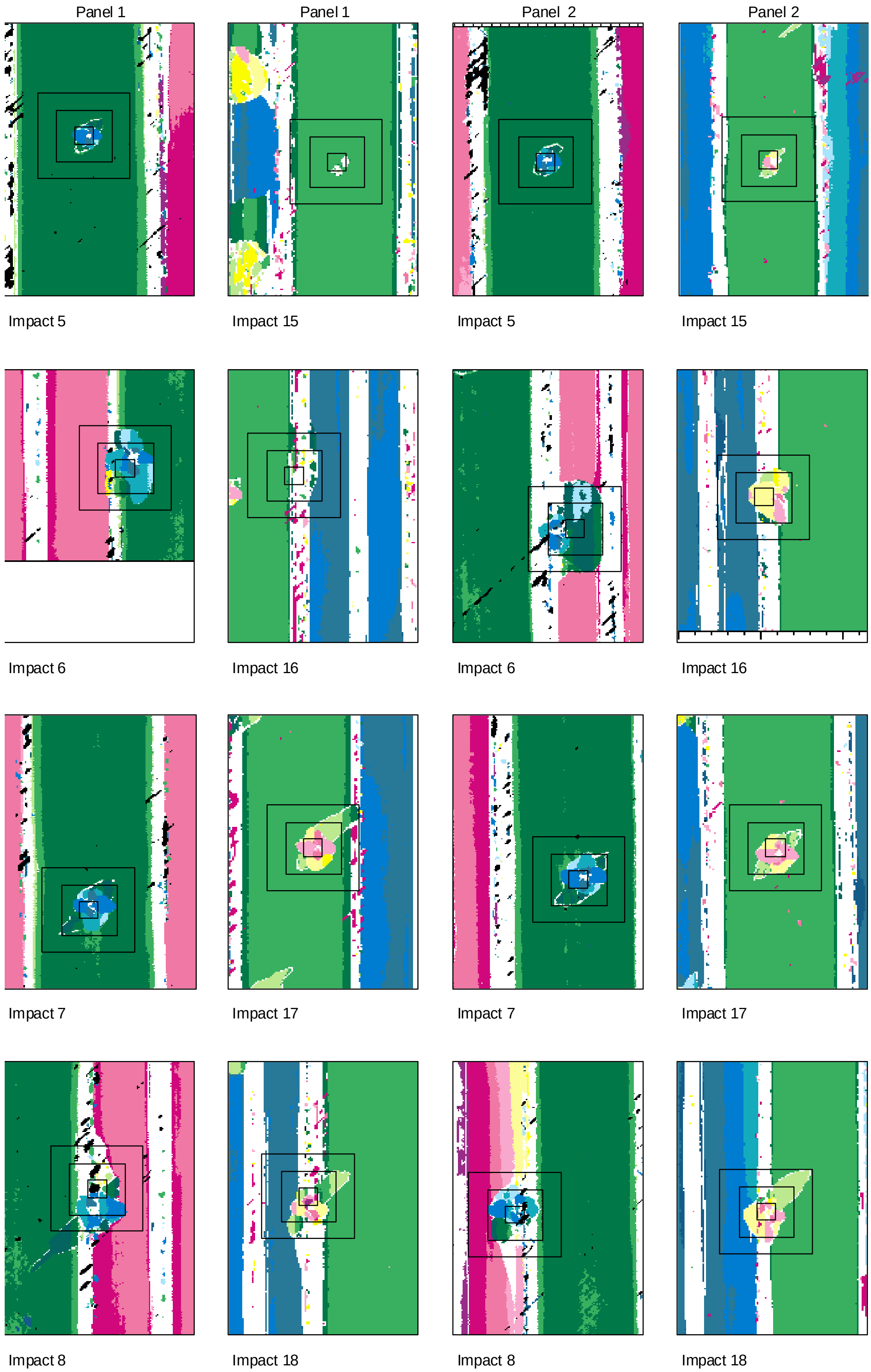


Table 8: Individual damages with superimposed damage category grid (Figure 20)

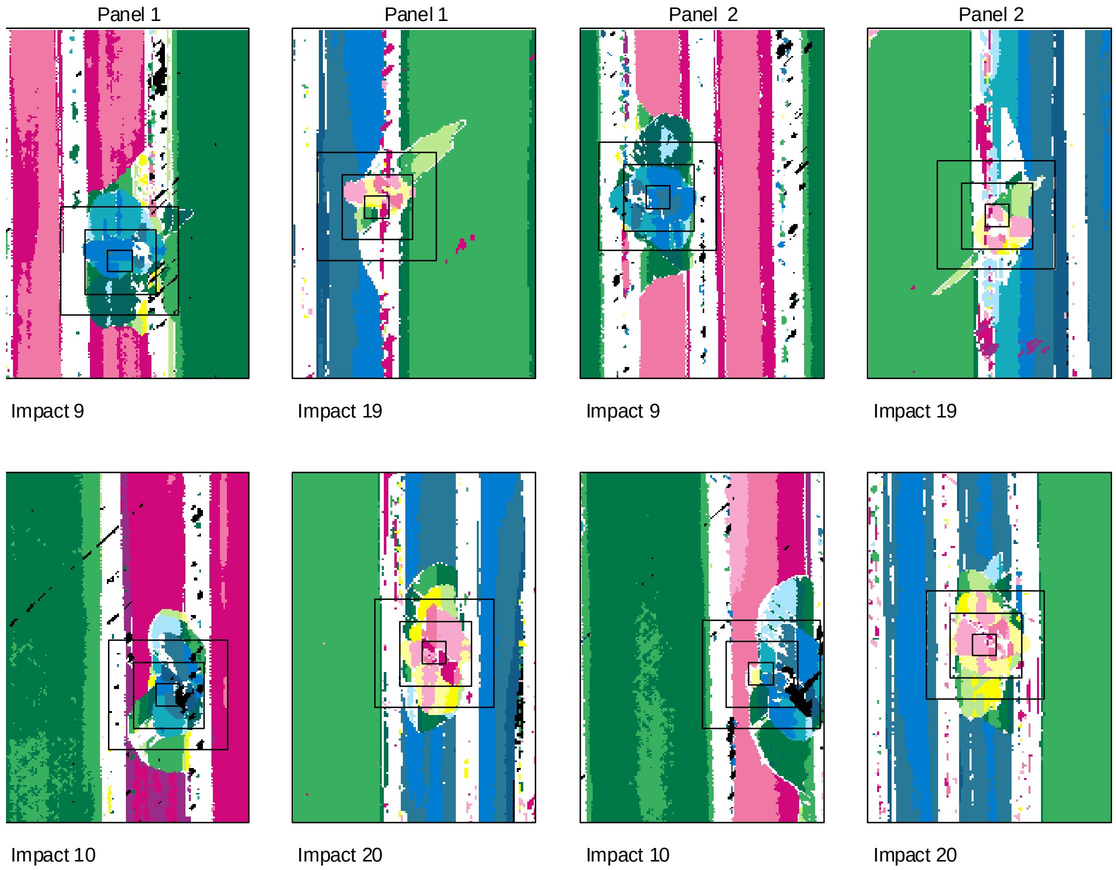


Table 9: Individual damages with superimposed damage category grid (Figure 20)

5.2.3 Visible impact damage

In order to relate internal damages to their visual appearance, the following ten figures show photographs of the damages in panel 1 along with the US-scan of the impact location. It was not easy to produce realistic images of the visual appearance of the damage, because the 3D effect of the dents is best viewed by slightly changing the visual angle while looking at the damage location.

The flat dents caused by the blunt impactor are visible in the reflection of a linear light source such as the fluorescent tubes (Figure 21, Figure 22, Figure 23). In order to increase the visibility of the dents in the photographs, a linear contrast pattern has been used in Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29. It was printed onto a white sheet of paper with a laser printer and glued onto cardboard. This method works well for photographing the more pronounced dents caused by the 1-inch impactor. For best results the spacing of the contrast grid should be somewhat smaller than the in-plane dimension of the dent.

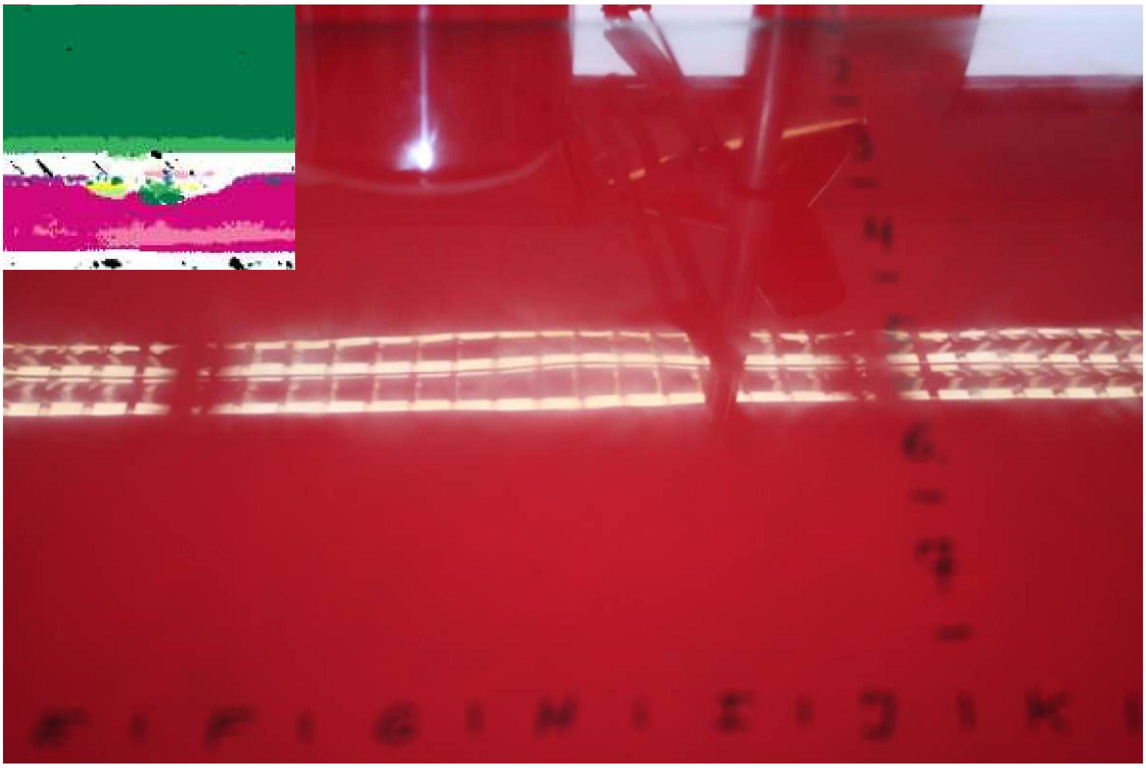


Figure 21: Panel 1, impact No. 1, at H5.

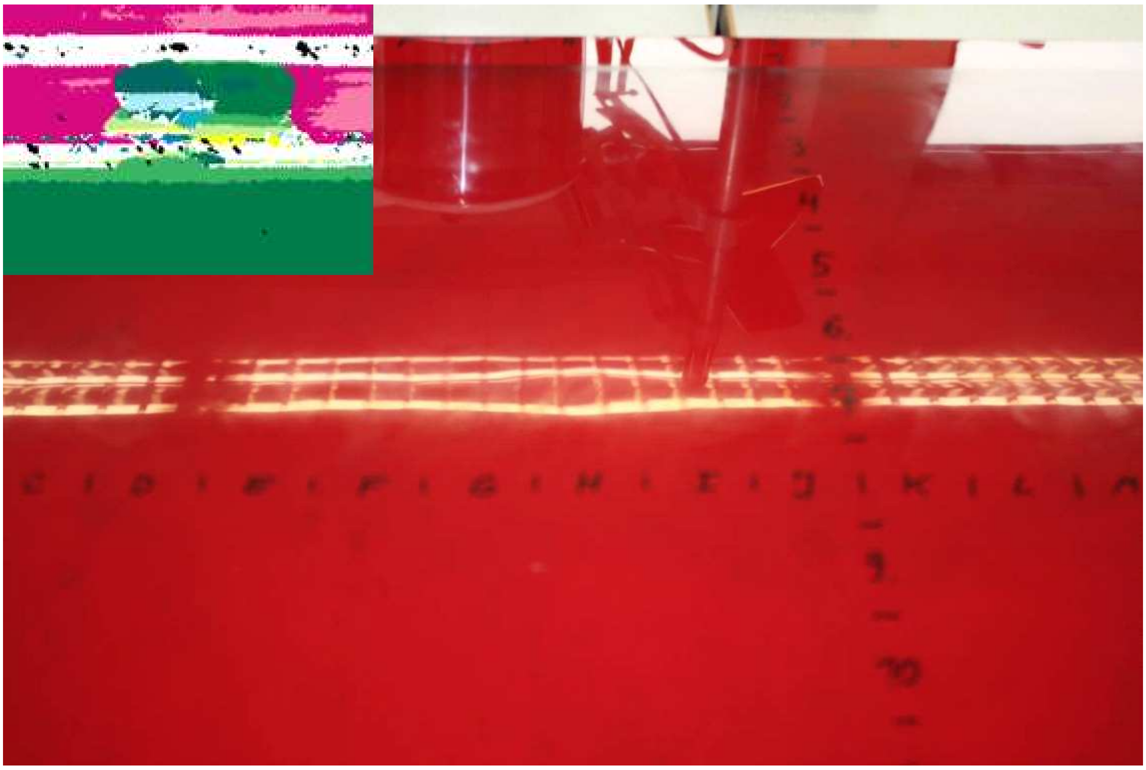


Figure 22: Panel 1, impact No. 2, at H7.

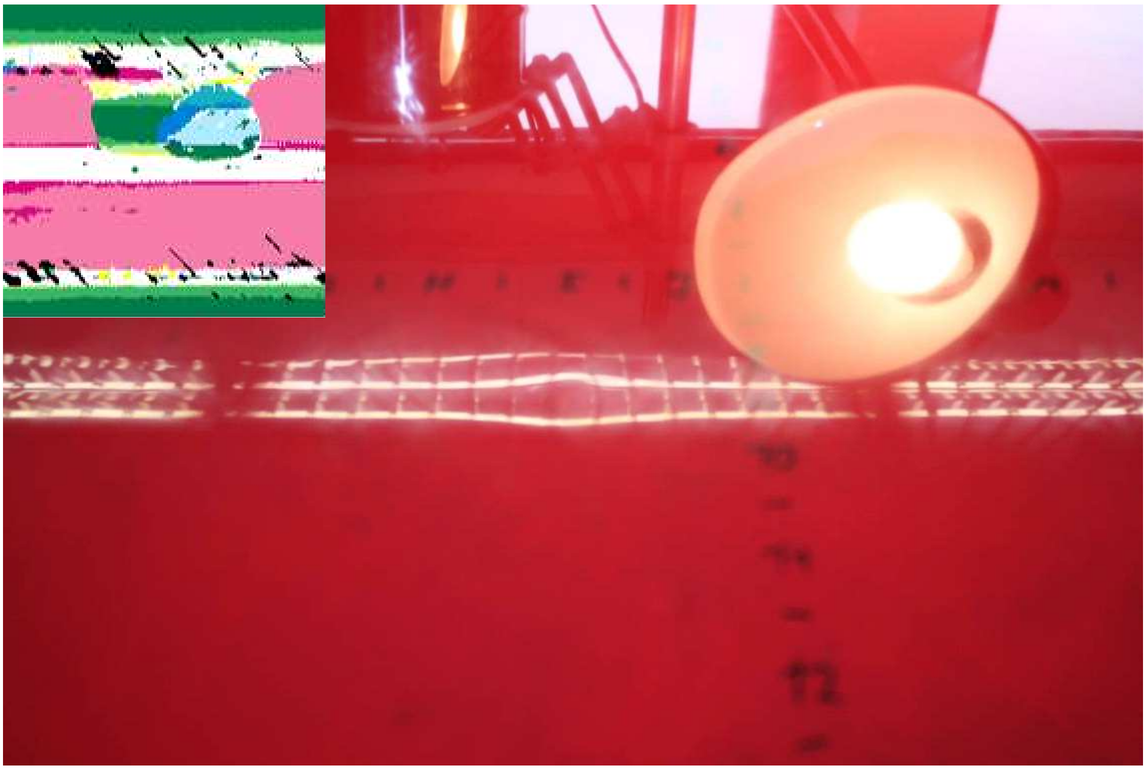


Figure 23: Panel 1, impact No. 3, at i9

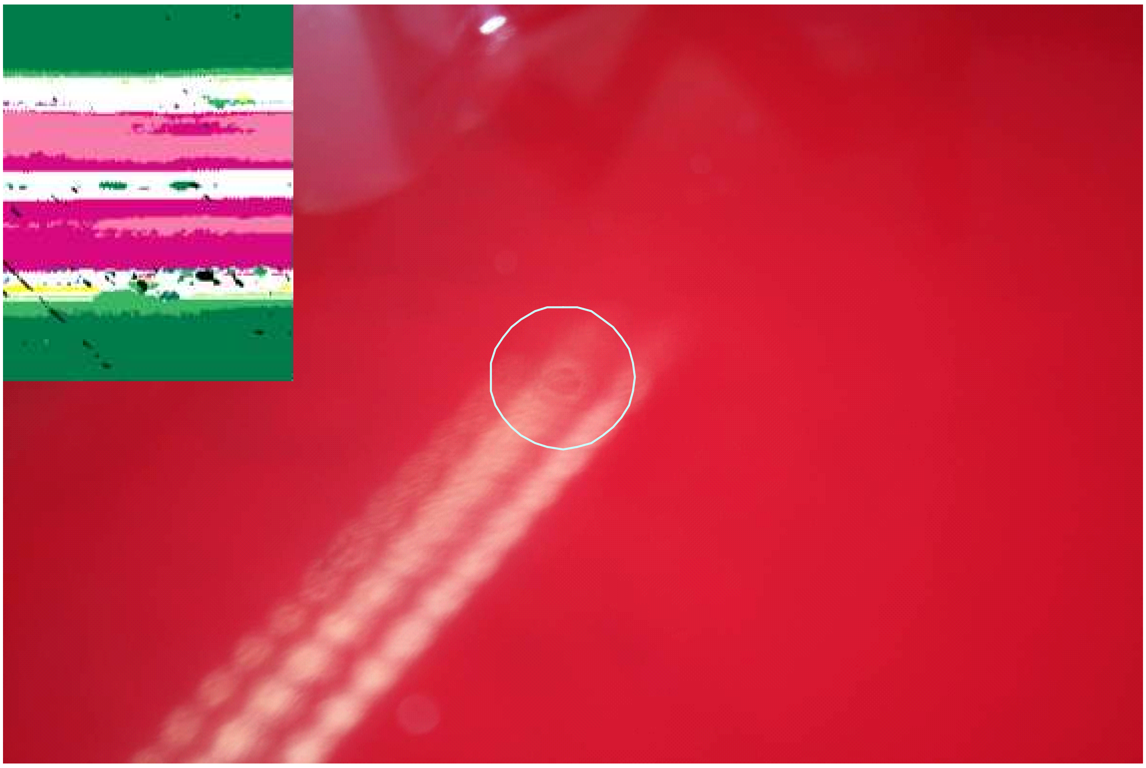


Figure 24: Panel 1, Impact No. 4. This impact did not cause internal damage in panel 2, but left a visible marking on the painted surface of both panels. The marking on panel 1 is located in the center of the circle above. The markings survived the application and removal of dirt.

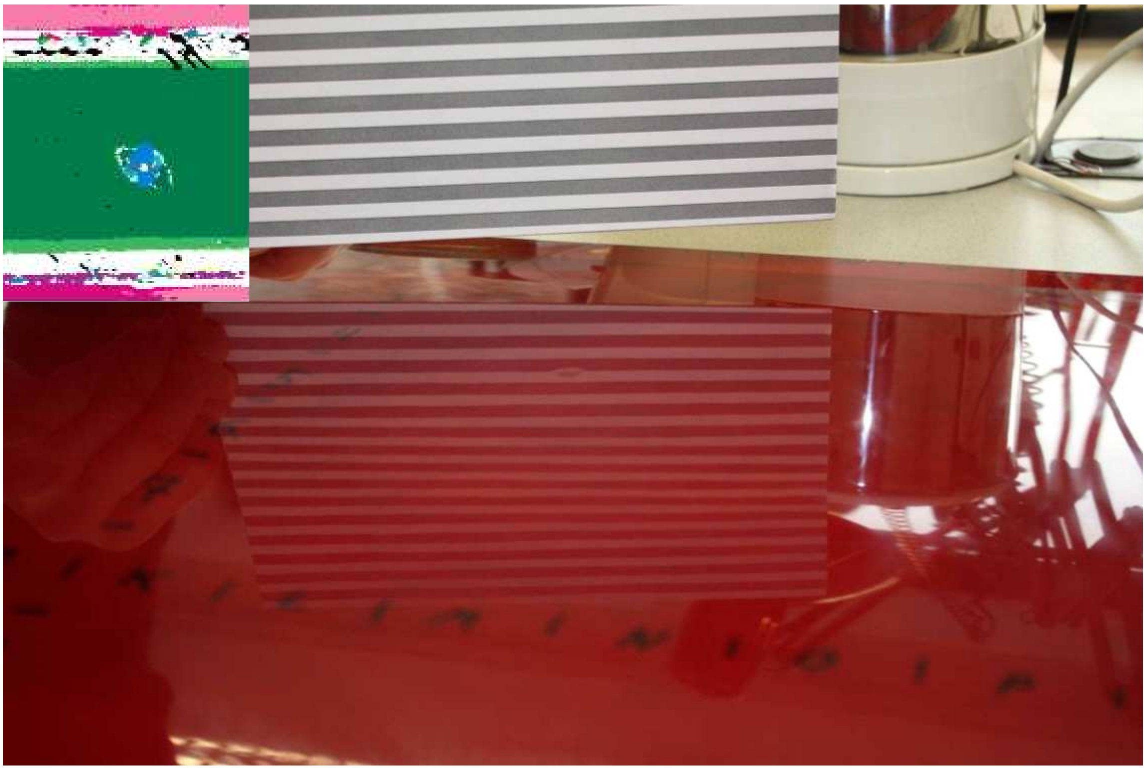


Figure 25: Panel 1, Impact No. 5

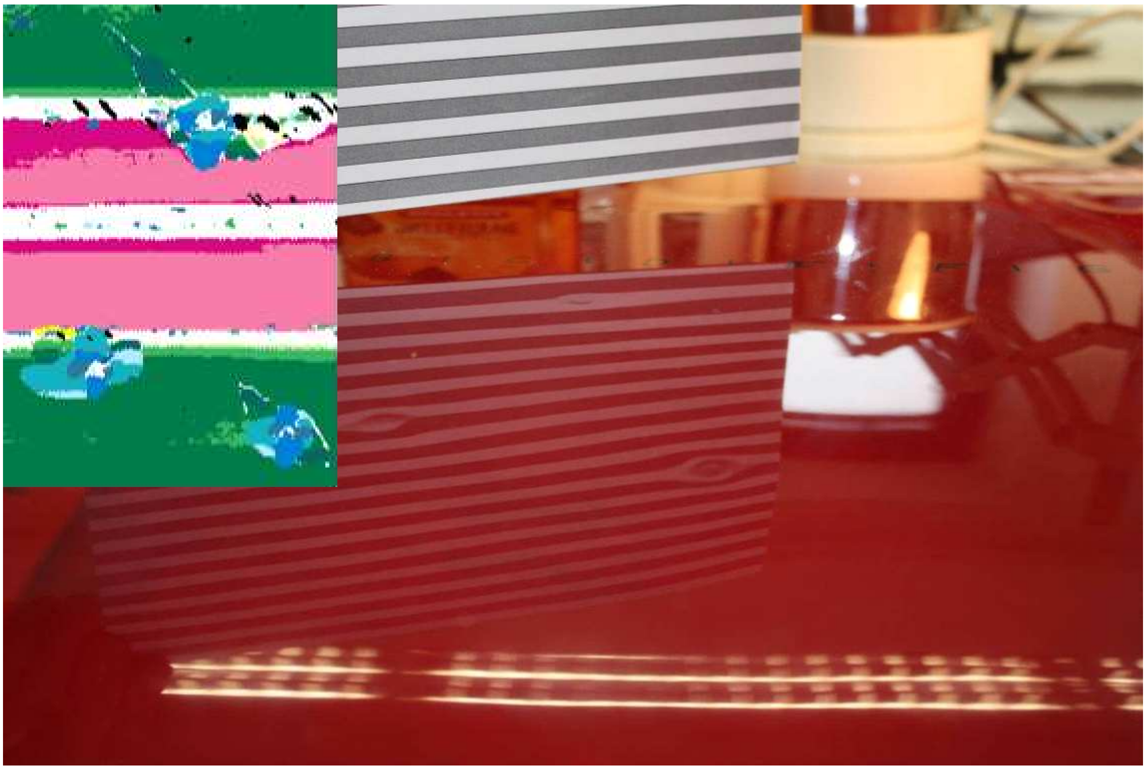


Figure 26: Panel 1, Impact No 6, 7 and 8.

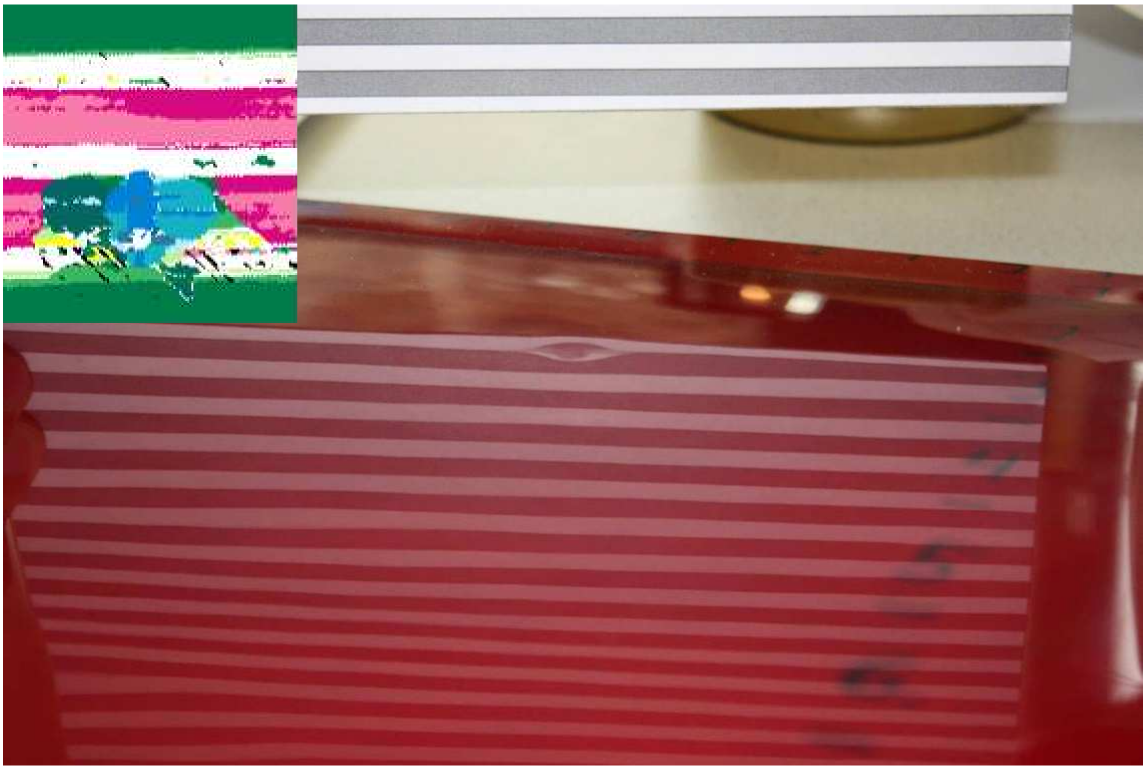


Figure 27: Panel 1, Impact No. 9

Figure 28: Panel 1, impact No. 10.

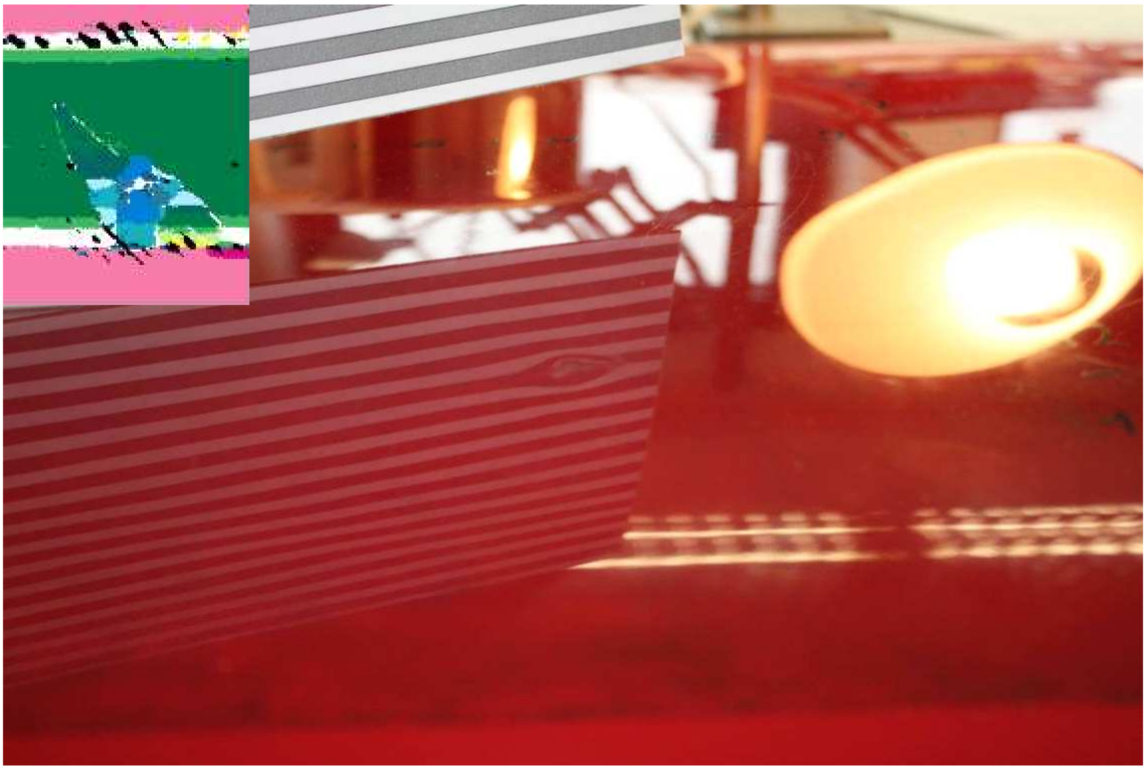


Figure 29: Panel 1, Impact No. 11.

5.3 Introduction of impacts – part 2

Further impacts were introduced after application of new paint (Air Berlin red / matt for panel 1 and BA-blue for panel 2. The impacts listed in Table 5 were once again applied at new locations. The supports were moved to the other side of the panels, to gain more room for the additional impacts (Figure 30).

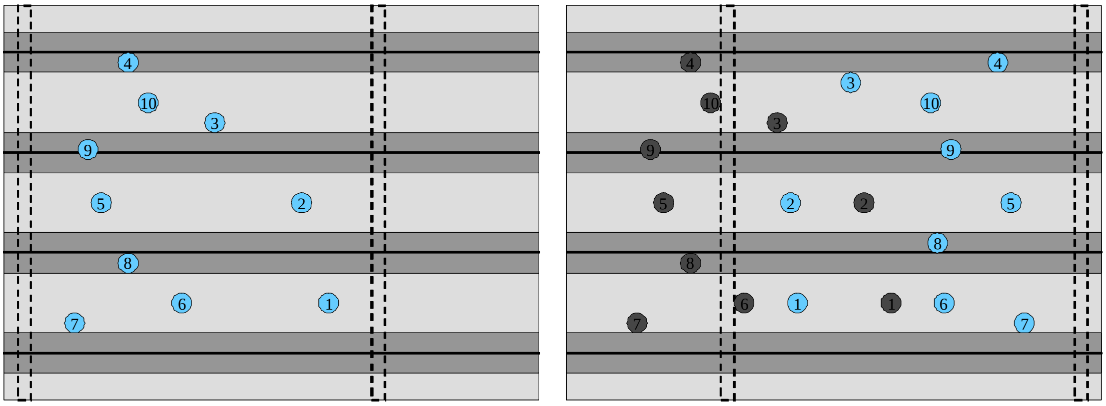


Figure 30: New impacts (light blue colour on right hand side picture) were introduced after revarnishment of the panels in between the old impacts (light blue colour on left hand side and dark grey colour on right hand side).

Figure 31 and Figure 32 show photographs of the panels with marked impact locations after introduction of impacts 11 to 20. The different appearance of damages on the matt surface finish is readily apparent when comparing Figure 32 to Figure 21 – Figure 29.

Figure 31: Impact locations 11-20 on panel 1 after impacting. The size of the markings on the panel does not correspond to size of internal damage.

Figure 32: Impact locations 11-20 on panel 2 after impacting. The size of the markings on the panel does not correspond to size of internal damage.

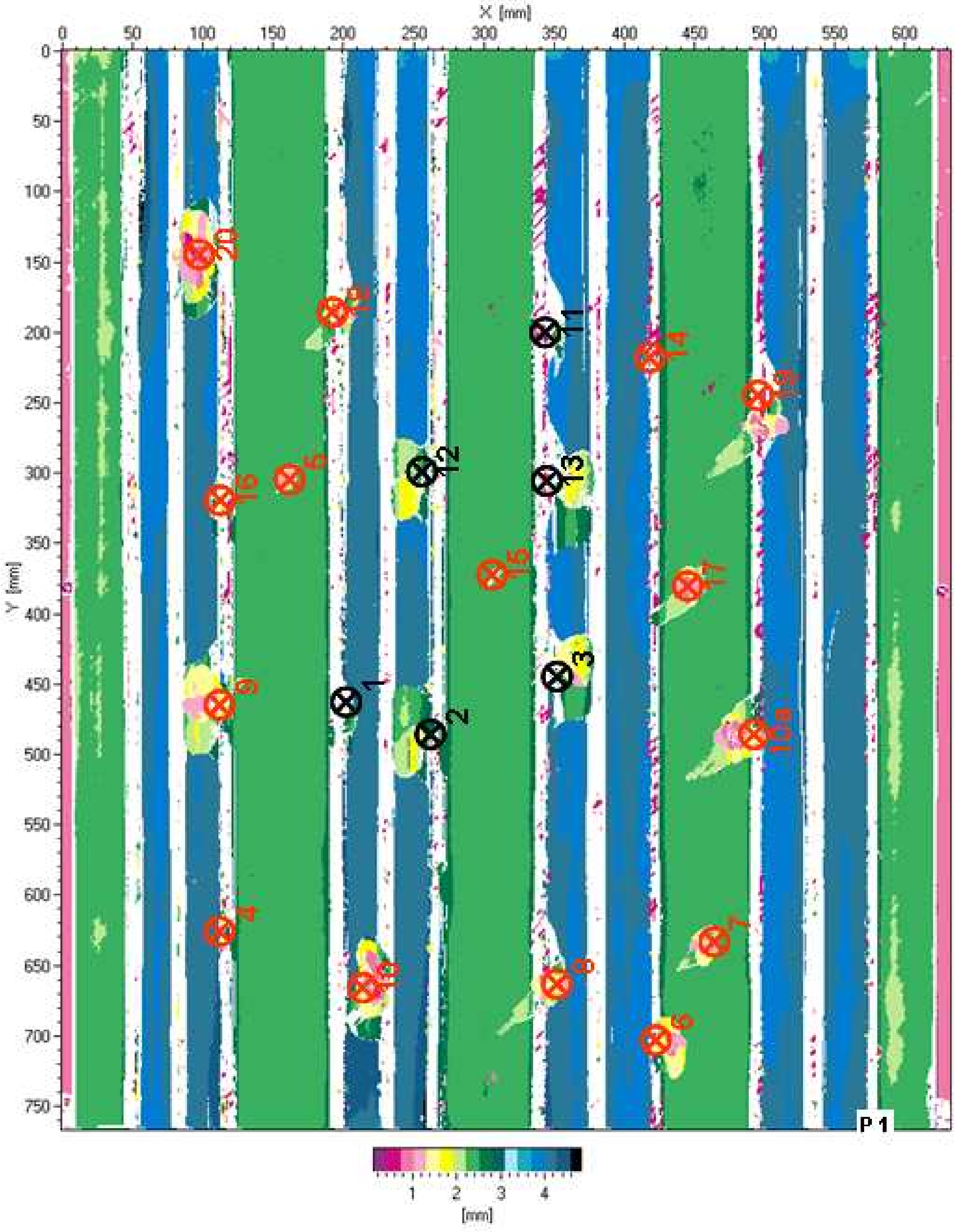


Figure 33: US-scan of panel 1 after 21 impacts.

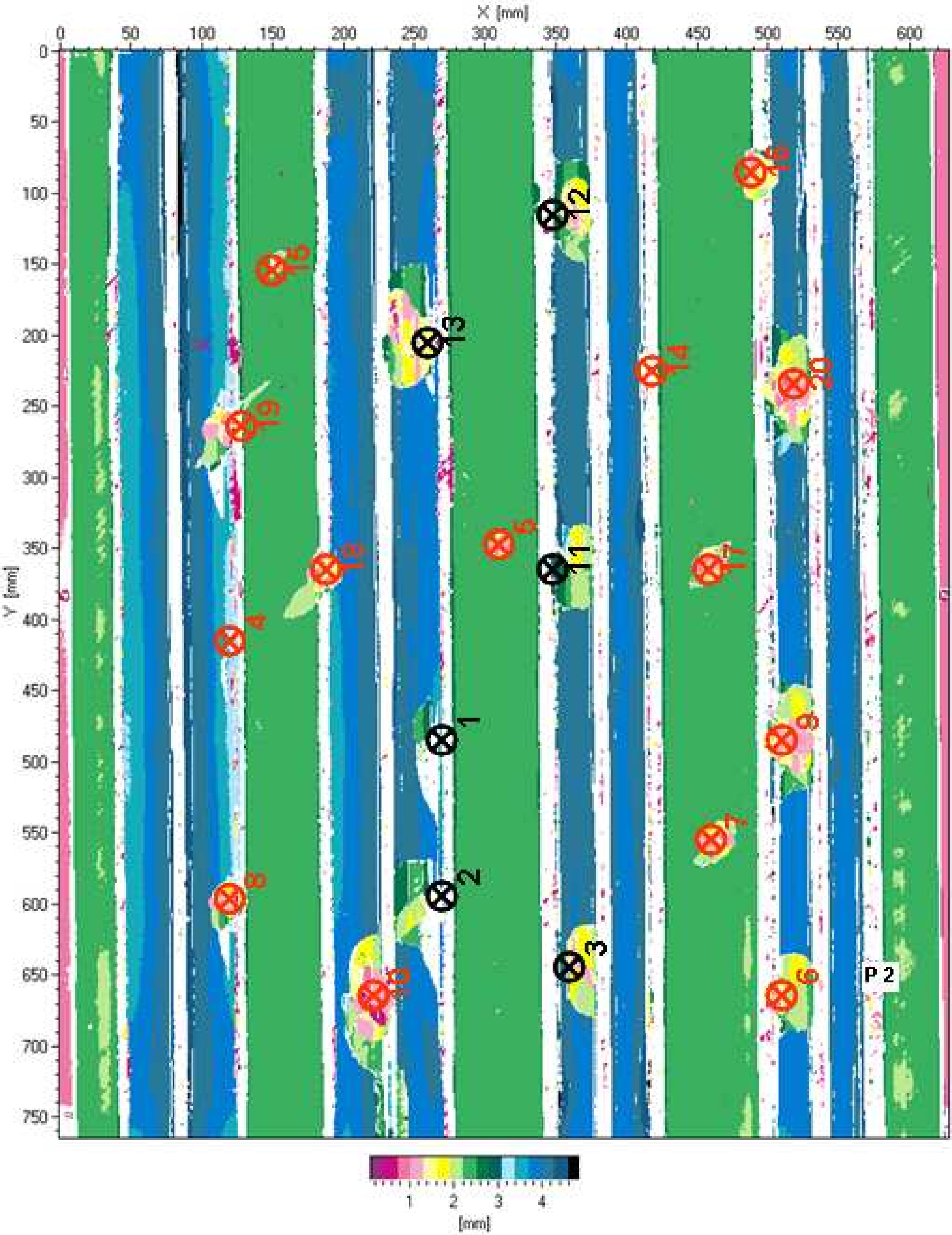


Figure 34: US-scan of panel 2 after 20 impacts.

Impact No	Energy	Impactor diameter	Impact location
	Joule	mm	
1, 11	40	320	Stringer foot edge
2, 12	60	320	Stringer foot edge
3, 13	75	320	Stringer foot edge
4, 14	10	2.54	Stringer foot edge
5, 15	10	2.54	Skin
6, 16	20	2.54	Stringer foot edge
7, 17	30	2.54	Skin
8, 18	40	2.54	Stringer foot edge
9, 19	60	2.54	Stringer foot edge
10, 20	75	2.54	Stringer foot

Table 10: Impact parameters for the 20 impacts.

5.4 Dent depth measurements

The dent depths of the first 10 impacts have been measured after the first series of inspections had been carried out, shortly before repainting both panels. The measurements are listed in Table 11. The first 3 / 4 impact locations could not be made out by the test personnel, so there are no measurements available for these impacts. The rest of the measurements was not free from imprecision, since the undamaged panel surfaces were not perfectly plane in the direction of the cylinder axis. Imperfections in the order of 10^{-2} up to 10^{-1} mm distorted the measured values in Table 11 and Table 12.

Figure 35: Set-up of dent depth measurements.

The setup of the dent depth measurement is shown in Figure 36.

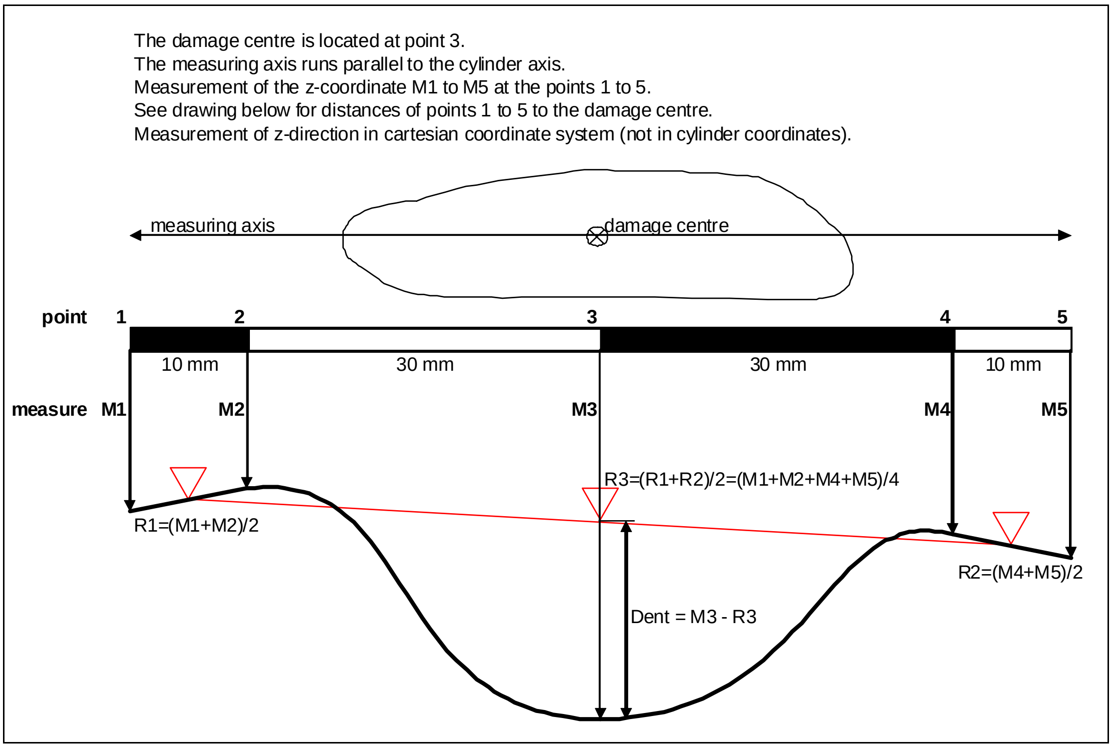


Figure 36: Measurement procedure of dent depths on the curved cylinder surface.

Panel 1

	M1	M2	M3	M4	M5	Dent
1	not visible					
2	not visible					
3	not visible					
4	not visible					
5	0.000	-0.003	-0.091	-0.054	-0.060	0.06
6	0.000	-0.028	-0.189	-0.147	-0.150	0.11
7	0.000	0.002	-0.032	0.315	0.302	0.19
8	0.000	0.006	-0.098	-0.011	-0.007	0.10
9	0.000	0.012	-0.070	0.062	0.067	0.11
10	0.000	0.009	-0.103	0.109	0.112	0.16
10a	0.000	0.005	-0.125	0.059	0.064	0.16

Panel 2

	M1	M2	M3	M4	M5	Dent
1	not visible					
2	not visible					
3	not visible					
4	0.000	0.014	0.015	0.090	0.088	0.03
5	0.000	-0.001	-0.082	-0.075	-0.078	0.04
6	0.000	-0.012	-0.101	-0.042	-0.029	0.08
7	0.000	-0.001	-0.088	0.076	0.098	0.13
8	0.000	0.039	-0.380	-0.300	-0.007	0.31
9	0.000	0.007	-0.065	0.025	0.040	0.08
10	0.000	-0.023	-0.128	-0.017	-0.007	0.12

Table 11: Dent depths in [mm] after the first 10 impacts on the panels with red colour / glossy finish.

There is a difference between dent depth measurements for the impacts 5 to 10a for panel 1 and 4 to 10 for panel 2 before and after the application of the matt colours, as can be seen by comparing the respective values in Table 11 and Table 12. This difference may partly be due to locally varying thickness of the matt colour coating.

Since the second dent depth measurement was done right after introduction of impacts 11-20 before the impact location marks were erased, dent depth measurements could be carried out even for damages 11-14.

	Panel 1							Panel 2					
	M1	M2	M3	M4	M5	Dent		M1	M2	M3	M4	M5	Dent
1	not visible						1	not visible					
2	not visible						2	not visible					
3	not visible						3	not visible					
4	not visible						4	not visible					
5	0.000	0.004	-0.080	-0.081	-0.085	0.04	5	0.000	0.000	-0.073	-0.080	-0.093	0.03
6	0.000	0.006	-0.178	-0.177	-0.178	0.09	6	0.000	-0.004	-0.085	-0.048	-0.032	0.06
7	0.000	-0.004	0.028	0.293	0.290	0.12	7	0.000	0.011	-0.027	0.070	0.091	0.07
8	0.000	-0.016	-0.084	-0.031	-0.015	0.07	8	0.000	0.038	0.041	0.021	0.028	-0.02
9	0.000	-0.008	-0.082	0.026	0.031	0.09	9	0.000	0.014	-0.085	0.006	0.022	0.10
10	0.000	0.001	-0.114	0.006	0.020	0.12	10	0.000	-0.024	-0.207	-0.003	0.019	0.21
10a	0.000	-0.001	-0.102	0.033	0.044	0.12							
11	0.000	-0.004	0.003	0.011	0.019	0.00	11	0.000	-0.006	-0.013	-0.030	-0.038	-0.01
12	0.000	-0.007	-0.021	0.000	-0.001	0.02	12	0.000	-0.010	-0.029	0.009	0.028	0.04
13	0.000	-0.010	-0.060	-0.070	-0.071	0.02	13	0.000	-0.006	-0.030	0.017	0.034	0.04
14	0.000	-0.016	-0.061	0.091	-0.121	0.05	14	0.000	-0.008	-0.068	-0.065	-0.073	0.03
15	0.000	-0.002	-0.037	-0.019	-0.016	0.03	15	0.000	-0.024	-0.124	-0.015	0.011	0.12
16	0.000	0.000	-0.036	-0.063	-0.078	0.00	16	0.000	0.016	-0.005	0.121	0.122	0.07
17	0.000	-0.015	-0.147	-0.093	-0.048	0.11	17	0.000	-0.009	-0.135	-0.073	-0.082	0.09
18	0.000	-0.001	-0.053	0.034	0.036	0.07	18	0.000	0.014	-0.074	0.042	0.037	0.10
19	0.000	-0.008	-0.047	-0.009	0.003	0.04	19	0.000	-0.004	-0.148	-0.035	-0.021	0.13
20	0.000	-0.013	-0.201	0.000	0.018	0.20	20	0.000	-0.022	-0.234	-0.121	-0.101	0.17

Table 12: Dent depths in [mm] after impacts 11 – 20 on the panels with blue / red colour / matt finish.

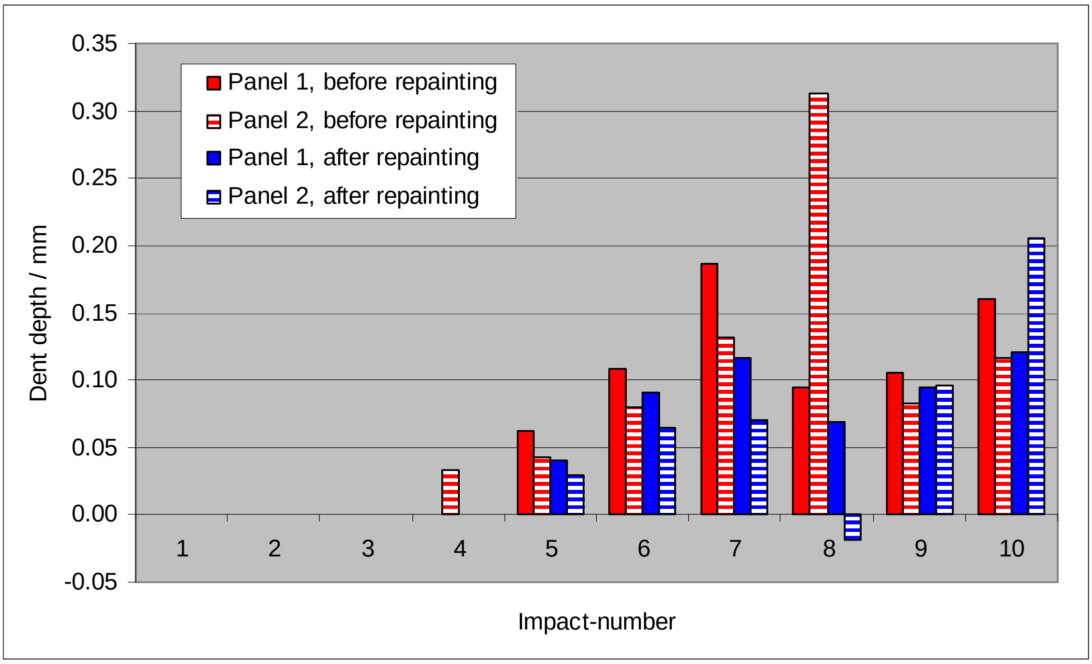


Figure 37: Influence of the repainting process on dent depths of impacts 1-10. The same dents were evaluated before and after the repainting process. Impacts 1-4 on panel 1 and impacts 1-3 on panel 2 were not visible for the laboratory personnel, so no measurement is available for these.

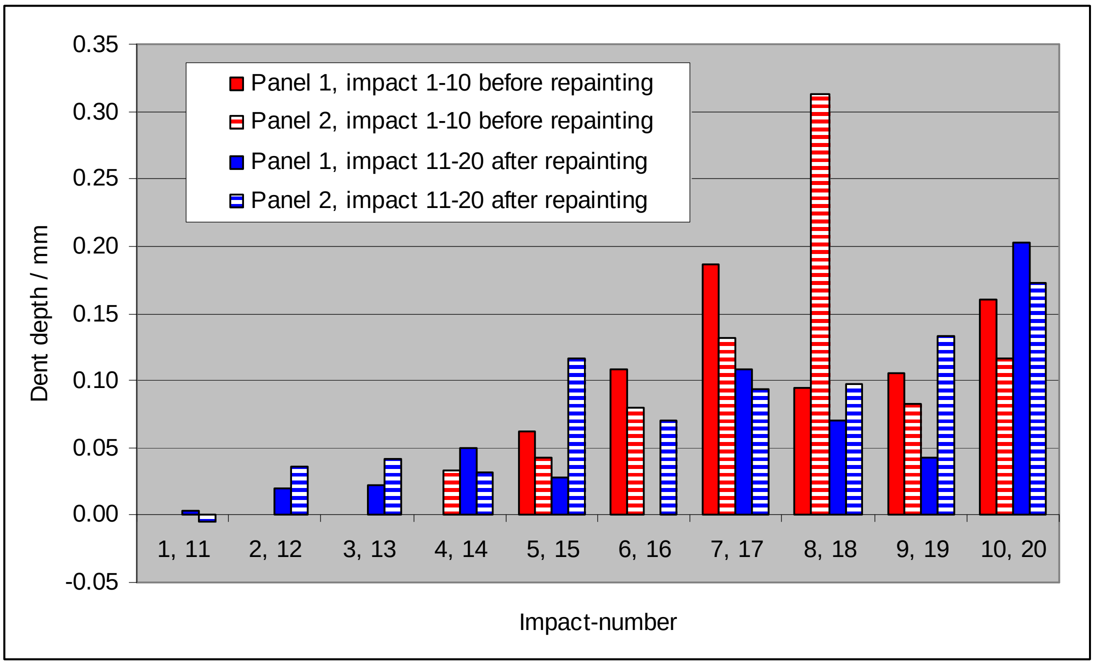


Figure 38: Influence of the repainting process on creation of dents. Comparison of dent depths of newly introduced impacts after repainting (impact No. 11-20) to dent depths of impacts No. 1-10 on the first panel coating.

The correlation between damage size and depth of the permanent indentation is displayed in Figure 39. Damages caused by the 320 mm impactor correspond to a significantly smaller dent depth than equally sized damages caused by a 1-inch impactor. A clear correlation between damage size and indentation depth has not been found. For example, a damage size of 2 corresponds to indentation depths between 0.00 and 0.18 mm. The largest indentation depth of 0.32 mm corresponds to a medium size damage of 4, while the largest damages only caused dents of around 0.10 mm depth.

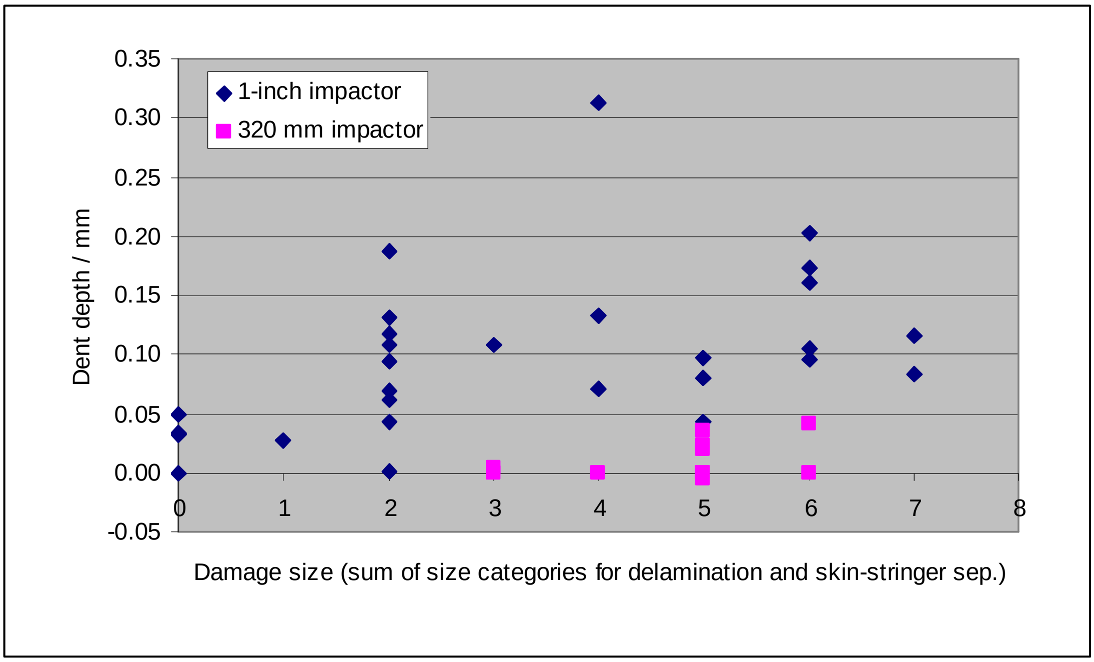


Figure 39: Damage size vs. depth of the permanent indentation. The damage size was determined by US-scanning, see Table 6.

Since the length and width of the dents has not been measured, the aspect ratio (length / depth) of the dents could not be calculated from the available data. It has been tried to measure at least the length of the dent along the cylinder axis, but such a measurement was not possible with an acceptable precision, because of the unevenness of the panels in their undamaged state.

5.5 Application of dirt

5.5.1 Oil film with soot

For large parts of the outer aeroplane surface a combination of soot and oil makes up a dirt film that influences the detectability of damages. In order to apply such a film of dirt to the surface, a few trials were made with painted aluminium specimens. Requirements for the dirt film are

- Relevance of the type of dirt with respect to aeroplane structure
- Reproducibility of type and amount of dirt applied
- Dirt film must reliably stick to the surface over a few weeks time
- Application of dirt must not take too long (not more than a few hours up to 1 day), since the time frame for the project is very tight.

If it were not for the 4th requirement in the above list, a good way to apply typical airplane dirt would have been to place the structures on the DLR airfield, where they would be exposed to typical environment for aeroplane structures, in order to accumulate a dirt film over time.

Because of the tight time frame, a few trials were conducted on painted aluminium specimens to speed up the process.

Figure 40: Trials for dirt application using acetylene soot for specimen 1 to 3, candle soot for specimen 4 and paraffin oil soot for specimens 5 and 6.

After application of different types of soot (acetylene flame, candle, paraffin oil) all specimens were completely covered with soot, like specimen 1 in (Figure 40) or even darker. Specimens 4 to 6 were sprayed with multifunction oil WD40 and wiped with a cotton cloth to adjust the amount of soot. It turned out, that the dirt film of paraffin soot / WD40 looks very much like a dirty aeroplane surface. The thickness of the dirt film is adjustable by the amount of wiping with a cotton cloth. The soot from acetylene does not stick to the specimen very well. It can be blown off the specimen by compressed air. This was tried out with specimen 3. After the application of oil and wiping with a cotton cloth the soot from paraffin oil stuck well to specimens 4 to 6.

Based on the trials it was decided to use the paraffin oil / WD40 / wiping method. Before covering the whole panel with soot of a flame it was confirmed that the heat of the flame did not have an effect on the colour of the panel.

A quantitative measurement of dirtiness is difficult to do. In the frame of this project it is considered sufficient to document the level of dirtiness by comparing photographs of the clean panel with the dirty panels, which are made under constant lighting conditions and with the same camera (Fuji FinePix F455).

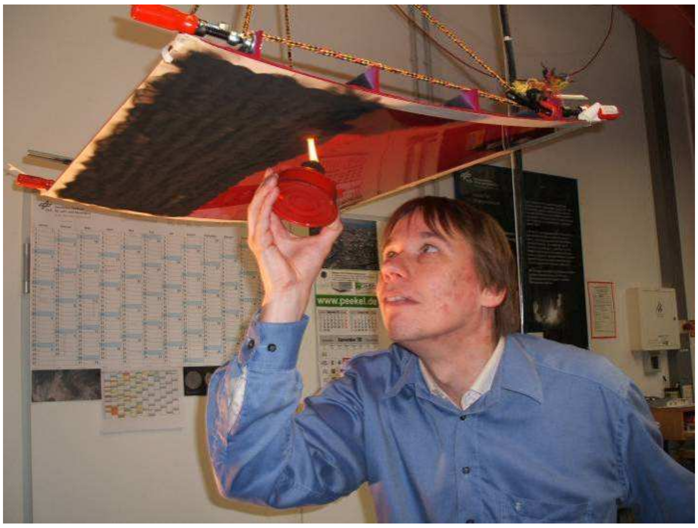


Figure 41: Application of paraffin oil soot on panel 1 with red glossy coating. The paraffin flame had no effect on the glossy coating.

Figure 42: Panel 1 completely covered with soot from paraffin oil.

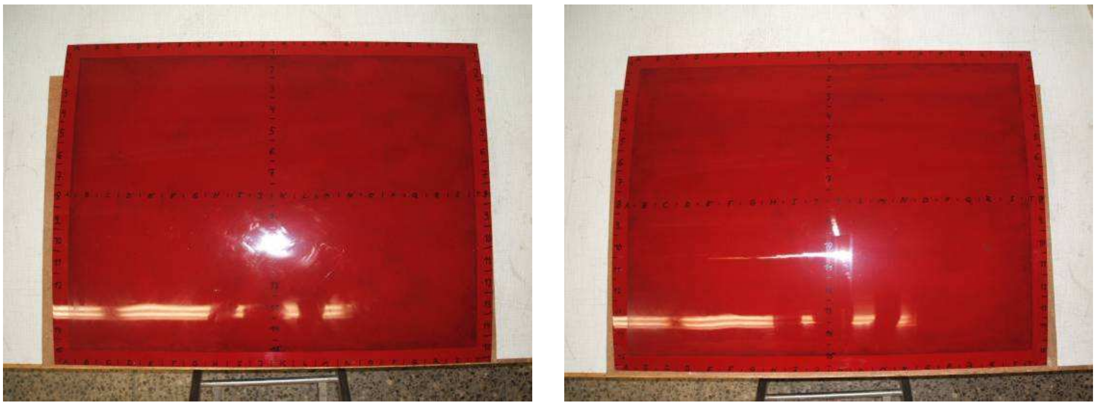


Figure 43: Panel 1 (left hand side) and panel 2 (right hand side) after application of soot, multifunction oil and wiping with cotton cloth. In the area around the border of the panels no dirt was applied, so these areas show the original colour of the panels.

5.5.2 Dust particles

Surfaces of aircraft exposed to the weather and the environment of airports typically accumulate a layer of dust particles, which, in the absence of oil, turns glossy surfaces to a matt appearance. This dust film also influences the colour appearance, depending on the colour of the dust particles.

The problems with application of such a layer of dust particles are to obtain a sufficient amount of such particles and to make the particles reliably stick to the panel. There seems to be no research regarding colour, particle size and composition of typical airplane dust or dust found on motor-car surfaces. The problems were solved by applying coffee particles. Coffee particles may be of slightly different colour than the standard dust particles found on aircraft, but there was no oil necessary to make the particles stick to the panels and the glossy surfaces received a matt appearance (Figure 44).

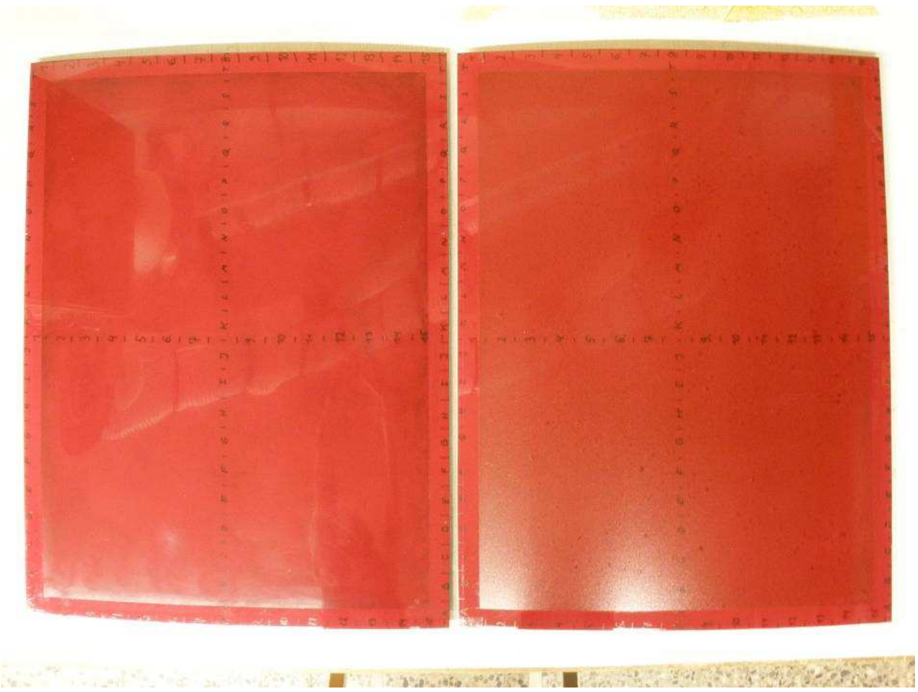


Figure 44: Comparison of gloss appearance for oil film / soot dirt (left hand side) and coffee stains/right hand side).

Filter coffee was brewed with a coffee machine using standard paper filters to filter out coarser particles. The coffee was then sprayed onto the panels. Warm air heated up the panels in order to accelerate the evaporation of the water, leaving a film of coffee particles behind. The process of spraying coffee and subsequently drying the panels with warm air was repeated over the course of about an hour per panel for a moderate dirtiness level and 90 – 120 minutes for “worst case dirtiness”. The result was a rather dark, matt dirt film on the panels.

Figure 45: Figure 1coffee stain on the blue / red matt panel surfaces.

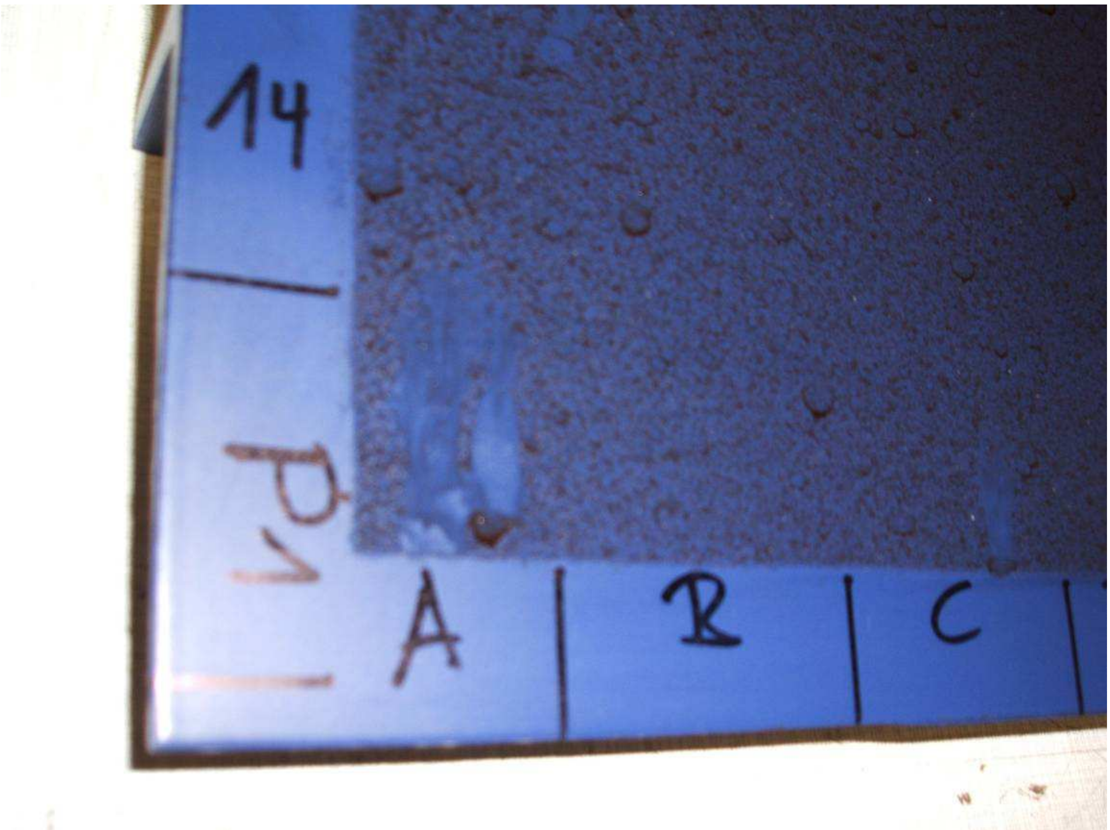


Figure 46: Close-up of coffee stains on panel 1.

5.6 Inspections

The visual inspection will be carried out under three different conditions for all parameters to be investigated: average, poor and very poor. The definition of these conditions was to be derived from the literature survey and from answers to questionnaires, which were sent out to aircraft operators participating in the study.

5.6.1 Choice of average / poor / very poor inspection conditions

Choice of colour-finish combinations

Regarding the choice of colour-finish combinations for the inspection study the literature survey did not yield clear information of the effect of colour- and finish combinations on the detectability of damage.

Contact was made to Cranfield University. The research at Cranfield University in this area has not been publicly available at the time of manufacturing the panels.

At the 2006 Composite Damage Tolerance and Maintenance Workshop in Chicago Waite [5] stated some research needs. An important aspect is the influence of colour / finish on damage detection. For example new gloss dark blue from British Airways lead to many visual indications, whereas old matt blue gave fewer visual indications. On the other hand there is contrary evidence regarding damage detectability on matt white and glossy white surfaces. Furthermore there is some (surprising) evidence that it is easier to find damage on green surface than white surface [5].

The obvious assumption is that a darker surface will reflect less light than a light-coloured surface and that therefore a dark surface is more difficult to visually inspect for damages than a bright surface. As long as an impact does not leave lightly coloured marks behind, the available range of contrast for surface irregularities due to damage is much smaller for dark surfaces than for brightly coloured surfaces. Also, the underlying material below the surface colouring is of dark colour (black CFRP) – any scratches penetrating the surface coating would therefore appear dark, rather than light-coloured.

The same reasoning applies to the matt versus glossy finish issue. A glossy finish allows more light to be reflected than a matt surface, therefore damage on a surface with glossy finish is expected to be better detectable than a matt surface, provided that there is no excessive lighting producing glare on the surface to be inspected.

Obviously the lighting issue is not independent from the colour / finish issue.

- The colour of the light source influences the colour appearance of the structure
- The amount of lighting influences the perceived contrast between surface irregularities and the surface and also the perceived glare.
- The ratio between ambient and directed lighting can influence the amount of glare as well.

An important consideration was the survey of airline colours. Six airlines responded to the requests for the colours they use in their liveries. It is apparent, that light shades of grey are very popular. Also red is used by a great number of airlines. There is some orange and blue, green is used only by Alitalia. According to Lufthansa Technik, the majority (roughly 90%) of airline structures use a glossy finish.

Summarizing the considerations with respect to the choice of colour / finish combinations:

- Concerning lighting influence the problem of having not enough lighting is considered more of a problem for inspection than the issue of too much lighting. Therefore adverse effects of too much lighting, such as glare, are not investigated in this study.
- Light grey and red are very frequently used airline colours. Orange, blue are used frequently, green, black and other colours are used rarely, if at all.

Based on the above limitations the following three colour / finish combinations will be investigated.

- Average conditions with respect to damage detectability: Air Berlin red with glossy finish.
- Poor conditions: Air Berlin red with matt finish.
- Very poor conditions: British Airways blue (colour code: BAC 51116) with matt finish.

The presumed worst case combination of some relevance (British Airways blue / matt) is considered. The other colour "Air Berlin red" is of relevance as well. Green, white and light grey presumably facilitate damage detection, so these colours should not be used. Yellow, orange and blue are other candidates, but red seems to be used more frequently. Air Berlin uses a rather dark shade of red. With the above colour / finish combinations the glossy / matt issue can be investigated for one particular colour. Also one data point for the colour issue (dark red / dark blue) at matt finish can be obtained.

Figure 47: Air Berlin livery

Later in the project the professional inspectors participating in the study were asked to rate the influence of surface colour, finish and the influence of colour / finish combinations on the detectability of damage based on their personal experience.

For the isolated influences of colour and finish the answers were quite consistent: 11 inspectors preferred light surfaces and 12 inspectors preferred glossy surfaces for damage detection, over 4 persons, who said that dark surfaces are easier to inspect and 2 inspectors finding matt surfaces easier to inspect than glossy surfaces.

A second question concerned the influence of colour / finish combinations improving or inhibiting damage detection. Here the answers were not quite as consistent. The number of answers favouring the four possible combinations of light / dark colour and glossy / matt finish are displayed in Table 13. Only the light/matt combination did not receive any votes, while the seven answers to this question are evenly distributed among the other three choices.

	light	dark
glossy	3	2
matt	0	2

Table 13: Number of inspectors favouring the four possible combinations of light / dark colour and glossy / matt finish for damage detection.

Lighting conditions

According to Lufthansa Technik inspection personnel the 350 lux (as measured indoor during the inspection at Lufthansa Technik) are average indoor lighting conditions. Walk around inspections are done during daylight, twilight and also at night with the help of a flashlight. A-check and C-checks are mostly done in the hangar under artificial lighting, while walk-around is done always outside in the airfield.

The following reasoning is the basis of choosing lighting conditions for this study.

- This study should not be done in daylight, because the amount of daylight strongly depends on season and weather. Allowing daylight would make it difficult to provide reproducible conditions for the study. In subsequent studies, however it is important to also look at the glare issue and how it influences defect detection.
- A flashlight should not be used by amateur inspectors in this study, because it is expected, that the test persons will have varying skill in using the flashlight, which should not influence the study.
- Average conditions ~350 lux, availability of directed lighting for the complete panel area at an inspection angle of 15°
- For poor and very poor inspection conditions the amount of directed light and of ambient light are both reduced.
- Inspections were held in a meeting room at the DLR site in Braunschweig, which provided for lighting conditions between 400 and 200 lux. Light-proof curtains were used to keep out daylight. Ceiling lamps are equipped with three light bulbs each. It is possible to turn on only one or two of the three light bulbs.
- Illumination is measured with a calibrated class B Luxmeter from LMT GmbH Berlin.

Figure 48: Lighting of a hangar at Lufthansa Technik on 24 Nov 2008.

Figure 49: Lighting in meeting room 101 of Building 118 at the DLR Braunschweig site. Three light bulbs in each ceiling lamp provide around 400 lux on the table surface in the foreground.

Note that the illumination in the hangar at Lufthansa Technik is composed of point source lights at the ceiling and of very large windows along two walls (see Figure 48). Inspections are conducted 24 hours a day, so at night the illumination of the hangar will be considerably less than the 350 lux, which were measured during the inspection.

Since the illumination of the DLR meeting room 101 also consists of point-source lighting from ceiling lamps the typical lighting conditions of a typical aircraft hangar are approximated reasonably well.

Inspection angle

For the 15° orientation four light sources in the ceiling are reflected by the panel towards the position of the inspector, facilitating damage detection on the glossy surface. For the 45° and 65° inspection angle, only two light sources are available for this purpose. This made damage detection more difficult.

Figure 50: Inspection angles 15° (left), 45° (middle), 65° (right hand side)

Since the inspections showed that a 45° angle caused a slightly greater reduction of the POD, the “very poor” condition is defined as an inspection angle of 45°; a 65° angle is defined as “poor” inspection condition.

Cleanliness

As described in section 5.5, average inspection conditions were created with a film of oil / soot. These conditions do not remove a glossy appearance of the surface while they may obscure some barely visible defects, which would be more clearly visible on a perfectly clean surface. Average cleanliness conditions are defined as “Level 3”-cleanliness in the tables below.

Poor conditions were covered with a thin layer of coffee stains, which partly removed the glossy appearance of the panels. Very poor conditions were created by a slightly thicker layer of coffee stains. Poor / very poor cleanliness conditions are defined as “Level 2” and “Level 1” cleanliness, respectively.

Inspectors from Lufthansa Technik suggested to investigate wet surfaces in further studies, as visual inspections sometimes are done in the rain (e.g. during daily walk-around).

Summary

	Average o	Poor -	Very Poor - -
Colour / Finish	Red / glossy	Red / matt	BA-blue / matt
Lighting	~400 lux	~300 lux	~200 lux
Insp. angle	15°	65°	45°
Cleanliness	Level 1 (oil/soot)	Level 2 (coffee stains)	Level 3 (coffee stains)

Table 14: Summary of average / poor / very poor inspection conditions

5.6.2 Experience levels of inspectors

Three experience levels of inspectors are defined as follows.

Level 1	No professional experience with composite structures and visual inspections.
Level 2	Some professional experience with composite structures or visual inspection of aircraft structures.
Level 3	Professional aircraft maintenance personnel with experience in visual inspection of composite structures.

Table 15: Experience levels of inspectors.

5.6.3 General procedure for visual inspections

1. Introduction to the project and inspection procedure (presentation): 20 min.
2. Inspections: 2 Panels, 10 min. each per person, 1.0 m distance to structure
3. Vision test: 5 min. per person

4. Questionnaire: 20 min. per person (see Appendix A)

5.7 List of inspections

Ten inspections have been carried out with a total of 112 inspectors. Conditions of inspections are listed in the table below.

Inspection	Date	Place	No. of impacts per panel	No. of inspectors lvl 1	lvl 2	lvl 3	total	angle [°] P1	P2	lighting lux P1	P2	cleanliness level 1, 2, 3 P1	P2	colour / finish lux P1	P2
1	2008-11-12	DLR FA, lab FT	10		9		9	15	15	1100	1100	3	3	red / glossy	red / glossy
2	2008-11-14	Lufthansa Technik	10			8	8	15	15	360	360	3	3	red / glossy	red / glossy
3	2008-11-24	DLR FA, room 101	10	10	3		13	45	65	422	422	3	3	red / glossy	red / glossy
4	2008-12-05	TUI fly	10	1		5	6	15	15	180	185	3	3	red / glossy	red / glossy
5	2008-12-17	DLR FA, room 101	10	5	7		12	15	15	409	426	3	3	red / glossy	red / glossy
6	2009-01-15	DLR FA, room 101	10	10	2		12	15	15	164	288	3	3	red / glossy	red / glossy
7	2009-01-26	DLR FB, hangar	10		10	8	18	15	15	420	420	2	1	red / glossy	red / glossy
8	2009-03-26	DLR FA, room 101	20	8	7		15	15	15	401	404	3	3	blue / matt	red / matt
9	2009-04-03	DLR FA, room 101	20	1	12		13	45	65	152	257	1	2	blue / matt	red / matt
10	2009-04-07	Lufthansa Technik	20			6	6	alternative damage metrics						blue / matt	red / matt

Table 16: List of visual inspections

5.8 Data processing of inspection results

The filled-out questionnaires were collected from the inspectors and given consecutive numbers. The inspection results, the answers to the questionnaire and the results of the vision test were translated from German into English and stored in a database together.

Each record in the database represents the inspection results of one inspector and contains the following fields.

1. Consecutive number of the record
2. Date of inspection
3. Personal data of inspector
    a) Age
    b) Sex
    c) Employer
    d) Profession
    e) Use of vision aids (glasses or contact lenses)
    f) Visual acuity measurement
    g) Colour vision (normal or defective)
    h) Professional experience in aircraft maintenance (number of years and level)
    i) Professional experience in aircraft inspection (number of years and level)
    j) Professional experience in inspection of composite structures (number of years and level)
4. Inspection data for panel 1
    a) Cleanliness level (1 – 3)
    b) Inspection angle (15, 45, or 65)
    c) Illumination (in Lux)
    d) For all impact damages the information whether the damage was found (1) or missed (0) and the corresponding damage metric entered by the inspector (mostly “dent” or “crack”).

e) Location and damage metric of all false positives.

5. Inspection data for panel 2

   a) Cleanliness level (1 – 3)

   b) Inspection angle (15, 45, or 65)

   c) Illumination (in Lux)

   d) For all impact damages the information whether the damage was found (1) or missed (0) and the corresponding damage metric entered by the inspector (mostly “dent” or “crack”).

   e) Location and damage metric of all false positives.

6. Inspection feedback

   a) Structure, which was (subjectively) easier to inspect (Panel 1, Panel 2, or equal inspection conditions). A justification for the answer was requested, if the inspectability was perceived to be different for the two panels.

   b) Feedback regarding the visual inspection (free form text, optional)

   c) Feedback regarding the complete study (free form text, optional)

7. Influence factors for visual inspections (only recorded for professional maintenance personnel)

   a) Influence of surface colour only on inspectability. A rating from -1 (unkown) and 0 (no influence) to 4 (strong influence) and examples for colours facilitating / impeding visual inspection were recorded.

   b) Influence of surface finish only on inspectability. A rating from -1 (unkown) and 0 (no influence) to 4 (strong influence) and examples for finishes facilitating / impeding visual inspection were recorded.

   c) Influence of colour / finish combinations on inspectability. A rating from -1 (unkown) and 0 (no influence) to 4 (strong influence) and examples for combinations facilitating / impeding visual inspection were recorded.

   d) Possibilities for improvement of inspection results. A rating from -1 (unkown) and 0 (not helpful) to 4 (very helpful) was recorded for the methods surface cleaning, adjustment of lighting, magnification, tap test, penetrant method. Additional methods that were added by the inspectors individually were recorded as well.

5.9 Evaluation of inspection results

5.9.1 Differences between damage detectability for the two panels

The fifth inspection was carried out under equal average inspection conditions for both panels. So damage detectability should be the same for equal impact numbers on both panels. A summary of the inspection conditions is shown in Table 17; the POD for all damages is shown in Figure 54.

Damages 1 to 4 are almost invisible. These were the ones from the blunt impact (damages 1-3) and the tiny markings cased by the 10J impact above the edge of the stiffener foot. The damages 7, 9 and 10 were found by almost all inspectors. Surprisingly, the quite severe impact No. 8 has been found by only half of the test persons on panel 1. This must be due to the fact that this impact was located in the middle of the panel in circumferential direction. Here, impacts were more difficult to detect than at the top and the bottom of the panel due to the available lighting. This must also be the reason, why impact No. 6 was less often found on panel 1 than on panel 2. Impact No. 5 on panel 2 was not only located in the middle of the panel, but was also slightly obscured by the grid markings in the middle of the panel, making it very hard to detect on panel 2. On panel 2 impact No. 10 was also located near the middle of the panel, but the dent of this impact was so large that it was easily visible nevertheless.

Inspection 5 12 Test persons

		Panel 1	Panel 2
Cleanliness	level	3	3
Angle	[°]	15	15
Illumination	[lux]	409	426
Colour		Air Berlin red	Air Berlin red
Finish		glossy	glossy

Table 17: Conditions for inspection 5 - reference inspection.

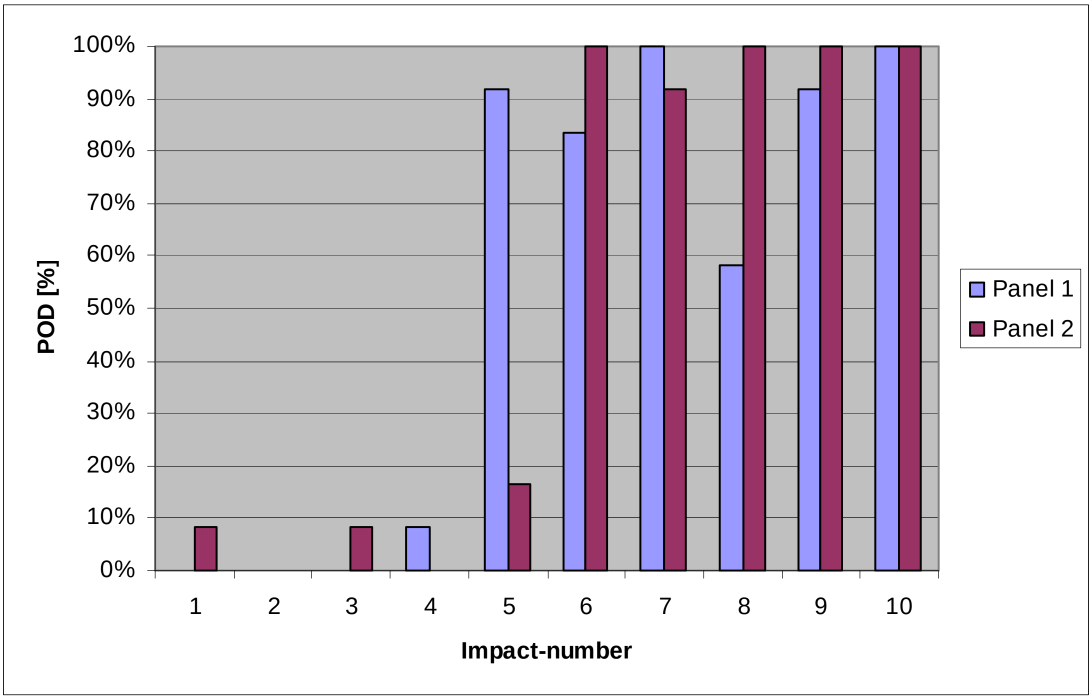


Figure 51: POD for both panels under equal inspection conditions.

Four inspections where held with nominal equal inspection conditions for both panels. When asked, for panel they felt more confident to have found all defects, 6 of the 35 inspectors answered Panel 1, 10 found Panel 2 easier to inspect and 15 said, conditions were equal for both panels. Four of the sixteen inspectors said, they were more confident for either Panel 1 or Panel 2, because it was the second one of the two panels ("inspection routine" in Table 18). With the experience of already having inspected one panel, they were confident that they did better on the other one. The rest had the impression that either Panel A or Panel B had different lighting of different cleanliness conditions. Details are shown in Table 18.

Inspection No.	equal conditions P1 & P2	lighting No. of inspectors favouring		cleanliness No. of inspectors favouring		inspection routine No. of inspectors favouring		no reason given No. of inspectors favouring	
		Panel 1	Panel 2	Panel 1	Panel 2	Panel 1	Panel 2	Panel 1	Panel 2
1	4	1			2		2		
2	5							1	
4	2		1	2	1				
5	4		1	1		1	1		2

Table 18: Subjective differences in inspection conditions at nominal equal conditions.

Overall it seems that the subjective impression of the inspection conditions were the same for both panels. The number of inspectors favouring panel 1 and panel 2 because of cleanliness was equal. Only a small number of persons found the lighting conditions to be different for both panels.

5.9.2 Dent depth

The influence of dent depth on the detectability of damage has been evaluated for the inspection No. 5 and 8. These were the inspections with overall average conditions for cleanliness, inspection angle and illumination. At inspection 5 both panels were painted with red / glossy colour and finish, for inspection 8 the panels were repainted blue (panel 1) and red (panel 2) with a matt finish for both panels.

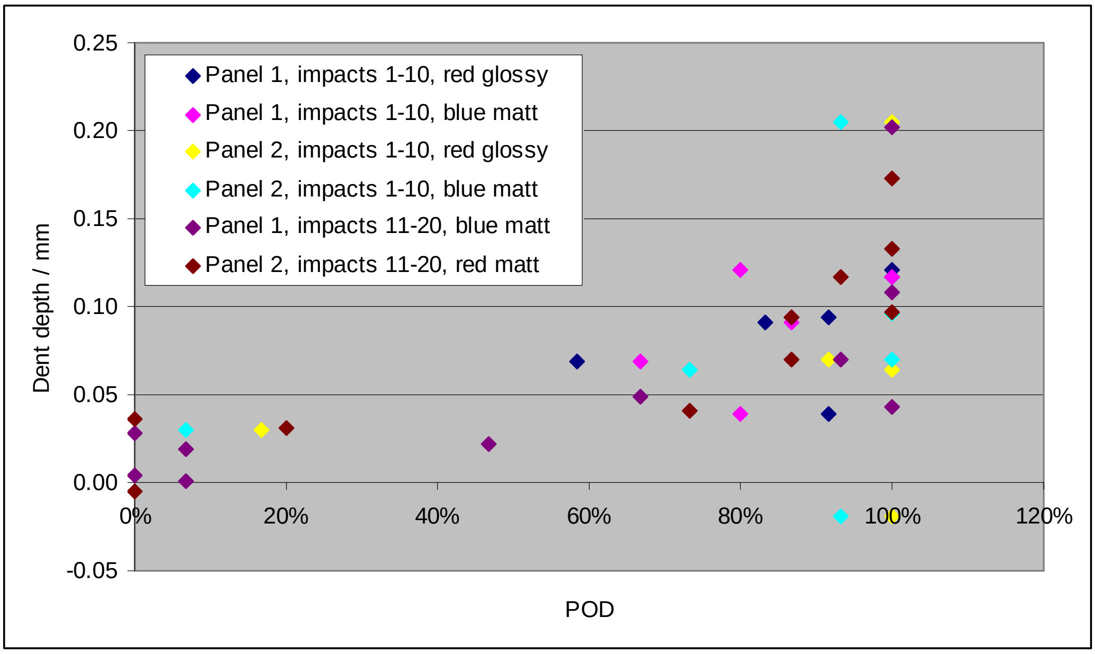


Figure 52: Influence of dent depth on detectability of damage.

Figure 52 shows the relation of dent depth and probability of detection. Impacts with a dent depth below 0.05 mm cover a range from 0% to 100%.

It seems that a dent depth of 0.06 mm ensures a POD of at least 60% and a dent depth of 0.12 mm ensures a POD of at least 80% for average inspection conditions as defined in this study. However, it must be mentioned, that although the measurement of dent depths was carried out carefully, it is not free from imprecision, since the undamaged panel surface was not perfectly plane in the direction of the cylinder axis.

For details on dent depth measurement see section 5.4.

5.9.3 Inspection angle

Table 19 shows the conditions for investigating the influence of different inspection angles.

Inspection 3 13 Test persons

		Panel 1	Panel 2
Cleanliness	level	3	3
Angle	[°]	45	65
Illumination	[lux]	422	408
Colour		Air Berlin red	Air Berlin red
Finish		glossy	glossy

Table 19: Conditions for inspection 3 – inspection angle

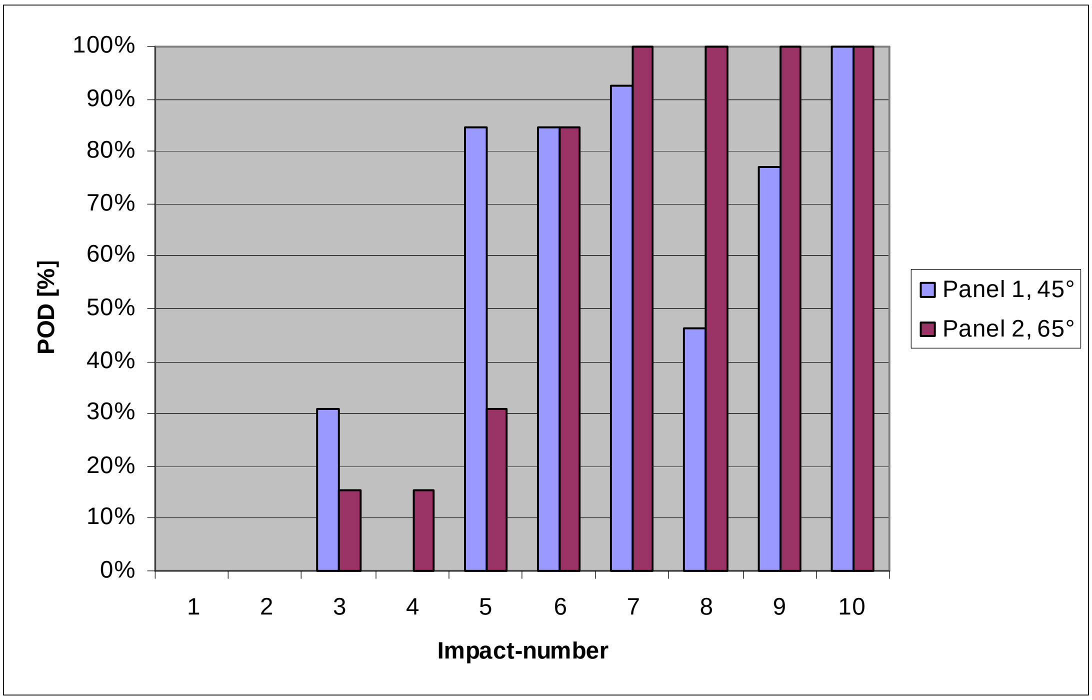


Figure 53: POD for panel 1 at an inspection angle of 45° and panel 2 at an inspection angle of 65°.

It is curious, that impact No. 3 is found much more often on panel 1 under the supposedly adverse circumstances. Obviously the combination of lighting direction and angle of vision were especially favourable for the detection of the flat dent at the specific location of impact 3 on panel 1. Again, quite a lot of inspectors did not find damage 8 on panel 1. At an angle of 45° also damage 9 became more difficult to detect.

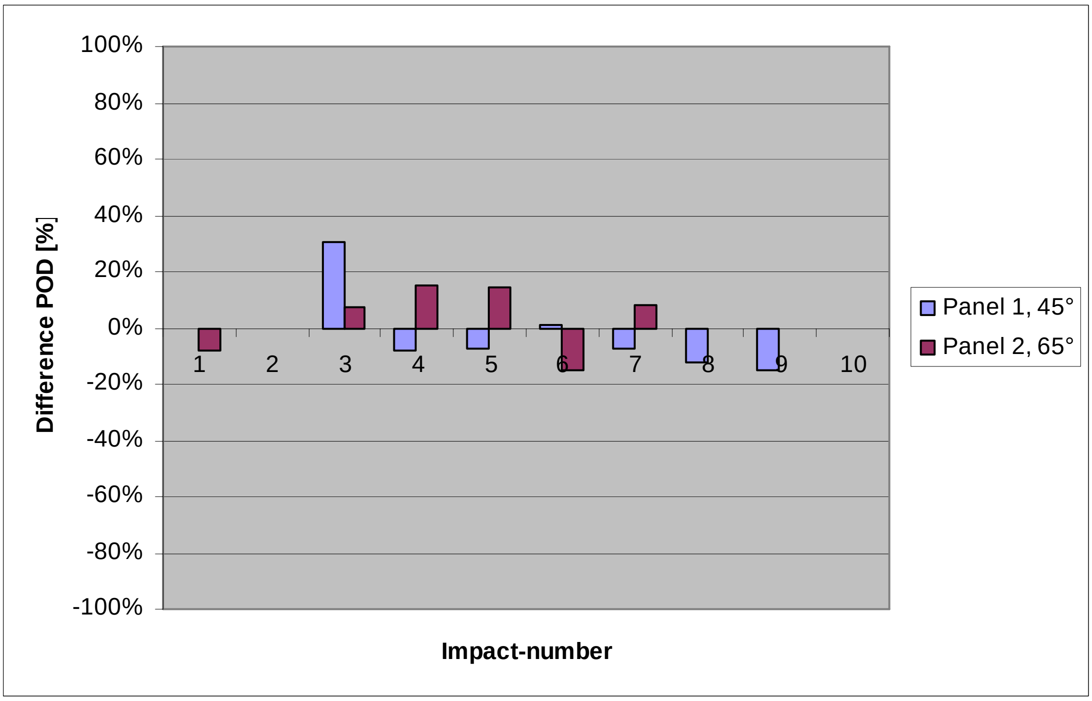


Figure 54: Influence of the inspection angle - difference in POD with respect to the reference inspection

Figure 54 displays the difference in POD to the reference inspection. A positive value means that the POD increases at altered inspection conditions. It was not clear in advance, which inspection angle would lead to the most unfavourable inspection conditions. It seems that an angle of 45° is slightly worse for inspectability than an inspection angle of 65°. This is inline with the comments from the inspectors, who found it more difficult to inspect panel 1. The differences in the POD are small, though, so the inspection angles chosen for this study do not affect the POD by much.

When asked, six of the 13 persons found Panel 2 at a 65° angle easier to inspect than Panel 1 at a 45° angle. Only one person found Panel 1 easier to inspect.

Overall, the inspection angle did not have a substantial effect on damage detectability

5.9.4 Cleanliness

The inspection for investigating the influence of cleanliness was not held in meeting room 101 of the Institute, but in a hangar in Braunschweig, in order to involve DLR maintenance personnel. The illumination conditions (~400 lux) were comparable to the conditions in the meeting room 101, see Table 20.

Inspection 7		18 Test persons	
		Panel 1	Panel 2
Cleanliness	level	2	1
Angle	[°]	15	15
Illumination	[lux]	414	425
Colour		Air Berlin red	Air Berlin red
Finish		glossy	glossy

Table 20: Conditions for inspection 3 – cleanliness

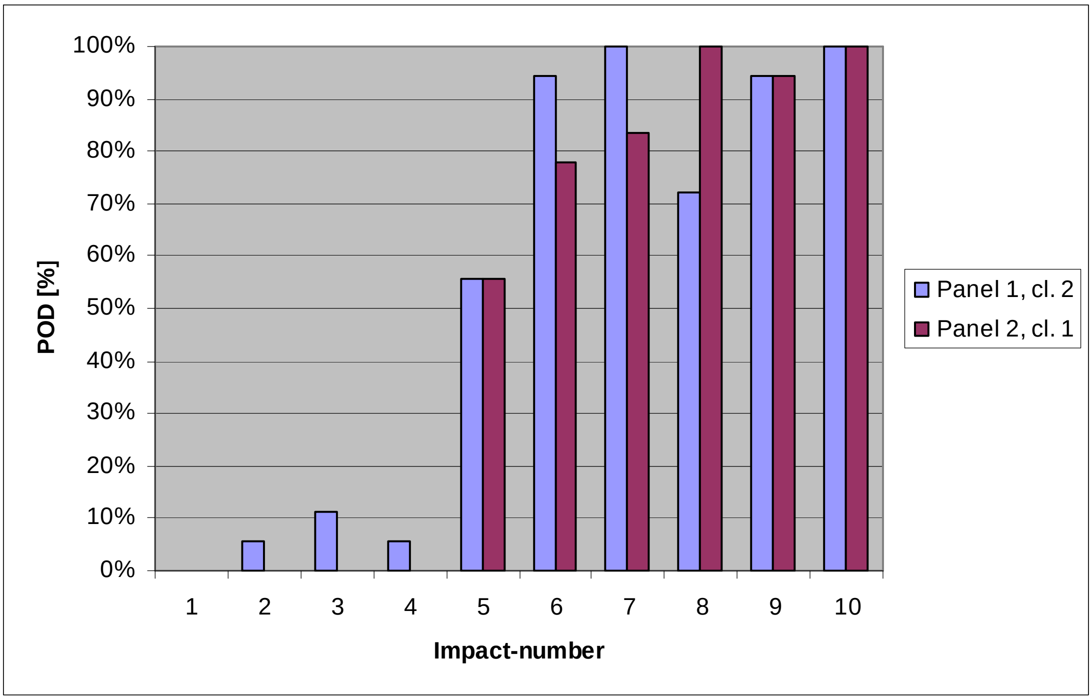


Figure 55: POD for panel 1 at a cleanliness level of 2 and panel 2 at a cleanliness level of 1.

Looking at Figure 56 it seems that the overall influence of cleanliness on the POD is not significant for the flat, spread-out dents, which are very hard to detect even on cleaner surfaces. Also the detection of more pronounced dents at locations 7 to 10 does not seem to be significantly affected. Taking a closer look at Figure 55 and Figure 56, however, reveals that the damage detectability is improved for most damages at a cleanliness level of 2 and decreased for a cleanliness level of 1. The reason may be less distraction from reflections on the moderately dirty surface of panel 1.

But also the illumination of the panels could be a factor. In the aircraft hangar the lamps were further away from the structure. More ambient lighting and less direct lighting might have improved the inspection conditions, although the illumination measurement gave almost equal numbers for the meeting room 101 and the aircraft hangar.

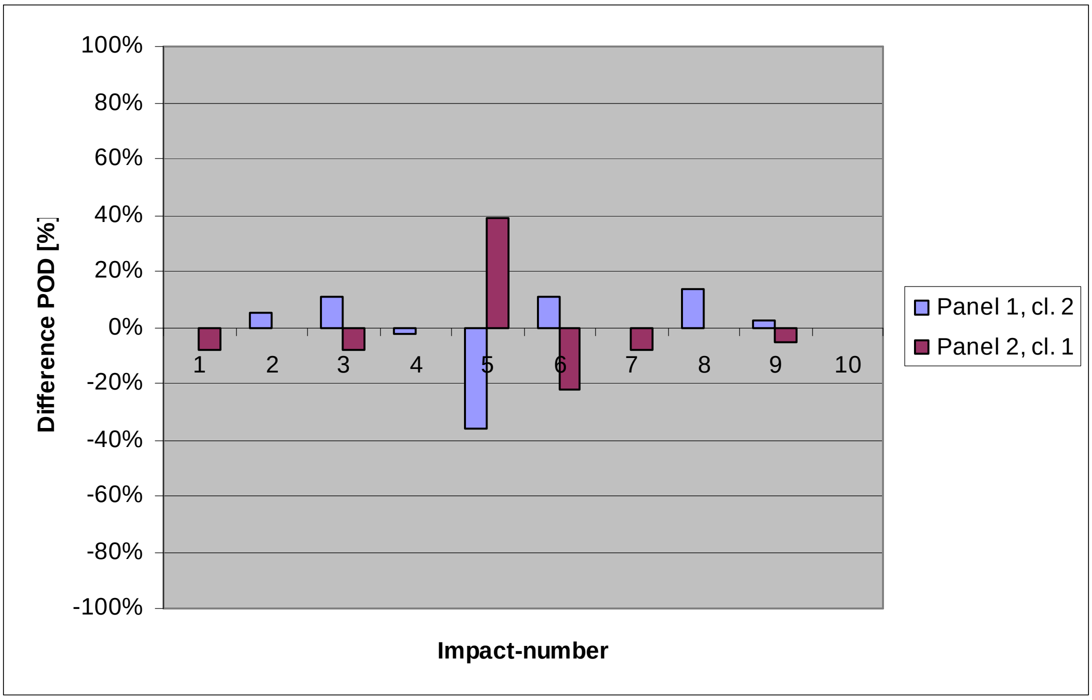


Figure 56: Influence of cleanliness - difference in POD with respect to the reference inspection.

Damage No. 5 is found more often than before on panel 2, most likely because the contrast between the grid markings of the panel and the panel surface decreased due to the dirt. Therefore the markings close to this damage are less distracting and the small dent is noticed more frequently. On panel 1, however, the small dent No. 5 is obscured by the coffee stains, making it much harder to detect.

To summarize the above the effect of cleanliness on the POD is small. Eight of the 18 inspectors found the slightly cleaner panel 1 easier to inspect, while four inspectors were more confident to have found all defects on panel 2.

5.9.5 Illumination

There are two inspections, which allow the investigation of the effect of illumination on the POD of the impact damages. One of them is inspection No. 6, where the illumination was reduced by removing one / two of the three light bulbs in each lamp for poor / very poor lighting conditions. The resulting illumination measurements are shown in Table 21.

Inspection 6 12 Test persons

		Panel 1	Panel 2
Cleanliness	level	3	3
Angle	[°]	15	15
Illumination	[lux]	164	288
Colour		Air Berlin red	Air Berlin red
Finish		glossy	glossy

Table 21: Conditions for inspection 6 – illumination

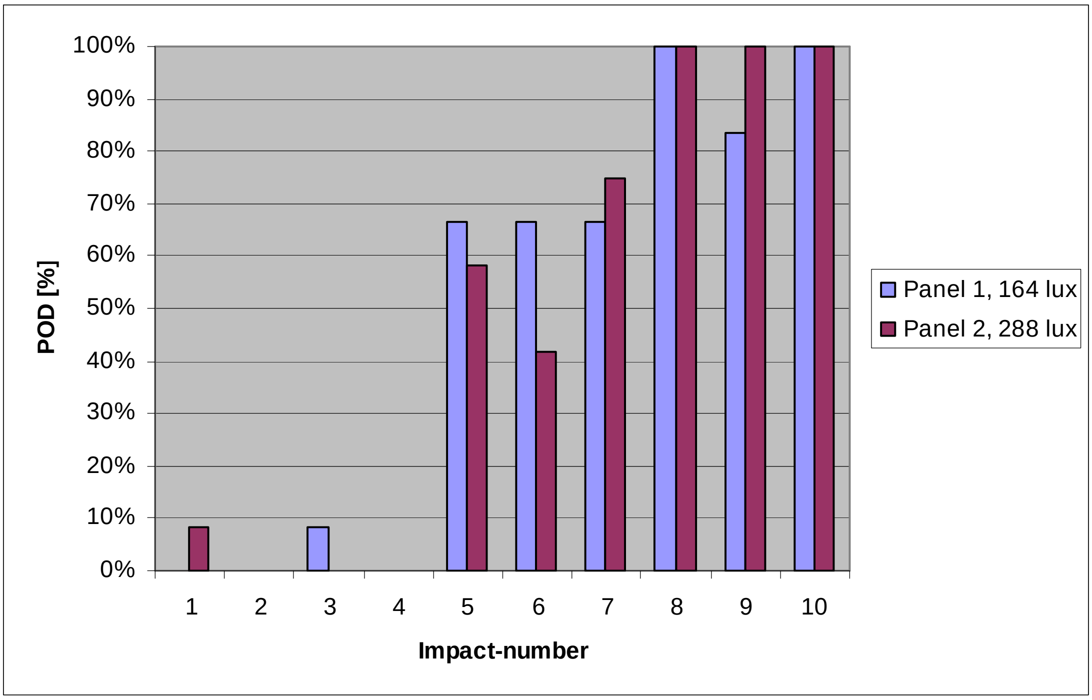


Figure 57: POD for panel 1 at an illumination of 164 lux and panel 2 at an illumination of 288 lux.

An illumination of 288 lux only had an effect on the detectability of small damages 5 to 7. Again the effect on the detectability of damage 5 is surprising at first, but once more this can be explained by smaller contrast of the nearby grid markings, leading to less distraction from the small dent. The detectability of the small damage No. 6 is greatly reduced.

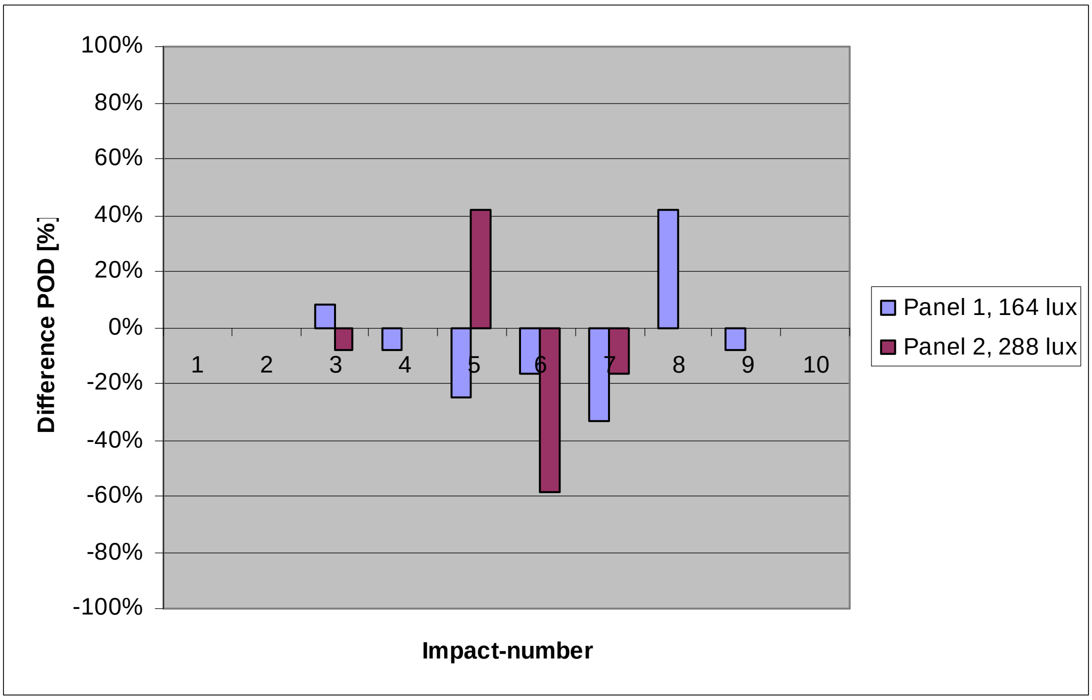


Figure 58: Influence of illumination - difference in POD with respect to the reference inspection.

An illumination of only 164 lux had an adverse effect on a wider range of damages, reducing the detectability of most of them. It is unclear, why damage No. 8 is now detected by all inspectors, while a lot of them missed this damage at much better lighting.

Three inspectors of inspection 6 found the badly lit panel 1 easier to inspect than panel 2. Two of them even complained about too much lighting for panel 2. Four inspectors found panel 2 easier to inspect. All of them gave the better lighting conditions as the reason for their answer.

Inspection No. 1 was conducted with equal conditions for both panels under very good lighting conditions, see Table 22 and Figure 59.

Inspection 1		9 Test persons	
		Panel 1	Panel 2
Cleanliness	level	3	3
Angle	[°]	15	15
Illumination	[lux]	1100	1100
Colour		Air Berlin red	Air Berlin red
Finish		glossy	glossy

Table 22: Conditions for inspection 6 – very good lighting conditions.

Figure 59: Inspection No. 1 at very good lighting conditions.

All inspectors found damages 6 to 10 on both panels, only one inspector missed the No. 5 damage on panel 2. Even the impact location No. 4 was found by quite a few inspectors. The US-scan did not even show internal damage here. But even the very good lighting conditions did not help much at locating the flat, spread out dents from the blunt impacts.

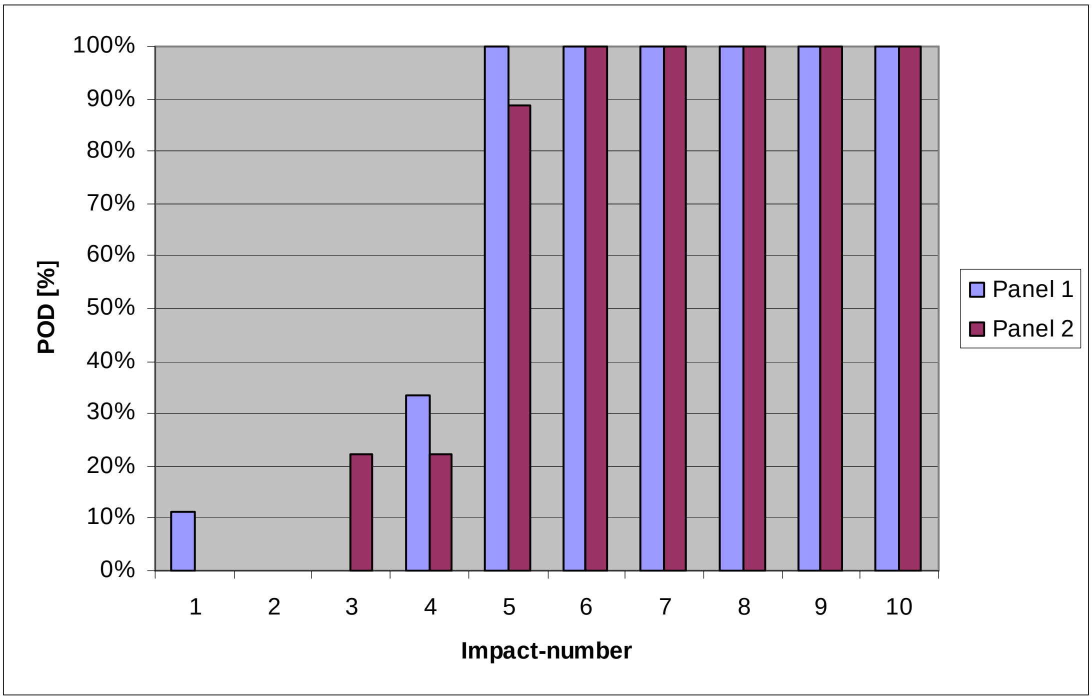


Figure 60: POD for both panels at an illumination of 1100 lux.

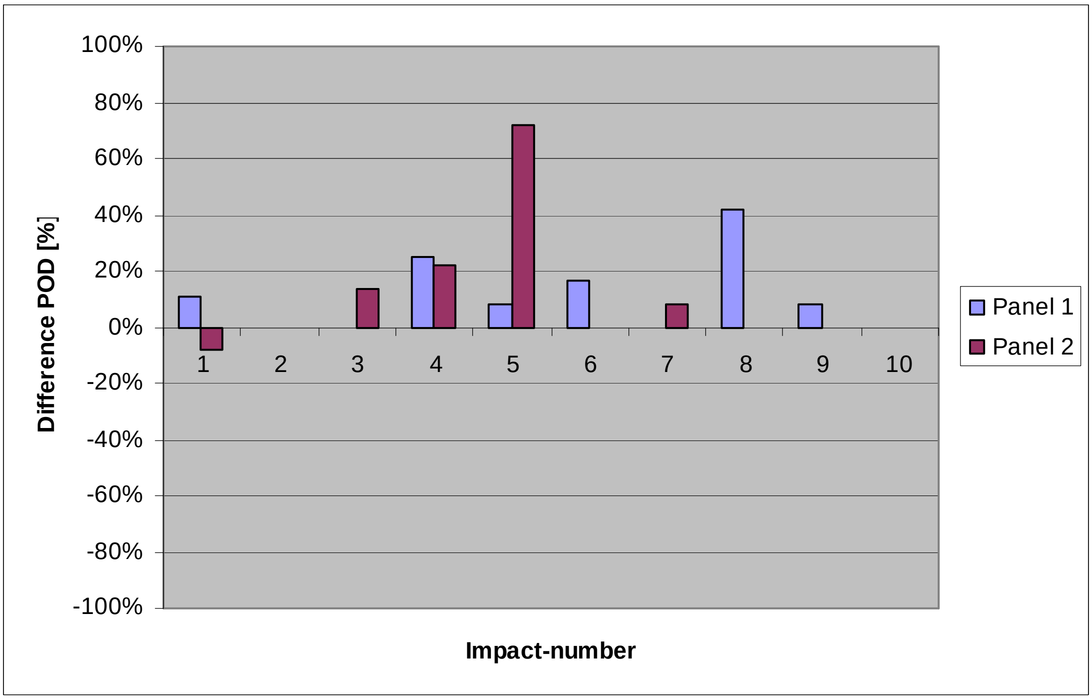


Figure 61: Influence of illumination - difference in POD with respect to the reference inspection.

Compared to the previously studied inspection parameters the effect of illumination is clearly the most significant one.

5.9.6 Colour

The previous inspection results were evaluated against the reference inspection No. 5 and three data points were obtained corresponding to average, poor and very poor conditions, with the reference inspection providing average inspection conditions for both panels. The effect of a certain inspection parameter could be studied by comparing inspection results on identical panels and identical damages. The colour influence, however, was studied on the basis of only two colours Air Berlin red and British Airways blue being applied to two different panels. Therefore there are three additional sources of error involved in evaluating the colour influence:

- The nominally equal panels were not exactly identical.
- The nominally equal damages were not exactly identical on both panels.
- Only two different states of the inspection variable were studied.

According to Lufthansa Technik there are two options for repainting structures:

- The old paint is removed before repainting, if the old paint is in bad condition or if weight is an issue.
- The old paint is not removed, if the paint is still in good condition and if the extra weight of the second coating is not an issue.

In this study the paint was not removed before the repainting process. It can be argued that the additional layer of paint could influence damage *size* and damage *detectability*. However, comparing indentation depths (i.e. damage *size*) on one and two colour coatings shows no clear influence in this respect (Figure 38). The influence of paint layer thickness on damage *detectability* can not be evaluated systematically from the data collected in this study, because the surface finish was changed from glossy to matt together with the change of paint layer thickness.

Inspection 8 15 Test persons

		Panel 1	Panel 2
Cleanliness	level	3	3
Angle	[°]	15	15
Illumination	[lux]	401	404
Colour		BA blue	Air Berlin red
Finish		matt	matt

Table 23: Conditions for inspection 8 – colour

Only the newly introduced impacts No. 11-20 were evaluated here. The damages introduced before applying the new colour were omitted, because differences in thickness of the colour coating modified the visibility of damages differently on the two panels. The impact parameters of impacts 11 to 20 were chosen equal to impacts 1 to 10.

Figure 62 shows the POD of the different damages. Not surprisingly, almost equal PODs were found for non / hardly visible damages 11 and 12 and 17 to 20. The impacts 15 and 16 were clearly visible only on the red panel, but left no mark on the blue panel, so the different PODs for these impacts cannot be attributed to the different colours.

Damage No. 14 looked equal on both panels. There was a tiny mark on the colour coating where the impactor hit the panel. This marking was noticed by 10 of the 15 inspectors on the blue panel, but only by three inspectors on the red panel. The most interesting results were obtained for damage 13, which also looked very much the same on both panels. On both panels there was a flat, spread out dent, which was accompanied by three or four diagonal cracks in the paintwork. While less than half of the inspectors noticed this on the blue panel, 11 of the 15 inspectors found this damage on the red panel. The different PODs for damage 13 and 14 are interesting, but more data is necessary to confirm that this difference can really be attributed to the colour difference.

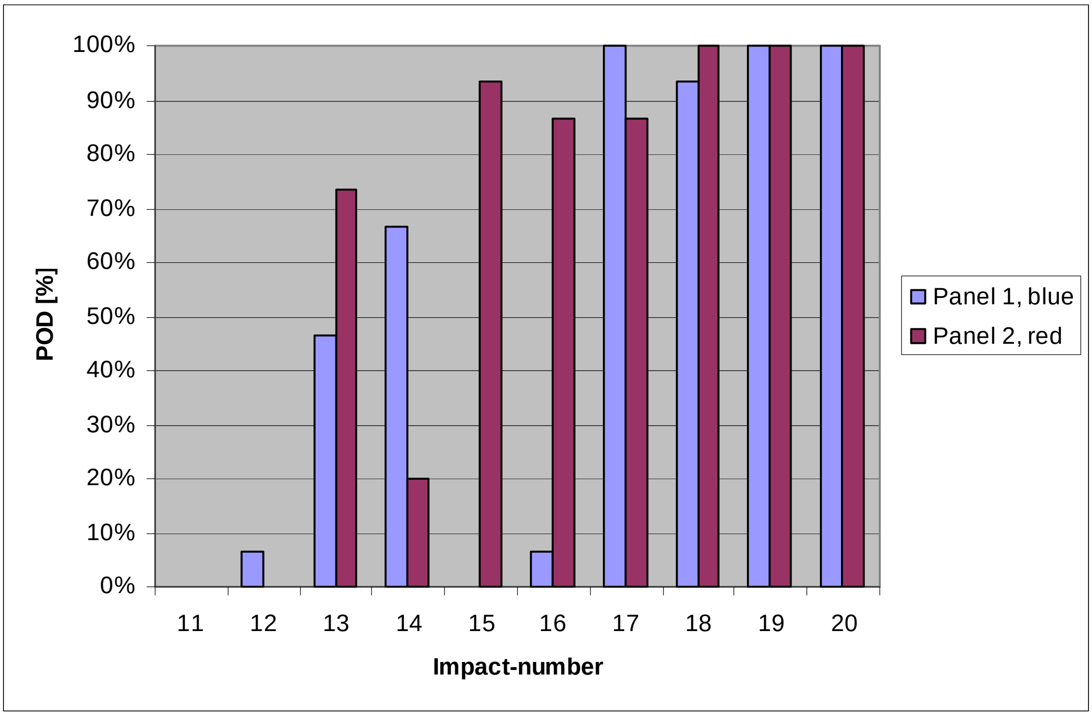


Figure 62: POD for differently coloured panels.

Summarising, there is no clear indication, whether colour influences the detectability of damages. However, the subjective impression of the influence of colour on damage detectability shows a very clear advantage for the colour red. Eight of the 15 inspectors found the red panel easier to inspect and six of them gave the colour as the reason. Only one inspector found the blue panel easier to inspect.

5.9.7 Finish

The evaluation of the influence of the finish on the POD can be done by comparing the panel 2 inspection results of the reference inspection No. 5 with the results of inspection No. 8. Both inspections were done on the same panel, but different inspectors were involved. Table 24 shows the inspection conditions for panel 2.

Inspection 5	12 Test persons
Inspection 8	15 Test persons

		Panel 2, Insp. 5	Panel 2, Insp. 8
Cleanliness	level	3	3
Angle	[°]	15	15
Illumination	[lux]	409	404
Colour		Air Berlin red	Air Berlin red
Finish		glossy	matt

Table 24: Conditions for inspections 5 and 8 for panel 2 –glossy and matt finish.

The repainting of the glossy panel obscured some signs of the damages 1-10, so the detectability of these damages is expected to decrease at equal inspection condition. After repainting the panel with a matt finish, ten more impacts were introduced, so it is also possible to compare inspection results for damages 1-10 of the glossy panel to the results for damages 11-20 on the matt panel. The POD for the three cases are shown in Figure 63.

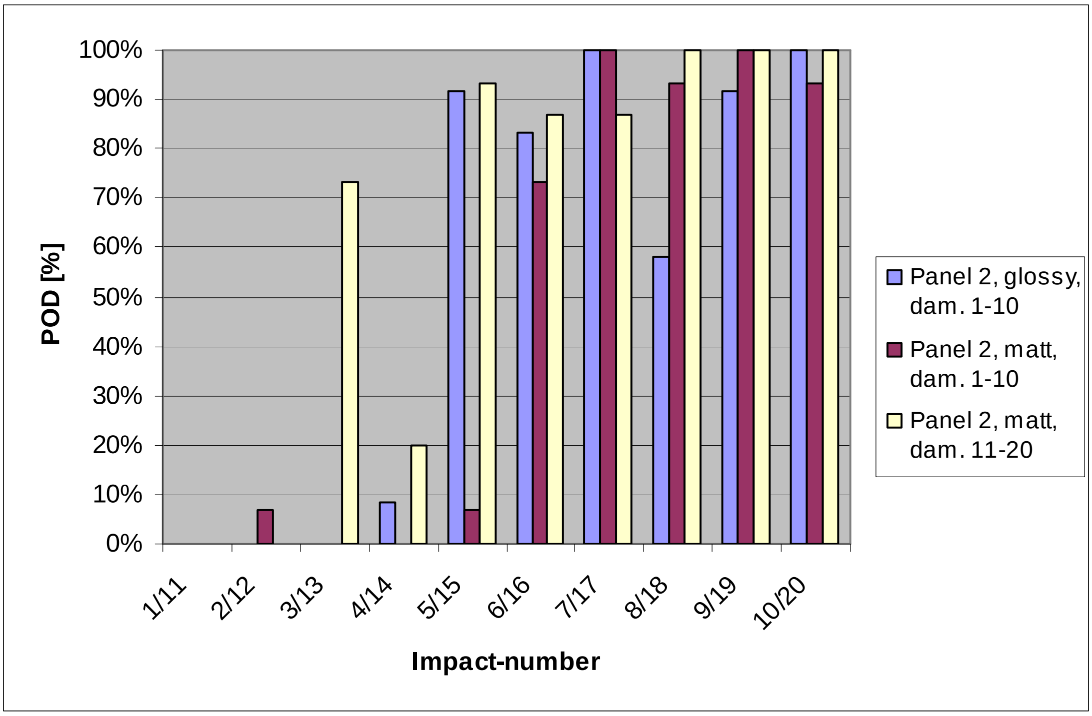


Figure 63: POD for panel 2 with different finishes.

The decrease in detectability due to repainting the panel causes impact No. 5 to be detected by only one inspector on the matt panel 2, while this impact was found by almost all inspectors on the glossy panel. Apparently the new colour filled out the dent completely, leaving no sign behind. Also the comparable impact No. 15 could be found easily on the matt panel. The same effect is apparent for impact No. 4, which could be noticed only by a slight colour change on the glossy panel. This sign of damage was removed during repainting. The same impact (No. 14) also caused a tiny mark on the colour coating of the matt panel. This mark was much better visible than the corresponding mark on the glossy panel. The dark red colour was covered by lighter-coloured scratches on the matt surface, leading to a POD of 20% (3 of 15 inspectors found this damage), while only one out of twelve inspectors found impact 4 on the glossy panel. More than 70% of the inspectors found impact No. 13 on the matt panel due to the clearly visible cracks in the matt paint. These cracks were not present in the glossy paint.

It is surprising, that impact No. 8 was found much more often after repainting the panel. This is an indication that a matt surface can sometimes facilitate damage detection.

Two inspectors missed impact No. 17, while damage No. 7 was found by all inspectors before and after repainting, but overall the damage detectability varies only slightly for impacts 1, 2, 6, 7, 9 and 10.

To summarize, most differences in the POD for matt and glossy panel must be attributed to different damage characteristics for nominally equal barely visible damages. The was only one damage, which was detected more often on the matt surface than on the glossy surface. However, the data basis of this study is not sufficient to make a definite statement on the influence of surface finish on detectability of damages.

Inspired by a publication on “enhanced visual inspection” [27], a small experiment has been conducted on the matt, blue panel 1 to find out, whether the visibility of a dent could be improved by wetting the surface with water and thereby creating a glossy appearance. In order to improve the detectability of small dents, the liquid film must be thin and of an evenly distributed thickness. Using pure water creation of such a thin, even water film did not succeed, because surface tension of the water resulted in the forming of water droplets, unless an excessive amount of water was used. A second experiment was performed by adding a small amount of soap to the water, in order to reduce the surface tension of the liquid. Now a thin, glossy film could be created by carefully avoiding the formation of foam. Now the difficulty was evaporation of the water film because of quite low humidity on that day, but for a short time, the water covered surface received a glossy appearance, the dent becoming clearly visible from a certain visual angle (Figure 64, left hand side). It has to be stated, though, that the impact damage, on which this was tried out, was detectable quite well also on the matt surface. The detectability of the damage on the matt surface was much better than it appears on the right hand side photo in Figure 64.

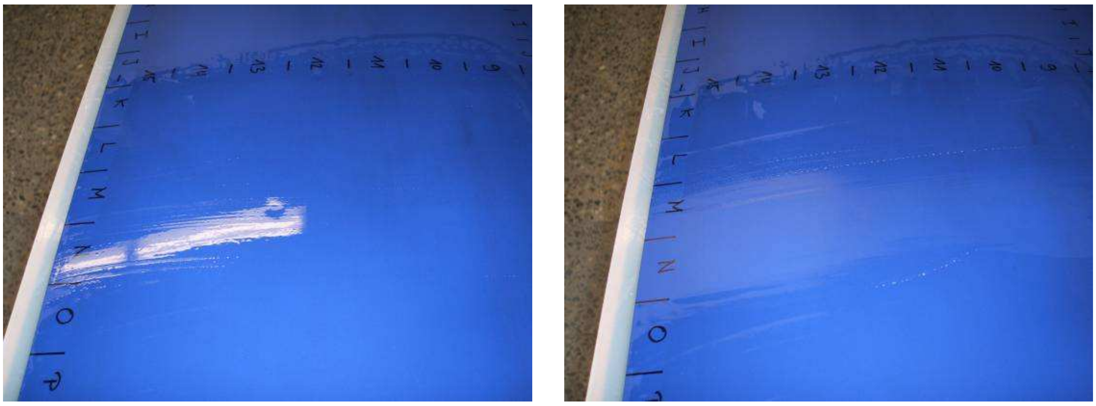


Figure 64: Surface wetting, to improve detectability of dents on matt surface.

5.9.8 Overall average / poor / very poor inspection conditions

There are two possibilities to evaluate the effect of overall poor and very poor conditions on the detectability of damages. Inspection No. 9 was conducted with very poor lighting, colour, finish and cleanliness condition for panel 1 and the respective poor conditions for panel 2, see Table 25.

Inspection 9		13 Test persons	
		Panel 1	Panel 2
Cleanliness	level	1	2
Angle	[°]	45	65
Illumination	[lux]	152	257
Colour		BA blue	Air Berlin red
Finish		matt	matt

Table 25: Conditions for inspections 9 – overall poor conditions for panel 2 and very poor conditions for panel 1.

Comparison of inspection No. 5 and inspection No. 9

The inspection results from inspection No. 9 can be compared to the results for inspection 5, where both panels were inspected under overall average conditions. The downsides of this evaluation alternative are that

- damages No. 1-10 are modified by the new paint coating

- appearances of damages 11-20 are at least partly not comparable to their counterparts 1-10.

Nevertheless this evaluation is displayed in Figure 65 and Figure 66.

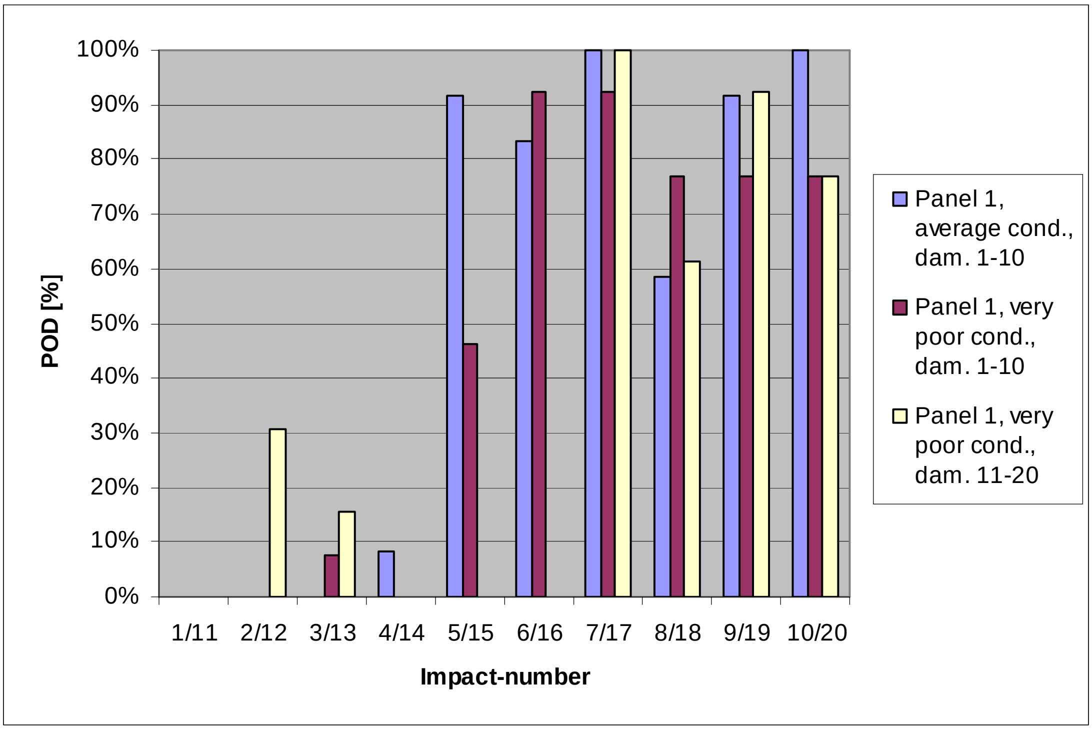


Figure 65: POD for panel 1, comparison of overall average and very poor inspection conditions.

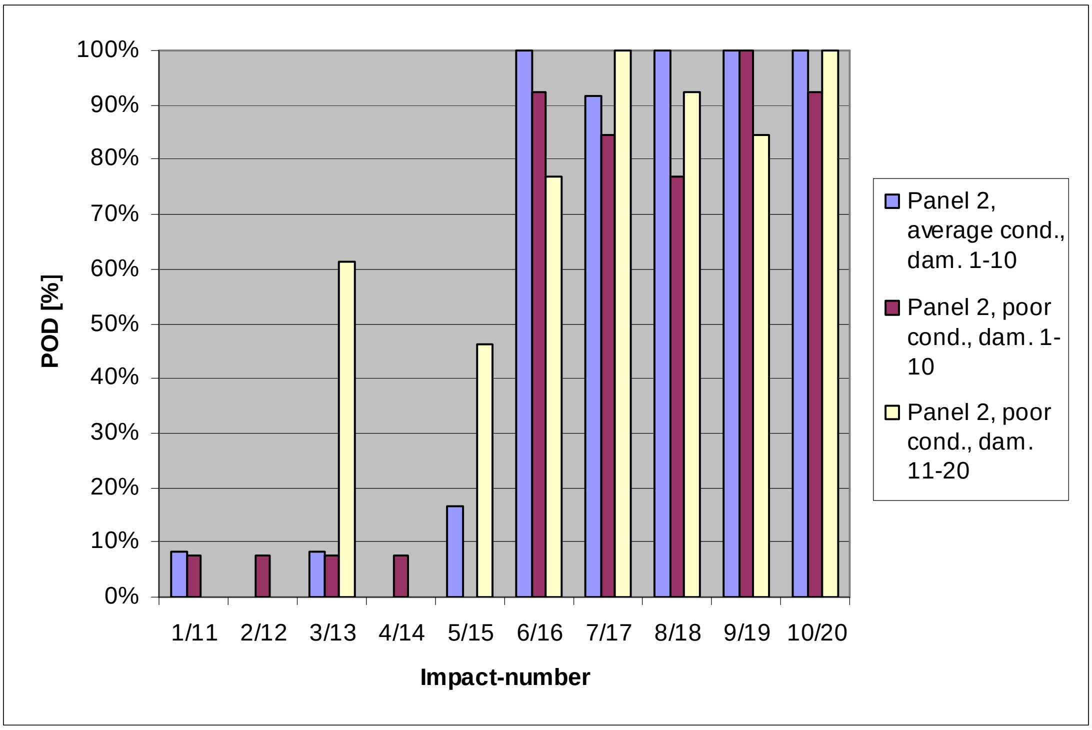


Figure 66: POD for panel 2, comparison of overall average and poor inspection conditions.

Comparing results under average conditions for panel 1 (blue columns in Figure 65) to the results under very poor conditions for the identical, but repainted damages 1-10 (purple columns) shows a clearly increased POD for damage 8. This is the clearly visible dent that was overlooked by surprisingly many inspectors in the reference inspection. Also the detectability of damage 6 is slightly increased by the adverse inspection conditions of inspection 9. On the other hand the detectability of damages 5, 7, 9, and 10 has become smaller.

When comparing the average conditions to the light yellow columns for the new damages 11-20 it has to be considered, that there was almost no dent at the impact locations 14, 15 and 16, therefore the POD for these damages is zero. The only case, where the adverse conditions clearly affected the POD is damage No. 20, which was missed by more than 20% of the inspectors.

Comparing results under average conditions for panel 2 (blue columns in Figure 66) to the results under poor conditions for the identical, but repainted damages 1-10 (purple columns) shows a slightly decreased detectability for all damages. The strong increase in POD for damage 11-20 under adverse conditions is caused by additional cracks at impact No. 13, which were not present at impact No. 3 and by the grid labels near impact 5, which obscured the small impact dent. Slight decreases of detectability for impacts 16, 18 and 19 under poor conditions are noted, as well as a surprising increase of POD for impact 17.

These results so far paint an inconsistent picture of the influence of adverse conditions on the detectability of damages: The poor conditions seemed to have a greater effect on detectability than the very poor conditions and for quite a few damages the detectability increased with supposedly worse inspection conditions.

Comparison of inspection No. 8 and inspection No. 9

An alternative option for evaluating the influence of adverse inspection conditions is to compare the results of inspection 9 to inspection 8, where the influence of colour on the POD was investigated under otherwise average condition. This removes the colour / finish parameter from the evaluation, but has the advantage that now 20 damage locations can be evaluated and the effect of repainting on damage appearance no longer distorts the inspection results.

Figure 67 and Figure 68 show the POD of this comparison, Figure 69 show the effect of worse conditions as the difference between the data series shown in Figure 67 and Figure 68.

Figure 69 shows a strong decrease of 20% or more for a total of six damages, under very poor inspection conditions. With damages No. 18 and 20 two larger dents are affected. Only two damages (number 14 and 15) are substantially more difficult to detect under poor conditions, both being very small damages / dents.

One damage, No. 12, is found significantly more often under adverse conditions.

The comparison with inspection 8 gives more consistent results on the effect of adverse inspection conditions than the comparison with results from inspection 5.

This evaluation documents not only the effect of poor / very poor inspection conditions. Additionally, it shows the substantial effects of repainting and of variance in damage visibility for nominal equal damages.

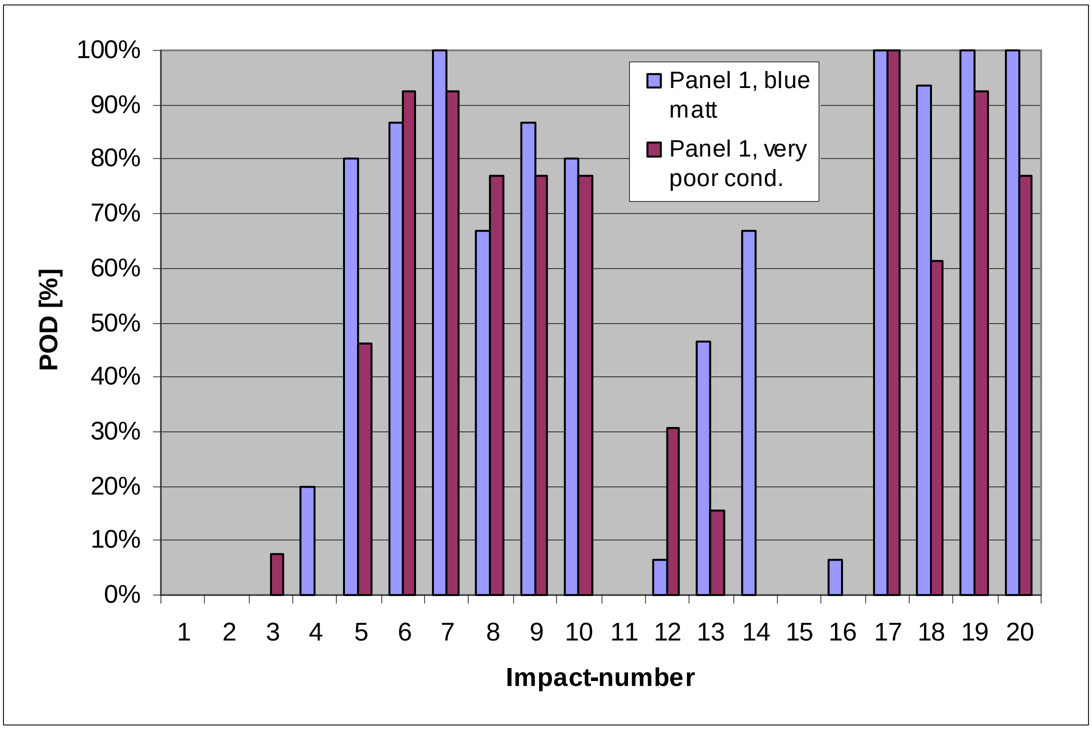


Figure 67: POD for the matt blue panel 1, comparison of otherwise average and very poor conditions.

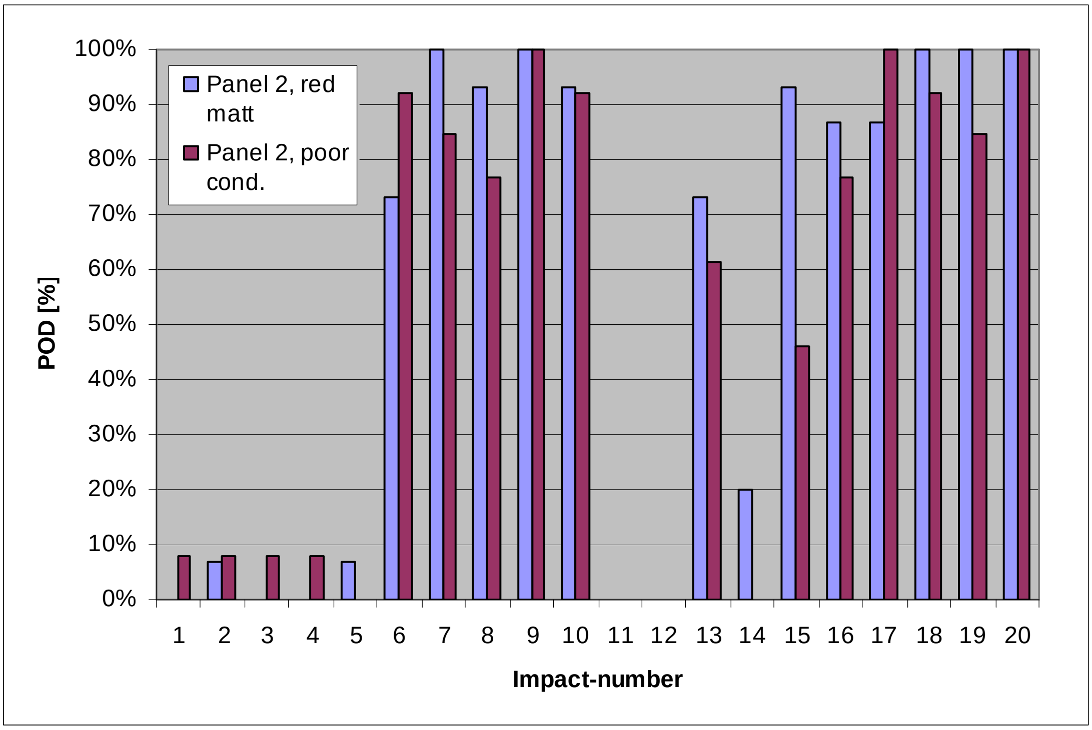


Figure 68: POD for the matt red panel 1, comparison of otherwise average and poor conditions.

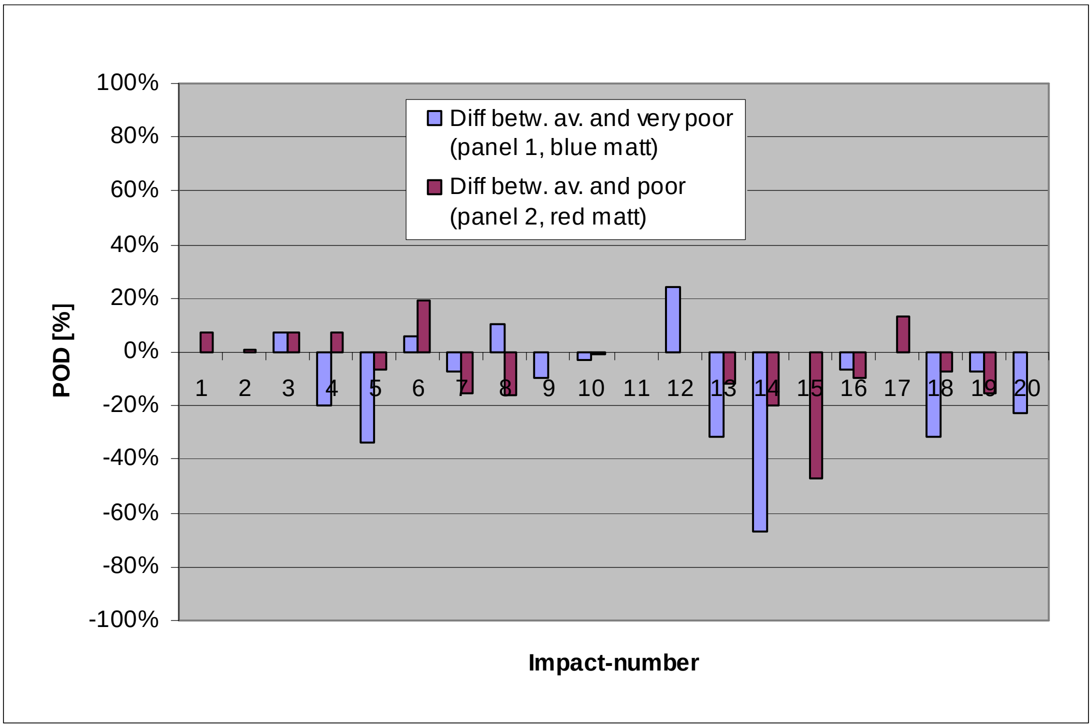


Figure 69: Influence of overall poor and very poor inspection conditions - difference in POD with respect to the inspection No. 8.

5.9.9 Person-related factors

Person-related factors are evaluated based on inspections 2 – 7 (cf. Table 16). In these six inspections the panels had ten impacts each. For all 69 inspectors of these inspections the total number of damages found is determined and evaluated together with their answers about their personal data:

- Experience with respect to inspection of composite structures. Categories are defined in section 5.6.2,
- Visual capability,
- Age,
- Sex.

In the strict sense, inspection conditions were not equal for all inspectors. Two of these inspections were carried out under overall average conditions (inspection No. 2 and 5), the inspections 4 and 6 had poor lighting conditions, inspection 3 was done with inspection angles of 45° and 65° and inspection 7 was carried out under poor cleanliness conditions. However, the previous section showed that varying a single inspection parameter did not affect the detectability of damage very much, with the exception of strongly increased illumination (inspection 1). Therefore inspection 1 is not considered in the following evaluation of individual-related factors. Also the inspections 8 and 9 are not considered here, because for these inspections each structure had 20 impacts.

The overall average number of impacts found on the two panels is 12.8, the overall average age is 36 years. The average qualification level, computed by weighting the number of persons of each level with the level number, is 1.9.

Experience

Table 26 displays average the number of damages found for persons of the three qualification groups defined in section 5.6.2.

Obviously there is a clear trend for persons with a greater experience in composite structures and / or visual inspection to find a greater number of damages.

qualification	No. of persons	av. No. of damages found
level 1	26	11.9
level 2	22	12.7
level 3	21	13.8

Table 26: Influence of experience on damage detection.

Visual capability

Evaluation of the inspection results for visual capabilities of the test persons shows some surprising trends. Test persons with lower visual acuity of 0.5 and 0.66 showed better performance than persons with average (1.00) or good contrast vision. However, three of the six test persons with a visual acuity below 1.00 were professional inspectors, including the one person with a visual acuity of 0.5.

In principle, good and excellent damage detection performance is possible, even with impaired visual acuity.

visual acuity	No. of persons	av. No. of damages found
0.50	1	13.0
0.66	5	14.4
1.00	33	12.5
1.25	30	12.8

Table 27: Influence of visual acuity on damage detection.

Three persons with impaired colour vision took part in inspections 2 to 7, finding 12, 13, and 14 damages, respectively. This is not enough data to draw conclusions with respect to the effect of impaired colour vision on damage detection, but the study shows that such persons can achieve average and even good results at least for the three colour/finish combinations investigated.

Age

The youngest participant in the study was a high school student, 15 years of age, while the oldest one was a 58-year-old technician, who took part in inspection 8. The oldest participant in inspection 2 to 7 was 57 years old.

Persons between 36 and 45 years were the most successful in finding damages, with steadily decreasing results towards younger and older ages.

The decrease towards younger ages can be explained by the average qualification of younger persons being lower. Towards older ages the decrease of the average qualification is only 0.3, while the average number of damages found decreases by 1.4. Therefore, there must be another influence factor involved.

age	No. of persons	av. No. of damages found	av. qualification	av. visual ac.
46 - 57	16	12.2	2.1	1.03
36 - 45	16	13.6	2.4	1.10
26 - 35	27	12.8	1.8	1.10
15 - 25	10	12.2	1.2	1.07

Table 28: Influence of age on damage detection.

Table 28 shows that the average visual acuity decreases slightly with increasing age of the test persons, but this small decrease is unlikely to have caused the strong drop in inspection results. The evaluation of the influence of visual capabilities above suggests that there is another factor involved that was not captured in this study.

Sex

The number of female participants is unfortunately quite small in comparison with the number of male participants.

Men found in average about one more damage on the two panels than women.

This might partly be due to the lower qualification of the participating women (average qualification level 1.6) compared to the male participants (average qualification level 2.0), but Table 26 suggests, that this is probably not the only reason, since a difference of a full qualification level also corresponds to about one damage difference. Furthermore, the participating women had slightly better visual capabilities than the men. All participants with impaired colour vision were male. The average age of male participants was 36 years, the average age of female participants was 38 years.

sex	No. of persons	av. No. of damages found	av. qualification	av. visual ac.
male	60	12.9	2.0	1.07
female	9	11.8	1.6	1.11

Table 29: Influence of sex on damage detection.

5.9.10 Alternative damage metrics

Questionnaire

All professional inspectors of inspections 2, 4 and 7 were asked, what could be done in order to improve detection results. Specifically the suitability of tap test, magnification and the penetrant method was rated by the 23 professionals by selecting one of the answers shown in Table 30. Additionally they were asked to rate the effect of surface cleaning and the adjustment of lighting. They were free to add further methods.

inspector's answer	associated rating
unknown	
not suitable	0
rarely helpful	1
sometimes helpful	2
often helpful	3
mostly helpful	4

Table 30: possible answers to suitability of detection methods and associated rating value.

The answers of the professional inspectors are shown in Table 31. The average rating is computed based only on the answers of the inspectors with an opinion on the different methods, i.e. inspectors answering "unknown" were not taken into account for the determination of the average rating.

	Number of inspectors without opinion	Number of inspectors with opinion	average rating
Surface cleaning	0	23	3.4
Adjustment of lighting	0	23	3.5
Magnification	2	21	2.6
Tap test	1	22	3.1
Penetrant method	10	13	1.0

Table 31: Suitability of methods for improvement of damage detectability.

Most important are the adjustment of lighting and surface cleaning. Also the tap test can often improve detection results. Magnification is less important but according to the inspectors sometimes / often helpful.

The penetrant method is not used for composite structures and can, if at all, only rarely support damage detection. Two inspectors added one further method each: "using polarised light" and "applying load". Those two inspectors rated their suitability by "often helpful".

Inspection 10

The tenth inspection was carried out at the Lufthansa Technik site in Hamburg with six professional maintenance staff. Each person was given a time of 20 minutes to find as may damages as possible on one of the panels. Both panels were cleaned from dirt. There were no restrictions regarding the distance to the panel or the inspection aids to be used. The inspectors were asked to bring their standard equipment. Inspecting the backside of the panel was not allowed, although normally both sides of a structure are inspected, if possible. During these inspections the following general observations were made:

- The **lighting** of the inspection site was very good, much better than in the aircraft hangar, where inspection No. 2 was carried out. The inspection site for inspection No. 10 is used by Lufthansa to inspect composite parts of aircraft before and after maintenance.
- The primary means to find damages is to look for dents. Most damage locations were identified by **visual search**. The inspectors looked carefully from all sides and from various angles onto the panel.
- Inspectors run with their hands over the surface of the panel, to feel dents. With the **combination of tactile and visual methods** it is possible to find some of the spread-out flat dents caused by the blunt impacts.
- Inspectors make extensive use of the **tap test**, in order to find delaminations, which are not accompanied by a visible dent.
- Two of the six inspectors used a **flashlight**.
- None of the inspectors used a magnification glass.

Detailed results were recorded onto a grid sketch by the inspectors. Since two of the six inspectors worked together, five of these detailed records have been produced, three of them for panel 1 (blue / matt) and two for panel 2 (red / matt). The detailed results are shown in Table 32 and Table 33.

Inspector No. 3 provides striking evidence of the damage detection capabilities of experienced maintenance personnel. He not only noted the very faint impact locations No. 14 and 16 with no signs of internal damage in the US-scan, he also found five of the six flat dents caused by the blunt impacts, missing only the smallest one at location No. 11. He also missed impact No. 15, which produced only very small internal damage, easy to miss even in the US-scan. On the other hand, an inexperienced inspector might not be able to find more damages than an average untrained person, as the results of inspector No. 4 show.

The flat dents of the blunt impacts are easy to miss even for professional maintenance personnel. Only damage No. 13 was found by all of them, but this is due to clearly visible cracks on the surface of the panel. These cracks are not present at locations 1-3 and 11 & 12.

Inspector		Panel	Damage No.																			
No.	Experience		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1 & 2	> 2 years	blue / matt				1	x	x	x	x	x	x		x	x	1			x	x	x	x
3	> 2 years	blue / matt	x	x	x	1	x	x	x	x	x	x		x	x	x1		x	x	x	x	x
4	< 2 years	blue / matt				1		x	x			x			x	1				x	x	x
5	> 2 years	red / matt			x	1		x	x	x	x	x			x	x1	x	x	x	x	x	x
6	< 2 years	red / matt	x			1		x	x	x	x	x	x		x	1	x	x	x	x	x	x

1 no damage in US scan
x damage found
(grey) blunt impact

Table 32: Detailed results of inspection No. 10

Inspector		Panel	total damages	damages found	damages missed	false positives
No.	Experience					
1 & 2	> 2 years	blue / matt	18	12	6	0
3	> 2 years	blue / matt	18	16	2	1
4	< 2 years	blue / matt	18	7	11	3
5	> 2 years	red / matt	18	13	5	1
6	< 2 years	red / matt	18	14	4	9

Table 33: Results summary of inspection No. 10.

The established alternative inspection method for composite structures is the tap test, which allows detecting not only the presence of internal delaminations but can also give indication regarding their size. This has been demonstrated by experienced aircraft maintenance personnel. A tactile test (running with hands over the panel surface) is a means to strengthen the damage impression. With the combination of these means it was possible for an experienced inspector to find even very small damages in one of the structures.

6 Outputs and Results

A survey of the literature related to visual inspection of composite structures formed the basis on which the present work has been developed.

Two composite stringer-stiffened panels were built. The panel design and material system is comparable to a possible future fuselage structure of an aircraft certified according to CS 25. The structures were painted according to aeronautic standards. Twenty damages were introduced into each of the panels.

A methodology for the conduction of a visual inspection study for composite structures has been developed, which comprises a plan for the introduction of damages of different sizes, an inspection plan, questionnaires and evaluation guidelines.

Inspection results of ten visual inspections with a total of 112 inspectors were recorded. These results have been transferred from the questionnaires to an Excel database, translating the answers from German to English where necessary.

The inspection results were evaluated to show the dependency of damage detectability on inspection parameters. Implications for subsequent research and recommendations for carrying out visual inspections are developed from the findings of this study.

7 Outcomes

The aims and objectives of the study were the determination of the influence of inspection parameters and the identification of damage metrics for composite structures. The influence of inspection parameters on the detectability of damages has been determined by ten visual inspections involving almost 100 inspectors producing 112 inspection records. These inspection records have been used to determine not only the influence of

- illumination
- cleanliness
- inspection angle
- surface colour / finish

on the detectability of damage. By collecting anonymous personal data of the inspectors it was also possible to evaluate the influence of

- professional qualification
- visual capability
- age
- gender

of the inspectors on inspection results.

While the investigated ranges of inspection angles and cleanliness only have a minor influence on inspection results, illumination is an important parameter, when it comes to the detection of small dents. Illumination and inspection angle are closely related. Due to the limited amount of surface colour / finish combinations investigated in this study, no definite statement can be made on the influence of these two variables.

This study confirmed that there are no ideal conditions allowing optimum detection results for all kinds of damage. A seemingly “improved” inspection parameter can for a specific damage lead to decreased detectability. This has been observed for the inspection parameters illumination and cleanliness, and might be explained by less distraction due to grid markings near that specific damage.

While impacts from small diameter impactors cause a visible dent, which is not difficult to detect by a careful visual inspection, the flat, spread out dents from blunt impactors are easily overlooked. Comparing the internal damage as it was detected by ultrasonic scanning for impact energies of 40 – 75 Joule, the damage areas caused by the blunt impacts were in the same category as the damage areas caused by 1-inch diameter impactors of the same energy.

Damage metrics corresponding to alternative inspection methods have been investigated to improve the detectability of internal damages of composite structures. Firstly, professional maintenance staff was interviewed for their experience regarding alternative damage metrics / inspection methods, secondly an inspection was carried out at the end of the study involving six professional aircraft maintenance technicians. It turned out that the primary damage metric is the visual impression of the permanent indentation. When complemented with the tap test it is possible for a skilled inspector, to detect even small internal damages and flat, spread out dents caused by blunt impacts.

While the methodology for carrying out the inspection program has been slightly modified during the course of the project, the procedures for the manufacturing of structures, for introducing the damages and for evaluation of the inspection results have been carried out as planned. The aims and objectives of the studies have been met. Further studies will be necessary to investigate an even wider range of damages, structures and inspection parameters. These studies can build up on this study and greatly benefit of the presented methodology, because the developed questionnaires, the inspection plan and the evaluation of inspection results are adaptable to different damages, structures and inspection parameters in a straightforward way.

To the knowledge of the author this is one of the first studies on the visual detectability of damage in composite structures, which has been conducted with the intention of making its results publicly available. This study extends the work of Erhart et al. [18] in that it deals with a wider range of damages and a wider range of inspection parameters. Of course OEMs also have conducted studies similar to this one, but their data is not publicly available. Therefore this work is considered an important step to sensitize the aeronautic industry other than the large OEMs to the problem of damage detection in composite structures, in conjunction with the problem of blunt impact.

8 Conclusions

Two nominally equal structures, with nominally equal impact damages have been manufactured, so inspection results for both structures could be compared to each other. Both structures could be exposed to different inspection conditions, thus enabling the determination of influences of single inspection parameters on detectability of damages.

Fabrication of composite stringer stiffened structures is a manual process, which inevitably results in small differences in mechanical properties. The impact damages on both structures were therefore not exactly equal, but four visual inspections with 35 inspectors showed that inspection results for both structures were similar enough for the purpose of this study.

The selection of damage sizes was very suitable for this kind of study. The range reached from damages, which were almost invisible up to clearly visible damages, for which the probability of detection was almost not affected by the inspection conditions. In between these, damages of different visual appearance could be used to evaluate effects of different inspection conditions.

Studying the effect of distraction by markings on the panel was interesting as well. One dent was located near a black grid marking on the glossy, red panel. At good lighting and cleanliness conditions the strong contrast between the grid markings and the panel colour inhibited the detection of this damage. When illumination was decreased or the amount of dirt was increased, the contrast between markings and panel colour decreased, facilitating the detection of the small dent. This shows that sometimes even seemingly worse inspection conditions can lead to improved damage detectability.

The visual inspections showed that variation of a single inspection parameter such as cleanliness, inspection angle and colour / finish combination did not have a large effect on inspection results. Illumination was the parameter with the greatest effect on damage detectability.

Influences of colour / finish, inspection angle and lighting are closely related to each other. The influences of colour / finish and lighting are related, because the appearance of an object is determined by both, the colour and reflectance of the object and the colour (i.e. wave length spectrum) of the light source. For example, a green object will appear to be black under red lighting. Furthermore, the amount of light reflected from an object towards the eye of an observer is not only determined by the amount of illumination. It also depends on

- the illumination angle between the surface normal of the object and the direction of the lighting,
- the visual angle between the surface normal of the object and the line of vision from the observer's eye towards the object.

From the limited amount of data collected in this study it seems that a dent depth of 0.06 mm ensures a POD of at least 60% and a dent depth of 0.12 mm ensures a POD of at least 80% for average inspection conditions as defined in this study. Although the measurement of dent depths was carried out carefully, it is not free from imprecision, since the undamaged panel surface was not perfectly plane in the direction of the cylinder axis. While damages caused by the 320 mm impactor correspond to a significantly smaller dent depth than equally sized damages caused by a 1-inch impactor, a clear correlation between damage size and indentation depth has not been found.

For the inspection of airframe structures a direct link between the severity of damage and the probability of its detection is desirable. While this study provides data on the probability of damage detection for different damages under variable conditions, an assessment of damage severity could not be provided. Damage severity can be defined in different ways. While this study simply used the overlapped size of impact-induced delaminations and skin-stringer separation as a measure for damage severity, a more profound assessment of the threat of specific damage would have to take damage tolerance data such as the fatigue life and the residual strength of the damaged structure into account. Furthermore the specific loading of an airframe part plays a role: delaminations and skin-stringer separations are much less dangerous under tensile loading than under compressive loading. This is reflected by different allowable damage limits for different areas of an airframe structure.

By evaluating questionnaires filled out by each inspector it was also possible to investigate the influence of certain person-related parameters such as visual capability, age, gender and professional qualification on inspection results. Surprisingly, visual capability did not have a large influence on the performance of an inspector. Professional qualification is an important influence factor, as is the age of the inspector. There is also an indication of an influence of the inspectors' gender on inspection results, but unfortunately there were only a small number of female participants, especially in the group of professional inspectors, so this result is not backed with sufficient data for definite conclusions yet.

At the end of the study, professional maintenance personnel from Lufthansa Technik demonstrated the effectiveness of visual inspection in combination with the tap test by finding even smallest damages.

9 Implications

- Investigations of larger structures under blunt impacts should be performed.

  Using 'reasonable' similar energy levels when impacting 'representative' structure, a larger diameter impactor (320 mm) generates less obvious visible damage (as may be expected) than the typical classic impactor (25.4 mm). This may be important because the 'less obvious' impact damage may not be detected, thus not prompting the appropriate subsequent NDI. For this statistically insignificant investigation (due to budget etc), and relatively small damages, this would typically be of limited significance for larger CS25 structures because the dimensions and form of the damage should be managed within the bounds of the BVID and ADL dimensions, i.e. damages which should maintain ultimate load capability for the life of the aircraft. However, the importance of this outcome may be that a potentially more significant damage may exist, undetected as a result of a non-typical damage metric following such a relatively blunt impact, in a structure of higher criticality with less margin. There may also be further implications for multiple blunt impacts which may go undetected and which could accumulate multiple cases of damage.

  In the future, details of structures with special risks should be taken into account. Realistic impacts could be introduced by ground vehicles. The structures should be much larger than the panels investigated in this study, in order to provide realistic boundary conditions for a typical blunt impact.

  Currently, blunt impact from ground vehicles would fall into category 5 damage [6] ("Severe damage due to anomalous ground or flight events"). The current requirement for this type of damage is that it is immediately obvious, so it does not have to be considered in design. The obviousness of the damage alone should ensure that it does not represent a safety risk. Further studies should investigate, if composite designs fulfil the requirements for category 5 damage. Alternatively blunt impact could be considered in design of composite structures, moving it from damage category 5 to a lower category.

- An important aspect of this study was the careful separation of environmental influences from physiological parameters of inspectors (sex, age, vision) and training (professional qualification).

  It became apparent during the study that the size of the inspectors should have been recorded. Not only did the average inspection angle differ slightly with different inspector sizes. Taller inspectors also had a wider range of inspection angles available, because a fixed standing position was deliberately not enforced during the inspection. Otherwise inspection conditions would have been too unrealistic.

- Evaluate different material systems and thickness of laminates.

  This study was focussed on a typical fuselage structure, implying a certain material system, a skin thickness of around 2 mm and a certain spacing / stiffness of the underlying stringers and frames. In further research transferability of the results of this study to different structural parts could be investigated, involving different laminate thickness and different material systems.

10 Recommendations

Based on the previously described outcomes and conclusions of the study the following recommendations can be given regarding the visual inspection of composite structures.

- Use standard visual inspection for detection of damages from small diameter impactors.

  In this study, care was taken, to produce a maximum of internal damage at a minimum of visibility. With the standard 1-inch impactor it has not been possible to produce internal damage that did not leave a visible dent on the painted, impacted surface behind. Before the formation of internal damage started, the paint coating was affected. The marks on the paint coating were very faint and are easy to miss, though. On the other hand, the smallest dents producing internal damage were visible to the naked eye, even on unclean surfaces and at unfavourable illumination conditions.

- Use the established procedure (combination of visual inspection, "feeling damages" by running with hands over the structure, and tap test) for detailed inspection of composite structures.

  It has been demonstrated by professional maintenance personnel that an experienced inspector can even find locations of blunt impacts, if internal damage is present.

- Make sure to have sufficient lighting available for visual inspections.

  Illumination has been found to have the largest influence on inspection results of amateur inspectors in this study. At a lighting of 1100 lux under combined artificial lighting and natural daylight the best inspection results have been obtained. Whether even more lighting further improves inspection results has not been tested. If possible, provide for tubular fluorescent lamps, because reflections of linear light sources greatly facilitate the detection of flat, spread-out dents on glossy surfaces.

- Carry out inspections under different environments.

  Different damages require different inspection conditions for better detection results. If optimal lighting conditions are not available, sometimes even reduced illumination (e.g. from 400 lux down to 200 lux) or a dirt cover can improve detectability of certain damages.

11 References

11.1 Glossary and list of abbreviations

AANC	Aging Aircraft Nondestructive Inspection Validation Center
AC	Advisory circular, issued by the FAA, contains aviation regulations and policies (e.g. AC 43-204)
ADL	Allowable damage limit
BA	British Airways
BAC	Colour matching system
BVID	Barely visible impact damage
CAA	Civil Aviation Authority, name for the national body governing civil aviation in a number of countries
CDT	Critical damage threshold. Damages below CDT and above ADL must sustain limit load until found by maintenance practices.
CFRP	Carbon fibre reinforced plastic
CLT	Classical laminate theory, can be used to predict the performance laminates from the properties of its plies.
Colour rendering	See definition in section 3.6.1
CS	Certification Specifications, issued by EASA
Damage tolerance	See definition in section 1.
DET	Detailed visual inspection, see definition in section 3.2.
Disbond	Separation of two adhesively bonded load carrying elements, such as skin-stringer disbond in a stiffened panel
Discrete source event	High energy impact load, which is known to the pilot if it occurs during service.
DLR	German Aerospace Center
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FOD	Foreign object damage
Glare	See definition in section 3.6.1
GVI	General visual inspection, see definition in section 3.2.
HFAMI	Human Factors in Aviation Maintenance & Inspection Research Program
IES	Illuminating Engineering Society

Illuminance	Intensity of the incident light, wavelength-weighted by the luminosity function to correlate with human brightness perception. Measured in lux.
Light level	See Illuminance
LL	Limit load. Maximum load per fleet lifetime.
Low velocity impact	See definition in section 3.1.2
NDE	Non destructive evaluation
NDI	Non destructive inspection
NDT	Non desctructive testing
NVID	non visible impact damage
POD	Probability of detection
Prepreg	Composite fibres pre-impregnated with resin. Composite laminates can be formed by stacking and curing layers of prepreg.
RAL	Reichsausschuß für Lieferbedingungen und Gütesicherung. Colour matching system.
Reflectance	Fraction of incident radiation reflected by a surface
Reflectivity	See reflectance.
RGB	Colour model, uses red, green and blue as primary colours
SHM	Structural health monitoring
Special detailed visual inspection	See definition in section 3.2
UD	Uni-directional
UL	Ultimate load. Typically UL = 1.5 * LL
US-scan	Ultrasonic scan, when used on composite laminates the US-scan typically reveals the location of internal delaminations and disbonds.
VIRP	Visual Inspection Research Project
Visual acuity	See definition in section 3.6.3
Visual inspection	See definition in section 3.2
Walkaround inspection	See definition in section 3.2

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Appendixes

Appendix A – Questionnaires for inspectors

Schadensorte Struktur A

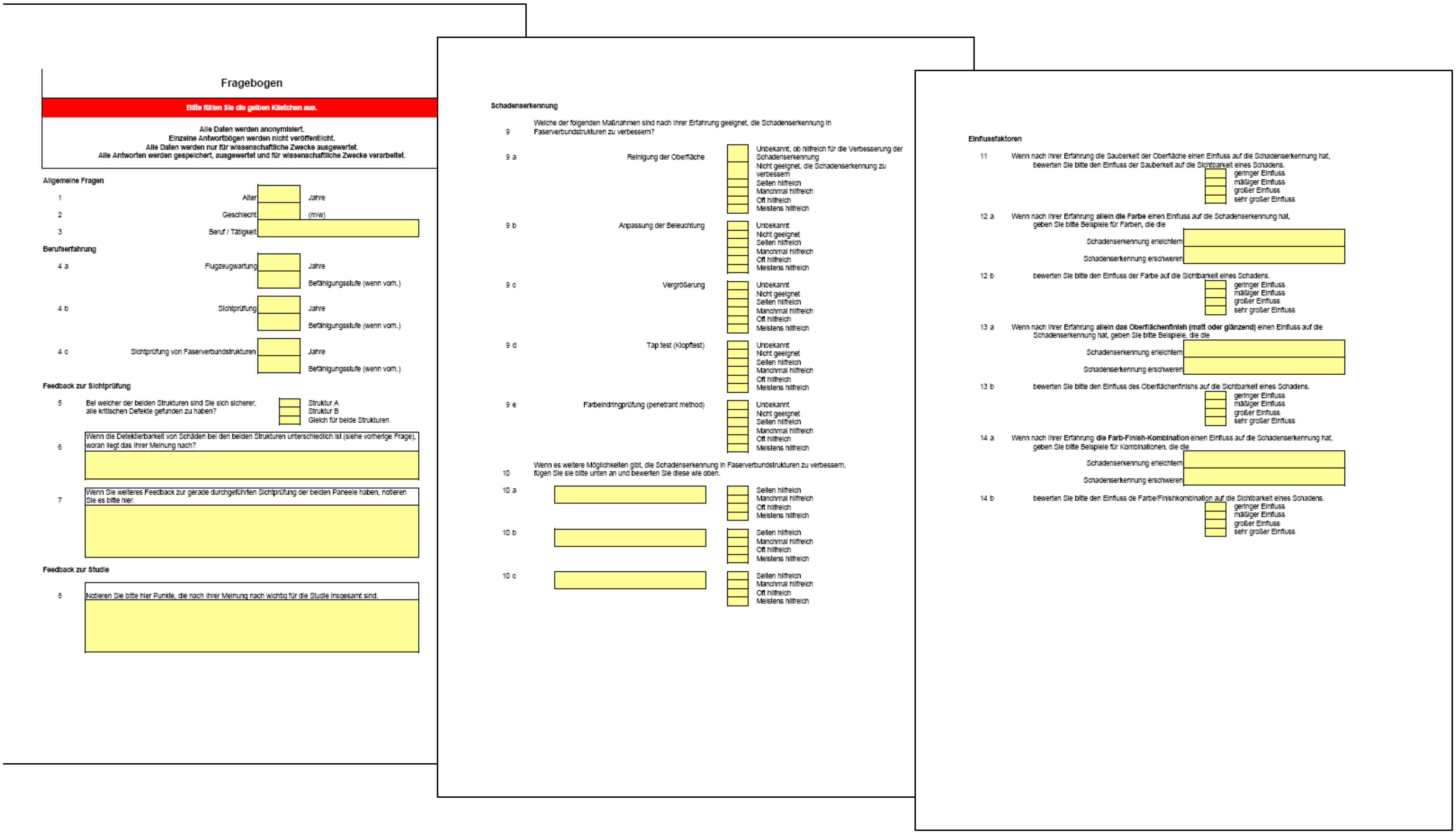
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
1																					1
2																					2
3																					3
4																					4
5																					5
6																					6
7																					7
8																					8
9																					9
10																					10
11																					11
12																					12
13																					13
14																					14
15																					15
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	

No	Schadensbeschreibung	No	Schadensbeschreibung
1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	

Schadensorte Struktur B

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
1																					1
2																					2
3																					3
4																					4
5																					5
6																					6
7																					7
8																					8
9																					9
10																					10
11																					11
12																					12
13																					13
14																					14
15																					15
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	

No	Schadensbeschreibung	No	Schadensbeschreibung
1		11	
2		12	
3		13	
4		14	
5		15	
6		16	
7		17	
8		18	
9		19	
10		20	



Fragebogen

Bitte füllen Sie die gelben Kästchen aus.

Alle Daten werden anonymisiert.
Einzelne Antwortbögen werden nicht veröffentlicht.
Alle Daten werden nur für wissenschaftliche Zwecke ausgewertet.
Alle Antworten werden gespeichert, ausgewertet und für wissenschaftliche Zwecke verarbeitet.

Allgemeine Fragen

1 Alter — Jahre
2 Geschlecht — (m/w)
3 Beruf / Tätigkeit

Berufserfahrung

4 a Flugzeugwartung — Jahre; Befähigungsstufe (wenn vorh.)
4 b Sichtprüfung — Jahre; Befähigungsstufe (wenn vorh.)
4 c Sichtprüfung von Faserverbundstrukturen — Jahre; Befähigungsstufe (wenn vorh.)

Feedback zur Sichtprüfung

5 Bei welcher der beiden Strukturen sind Sie sich sicherer, alle kritischen Defekte gefunden zu haben?
Struktur A
Struktur B
Gleich für beide Strukturen

6 Wenn die Detektierbarkeit von Schäden bei den beiden Strukturen unterschiedlich ist (siehe vorherige Frage), woran liegt das Ihrer Meinung nach?

7 Wenn Sie weiteres Feedback zur gerade durchgeführten Sichtprüfung der beiden Paneele haben, notieren Sie es bitte hier.

Feedback zur Studie

8 Notieren Sie bitte hier Punkte, die nach Ihrer Meinung nach wichtig für die Studie insgesamt sind.

Schadenserkennung

9 Welche der folgenden Maßnahmen sind nach Ihrer Erfahrung geeignet, die Schadenserkennung in Faserverbundstrukturen zu verbessern?

9 a Reinigung der Oberfläche
Unbekannt, ob hilfreich für die Verbesserung der Schadenserkennung
Nicht geeignet, die Schadenserkennung zu verbessern
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

9 b Anpassung der Beleuchtung
Unbekannt
Nicht geeignet
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

9 c Vergrößerung
Unbekannt
Nicht geeignet
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

9 d Tap test (Klopftest)
Unbekannt
Nicht geeignet
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

9 e Farbeindringprüfung (penetrant method)
Unbekannt
Nicht geeignet
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

10 Wenn es weitere Möglichkeiten gibt, die Schadenserkennung in Faserverbundstrukturen zu verbessern, fügen Sie sie bitte unten an und bewerten Sie diese wie oben.

10 a
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

10 b
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

10 c
Selten hilfreich
Manchmal hilfreich
Oft hilfreich
Meistens hilfreich

Einflussfaktoren

11 Wenn nach Ihrer Erfahrung die Sauberkeit der Oberfläche einen Einfluss auf die Schadenserkennung hat, bewerten Sie bitte den Einfluss der Sauberkeit auf die Sichtbarkeit eines Schadens.
geringer Einfluss
mäßiger Einfluss
großer Einfluss
sehr großer Einfluss

12 a Wenn nach Ihrer Erfahrung **allein die Farbe** einen Einfluss auf die Schadenserkennung hat, geben Sie bitte Beispiele für Farben, die die
Schadenserkennung erleichtern
Schadenserkennung erschweren

12 b bewerten Sie bitte den Einfluss der Farbe auf die Sichtbarkeit eines Schadens.
geringer Einfluss
mäßiger Einfluss
großer Einfluss
sehr großer Einfluss

13 a Wenn nach Ihrer Erfahrung **allein das Oberflächenfinish (matt oder glänzend)** einen Einfluss auf die Schadenserkennung hat, geben Sie bitte Beispiele, die die
Schadenserkennung erleichtern
Schadenserkennung erschweren

13 b bewerten Sie bitte den Einfluss des Oberflächenfinishs auf die Sichtbarkeit eines Schadens.
geringer Einfluss
mäßiger Einfluss
großer Einfluss
sehr großer Einfluss

14 a Wenn nach Ihrer Erfahrung **die Farb-Finish-Kombination** einen Einfluss auf die Schadenserkennung hat, geben Sie bitte Beispiele für Kombinationen, die die
Schadenserkennung erleichtern
Schadenserkennung erschweren

14 b bewerten Sie bitte den Einfluss de Farbe/Finishkombination auf die Sichtbarkeit eines Schadens.
geringer Einfluss
mäßiger Einfluss
großer Einfluss
sehr großer Einfluss

igure 70: Questionnaire for inspectors from airlines. Amateur inspectors only filled out page 1.

Appendix B – Questionnaire for airlines

Visual inspection of composite airframe structures

Questionnaire
Inspection procedures and inspection environment

This questionnaire has been designed for a research project on the visual inspection of airframe structures of large category aircraft (Part 25). The special focus of the study is the detection of damage in composite structures.

Your answers to the questions below will help in defining the inspection conditions for the study

Inspector personnel

How many staff are performing visual inspections of airframe structures in your organisation (by level of c

	Number of staff with competence in airframe inspection	Number of staff with competence in inspection of composite structures.
Trainee		
Limited		
Level 1		
Level 2		
Level 3		

Inspection procedures for aircraft types

If you have more than one type of large aeroplane (Part 25, large category aircraft) in your organisation, are there different procedures for different aircraft regarding visual inspection of aircraft structure? If yes, please briefly list the main differences.

	AC type 1	AC type 2	AC type 3	AC type 4
Please list typical aircraft models (e.g. A320, B747, ...)				
Briefly describe procedures for visual inspections, which differ between AC types.				

Inspection types

Please list inspection types and inspection intervals for inspections, that involve visual inspection of airframe structures

Inspection type	Inspection type 1	Inspection type 2	Inspection type 3	Inspection type 4
Name (E.g. walk-around, A-Check, ...)	walk-around			
Inspection interval (daily, monthly, every two years, ...)				

Figure 71: Questionnaire for airlines, page 1 of 3.

Inspection location

Where are the different inspections typically carried out?

Inspection type	walk-around	0	0	0
Airfield				
Hangar				
Lab				

General inspection conditions

Please fill in details concerning general inspection conditions.

Inspection type	walk-around	0	0	0
Typical part or typical size of visually inspected structure				
Average distance to structure during visual inspection				
Approximate time for visual inspection				

Lighting conditions (worst cases)

Please check appropriate boxes for the worst-case lighting conditions, which are still acceptable for the different inspection types. Check more than one box per column, if you are unsure, which lighting condition may be worst case. Feel free to add lines, which better describe the worst-case lighting conditions for the different inspection types.

This question is about the lighting conditions, which are present at the initial detection of damage. Any additional illumination applied by the inspector for verification or falsification of damage is NOT to be taken into account when answering this question.

Inspection type	walk-around	0	0	0
artificial lighting in hangar				
natural daylight				
twilight				
darkness + flashlight				

Figure 72: Questionnaire for airlines, page 2 of 3.

Surface condition (worst cases)

Please check appropriate boxes for the worst-case surface conditions, which are still acceptable for the different inspection types. Check more than one box per column, if you are unsure, which surface condition may be worst case. Feel free to add lines, which better describe the worst-case surface conditions for the different inspection types.

This question is about the surface conditions, which are present at the initial detection of damage. Any surface cleaning applied by the inspector for verification or falsification of damage is NOT to be taken into account when answering this question.

Inspection type	walk-around	0	0	0
Special surface cleaning applied for inspection				
Shortly after regular washing				
About half-way between 2 washings				
Shortly before aircraft would have to be washed)				

Inspection aids

Please check boxes for the inspection aids used in visual inspection of the aircraft structure. If appropriate, add further inspection aids.

Inspection type	walk-around	0	0	0
Cherry picker				
Flashlight				
Magnification glass				
Mirror				

Special procedures for visual inspection of composites

Are there any special procedures for visual inspection of composite structures (as opposed to metallic structures)? If yes, please briefly describe them.

Inspection type	walk-around	0	0	0
Special procedures for composite structures				

Further remarks not covered by previous questions

Please write down anything else regarding visual inspection of aircraft, that you feel is important and which is missed by the above questions.

Figure 73: Questionnaire for airlines, page 3 of 3.

Appendix C – Inspection types according to CA 43-204

Definition of walkaround inspection [17]

“The walkaround inspection is a general check conducted from ground level to detect discrepancies and to determine general condition and security.

NOTE: This is the only one of the four inspections that may be accomplished by either flight or maintenance personnel. The focus and perspective will vary based on the relation of the inspection to flight or maintenance operations.

(1) Basis for Inspection. Most maintenance instructions mandate walkaround inspections on a periodic basis. The overall purpose is to serve as a quick check to determine if detectable inconsistencies exist which would affect the performance of the aircraft.

(2) Preparation for the Inspection. Aircraft history should be used to gain information useful in inspecting the aircraft (e.g., are there recurring problems or have there been hard landings?). In addition the aircraft should be clean enough for an effective inspection to take place, the necessary tools and equipment should be available (e.g., flashlight, rag, notebook), and other aids, tools, and procedures may be necessary […].

(3) Implementation. […]

Examine according to what the standard condition is. (Question the existence of any unusual condition.) Look for anything different from one side to another. (It is important to shake, push, pull, listen, and feel when possible.) Run your hand over skin junction areas or composite surfaces. […]

Are there major dents or intrusions in the skin? Look for evidence of flexing parts, waves in the skin, weave or bubble in fiber glass or composite components, eroded fairings, and bulging or flattened seals. Are any external components bent? Is there evidence of damage? […]”

Definition of general visual inspection (GVI) [17]:

“A general inspection is made of an exterior with selected hatches and openings open or an interior, when called for, to detect damage, failure, or irregularity.

(1) Basis for Inspection. When a specific problem is suspected, the general inspection is carried out to identify, if possible, the difficulty. General inspections are also routinely used when panels are open for normal maintenance.

(2) Preparation for the Inspection. Ensure cleanliness of the aircraft. The necessary tools and equipment required may include flashlight, mirror, notebook, droplight, rolling stool, tools for removal of panels, ladders stands, or platforms. Other aids such as jacking of the aircraft may or may not be discretionary; knowledge of a specific aircraft may be essential; and common problems may require information, even if not on the inspection card.

(3) Implementation. General looking is not enough. As the inspector, you should continually ask "What is wrong with this picture?" Be inquisitive. Question whether you have seen this before. Move, shake, pull, twist, and push all parts possible. Apply weight to load bearing components. Compare one side to the other if applicable. Be aware of other systems in the inspection area. Look for abnormalities in the area, even if not related to this inspection. Adjusting the source of illumination, view items under inspection from different angles. […] Check condition and security of load and stress points. […] Look for loose or missing fasteners, use of proper sealants, noticeable cracks, indications of corrosion, and debris in closed areas. […] Observe rivets for damage. Look for smoked rivets and discoloration of paint. (Localized chipping of paint, cracked paint on sealant, or fretting corrosion are indicative of movement.) […]”

Definition of detailed visual inspection [17]:

“A detailed visual inspection is an intensive visual examination of a specific area, system, or assembly to detect damage failure or irregularity. Available inspection aids should be used. Surface preparation and elaborate access procedures may be required.

(1) Basis for Inspection. A detailed inspection is called for when a specific problem is suspected and the general inspection dictates additional inspection. Or, if the inspection is otherwise mandated, a detailed visual inspection is carried out to identify, if possible, the difficulty. Detailed inspections are also periodically called for on damage-tolerant aircraft to ensure the airworthiness of the critical structure.

(2) Preparation for the Inspection. Tools and equipment will vary, but may include a prism, supplemental lighting, mirror, magnifying glass, flashlight, dye penetrant, notebook, droplight,

rolling stool, and standard and specialized hand tools. Documentation required is specific to the procedures outlined by steps on work cards. Also review the SBs, ADS, aircraft history, and accident reports. Other aids such as knowledge of a specific aircraft and common problems may be essential even if not on the inspection card.

(3) Implementation. The reasoning that originally dictated the inspection should be considered. If it was because some corrosion was found, then a more in-depth examination is required. If the inspection is in response to an AD for a crack, carefully inspect the surrounding area to rule out additional occurrences or stress induced because of the crack. In a detailed inspection, you are usually searching for failure, damage, or irregularity. Check the condition and security of lockwires and the load and stress points. Look for fretting corrosion. Observe proximity of one part to another. Look for loose or missing fasteners, use of proper sealants, obvious cracks, indications of corrosion, and debris in closed areas. […]"

Definition of special detailed visual inspection [17]:

"A special detailed inspection is an intensive examination of a specific item, installation, or assembly to detect damage, failure, or irregularity. It is likely to make use of specialized techniques and equipment. Intricate disassembly and cleaning may be required.

(1) Basis for Inspection. As systems and structures have become more complex, special inspections using extraordinary techniques and equipment have evolved to ensure airworthiness. These are covered in instructions for special detailed inspections. Special detailed inspections are also periodically called for on damage-tolerant aircraft to ensure the airworthiness of the critical structure. This level of inspection may also be invoked based on recommendations from a lower level.

(2) Preparation for the Inspection. Tools and equipment will vary but may include a flashlight, mirror, video borescopes, special aids and tooling, Dremel, rolling stool, image enhancement and recording devices, supplemental lighting, magnifying glass, dye penetrant, notebook, and standard and specialized hand tools. Documentation required is specific to the procedures outlined by steps on work cards; review of SBs, ADS, and aircraft history; and reference to the original or referred discrepancy, if any. Another aid is the discrepancy report from the contracting NDI company.

(3) Implementation. Procedures are defined in detail by the specific instruction procedure, but they are limited to the scope of visual inspection. The locations to be inspected will vary greatly, but may include portions of the aircraft that are inaccessible without major disassembly, such as the interior surface of the wing skin, pylon butt joints, and lap joints. In some of these cases the objective of the inspection may be best served both practically and economically through the use of NDI techniques."

Appendix D – Light characteristics

From the CAA, Safety Regulation Group, Aviation maintenance and human factors, 2003 [20]:

"Four fundamental light characteristics (i.e., light level, colour rendering, glare and reflectance), the principles of specialised lighting, and the basic requirements of lighting design need to be considered in relation to aircraft inspection.

Light Level

The recommended illumination depends upon the type of task and whether the visual task is of high or low contrast. General lighting requirements for different tasks can be found in Eastman Kodak (1983) [21] and Illuminating Engineering Society (IES) [22], [23]. Vision can be improved by increasing the lighting level, but only up to a point, as the law of diminishing returns operates. Also, increased illumination could result in increased glare. Older persons are more affected by the glare of reflected light than younger people, and inspectors are often senior personnel within a maintenance organisation. According to IES (1987), direct, focused lighting is recommended for general lighting in aircraft hangars. Inspection of aircraft takes place in an environment where reflections from aeroplane structures can cause glare so that low brightness luminaries should be installed. Often, additional task lighting will be necessary when internal work, or shadowed parts around the aircraft, result in low illumination levels.

Table 34 presents the required illumination levels for aircraft maintenance and inspection tasks (IES, 1987). Generally, most maintenance tasks require between 750 lux and 1000 lux, although more detailed maintenance tasks may require additional illumination. General line inspections (e.g., easily noticeable dents) may only require 500 lux; however, most inspection tasks demand much higher levels. From the site observations of actual defects, it is apparent that many difficult inspection tasks may require illumination levels up to or exceeding 5000 lux. Based upon the current IES standards, it is recommended that the ambient light level in a maintenance hangar be at least 750 lux in order to perform pre- and post-maintenance/inspection operations and some general maintenance/inspection tasks without the necessity for additional task lighting. Furthermore, adequate illumination levels may be obtained in a majority of inspection tasks and many maintenance tasks through the utilisation of task lighting.

TASK	lux
Pre-Post-maintenance and inspection	300-750
Maintenance	750-1000
Inspection	
Ordinary	500
Detailed	1000
Fine	2000

Table 34: Levels of Illumination Required in Aircraft Inspection/Maintenance (IES, 1987)

Colour Rendering

Colour rendering is the degree to which the perceived colours of an object illuminated by various artificial light sources match the perceived colours of the same object when illuminated by a standard light source (i.e., daylight). The colour rendering of task lighting is important for inspection because "change in colour" of sheet metal is often used as a clue to detect corrosion, wear or excessive heating. The difference in the spectral characteristics of daylight, incandescent lamps, fluorescent lamps, etc., have a large effect on colour rendering. Such effects are described in detail in IES (1984). Table 35 presents some of the commonly used lighting sources and their characteristics (adapted from Eastman Kodak, 1983).

TYPE OF LIGHT SOURCE	COLOUR	COMMENTS
Incandescent	Good	Commonly used, but prone to deterioration over time. High energy lost, but convenient and portable. Lamp life

		about 1 year.
Flourescent	Fair to good	The efficiency and colour rendering capabilities vary greatly depending upon tube type. Problems of flicker may have an annoying effect while performing inspections. Can be dangerous with rapidly cycling machinery. Lamp life 5-8 years.
Mercury vapour	Very poor to fair	Green/blue coloured light; output drops rapidly with age. Lamp life 9-12 years.
High pressure sodium lamp	Fair	Monochromatic yellow light. High efficiency lamp ranging from 90-100 lumens per watt. Lamp life 3-6 years.
Low pressure sodium lamp	Poor	Highly efficient light source but yellow in color. Lamp life 4-5 years

Table 35: Commonly Used Lighting Sources

Glare

Direct glare reduces an inspector's ability to discriminate detail and is caused when a source of light in the visual field is much brighter than the task material at the workplace. Thus, open hangar doors, roof lights, or even reflections from a white object such as the workcard can cause glare. Glare can also arise from reflections from the surrounding surfaces and can be reduced by resorting to indirect lighting. The lighting system should be designed to minimise distracting, or disabling glare, using carefully designed combinations of area lighting and task lighting.

Reflectance

Every surface reflects some portion of the light it receives as measured by the surface reflectance. High reflectance surfaces increase the effectiveness of luminaires and the directionality of the illumination. Specula, or mirror-like, reflectance should be avoided as it produces glare. Diffuse reflection, for example, from a semi-matte surface is preferred. Thus, for an aircraft hangar, it is important that the walls and floors are of high diffuse reflectance (i.e., light paint, patterned plastics) so that they help in reflecting light and distributing it uniformly. This is more critical under the wings and fuselage where there may not be adequate lighting, due to aircraft shadows. Table 36 presents recommended surface reflective values to assist in obtaining an adequately uniform visual environment.

SURFACE	REFLECTANCE
Ceiling	80-90%
Walls	40-60%
Equipment	25-45%
Floors	Not less than 40%

Table 36: Recommended Diffuse Reflective Values (Adapted from IES, 1987)

Specialised Lighting

During visual inspection of an aircraft fuselage the inspector is looking for multiple defects, including corrosion, ripples, hairline cracks in the metal components, dents in the fuselage, missing rivets, damaged rivets ("pooched," "dished" rivets), and rivet cracks.

It is possible that no one single lighting system is suitable for detecting all defects. Therefore, the use of specialised lighting systems which make each class of defect more apparent may be necessary. However, the use of special light systems implies that the area must be examined for each class of defects sequentially rather than simultaneously, which could involve time and expense. For example, the diffused nature of general illumination tends to wash out the shadows while surface grazing light relies upon showing shadows to emphasise objects that project above or below the surface. Task visibility is distinctly better for surface topography with grazing light even though a lower level of illumination is used. An example of this scenario is the inspection of the fuselage for ripples. Ripples are easier to detect using surface grazing lighting because general illumination tends to wash them out. However, normal-incidence lighting may mask important textural and colour differences. The lighting should be compatible with the visual objective regarding the form and texture of the task object. Grazing light reinforces an impression of the texture while normal incident light allows the discrimination of colour and surface, but minimises the perception of surface variations.

Design Requirements For Lighting

Literature on visual search has shown that the speed and accuracy with which the search process can be accomplished is dependent on the conspicuity of the defect which in turn is dependent on size of the defect, defect/background contrast, and lighting intensity (Drury and Fox, 1975). […]"

Appendix E – NDI methods

Penetrants

AC 43.13-1b, section 5-60 [24]

> “Penetrant inspection is used on nonporous metal and nonmetal components to find material discontinuities that are open to the surface and may not be evident to normal visual inspection. The part must be clean before performing a penetrant inspection. The basic purpose of penetrant inspection is to increase the visible contrast between a discontinuity and its background. This is accomplished by applying a liquid of high penetrating power that enters the surface opening of a discontinuity. Excess penetrant is removed and a developer material is then applied that draws the liquid from the suspected defect to reveal the discontinuity. The visual evidence of the suspected defect can then be seen either by a color contrast in normal visible white light or by fluorescence under black ultraviolet light.”

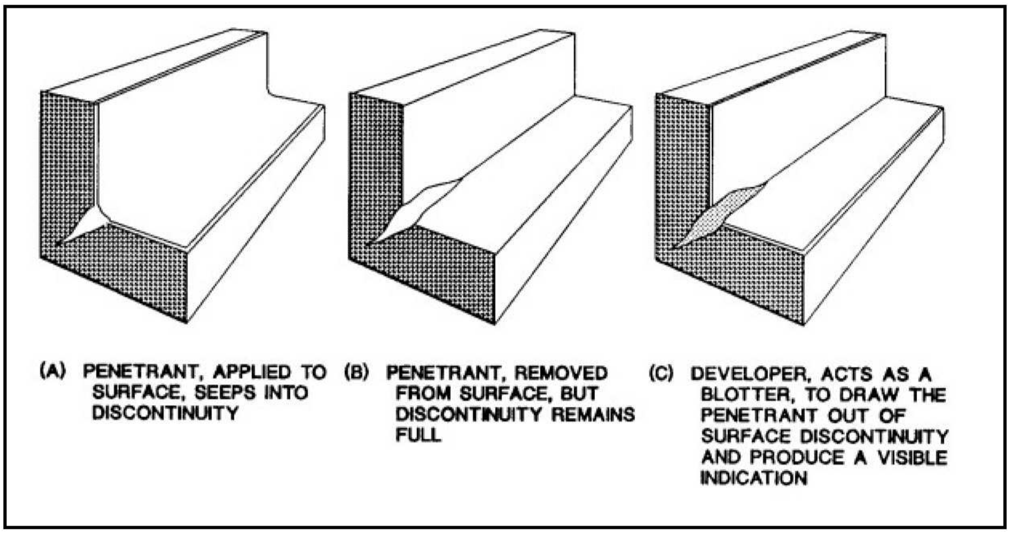


Figure 74: Penetrant method (source: AC 43.13-1b).

Radiography (X-ray) inspection

AC 43.13-1b, section 5-73 [24]

> „Radiography (x-ray) is an NDI method used to inspect material and components, using the concept of differential adsorption of penetrating radiation. Each specimen under evaluation will have differences in density, thickness, shapes, sizes, or absorption characteristics, thus absorbing different amounts of radiation. The unabsorbed radiation that passes through the part is recorded on film, fluorescent screens, or other radiation monitors. Indications of internal and external conditions will appear as variants of black/white/gray contrasts on exposed film, or variants of color on fluorescent screens.“

There are several methods of using X-ray radiography, namely the

- Film or paper radiography, where the radiation is projected onto a film, which has to be developed before NDI results can be viewed.
- Real-time radiography, where the image can be viewed immediately on a screen, with the advantage, that the object can be manipulated during the inspection.
- Computed tomography, allowing the generation of cross-sectional views instead of planar images.

Computed tomography is being used for the inspection of composite helicopter rotor blades [25].

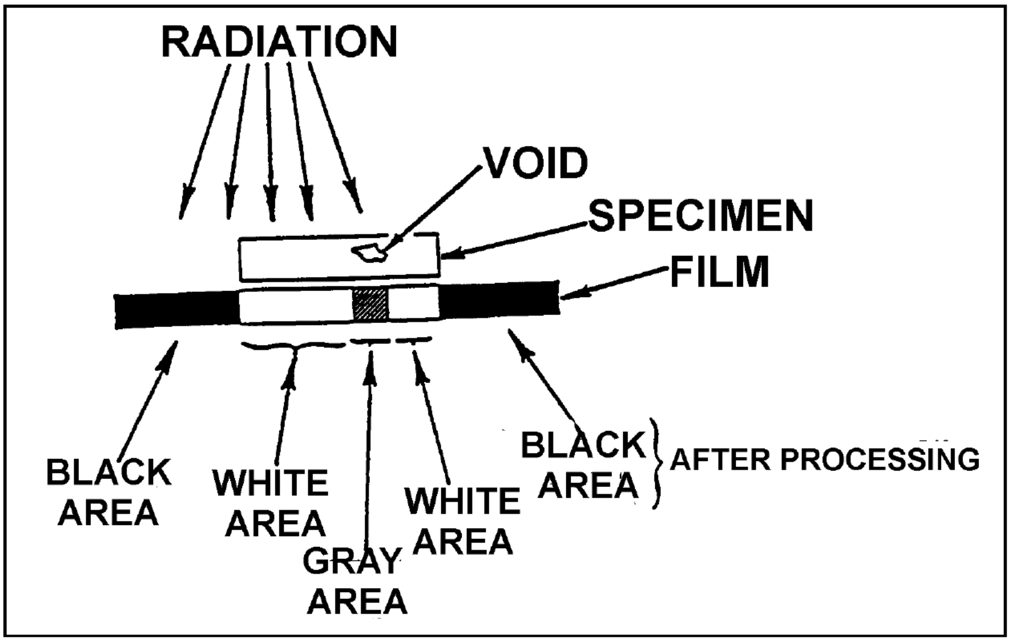


Figure 75: Radiation method (source: AC 43.13-1b).

Ultrasonic

Ultrasonic detection of faults is used widely for quality control of composite aircraft structures.

The sound waves are generated by a transducer and travel through the specimen. They are reflected by internal defects. These reflections are detected by the transducer. A so-called C-scan displays the two-dimensional distribution of internal defects over the test surface. By evaluating the time of flight of the sound waves the thickness of the part and the depth of the defects can be evaluated as well. Usually liquid or gel is used as coupling medium between the transducer and test piece to reduce impedance mismatch between coupling medium and test specimen. Under certain circumstances it is possible to go without a liquid coupling medium (air coupled ultrasonics).

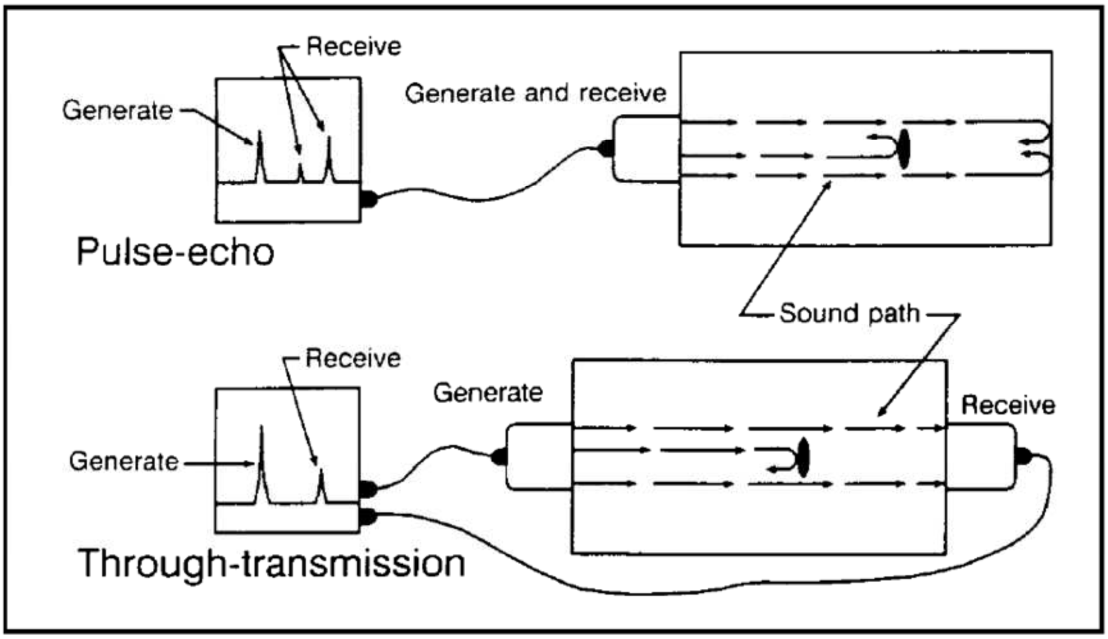


Figure 76 Pulse-echo and through-transmission ultrasonic inspection techniques (source: AC 43.13-1b).

Acoustic emission

AC 43.13-1b, section 5-112 [24]:

> „Acoustic-Emission is an NDI technique that involves the placing of acoustical-emission sensors at various locations on the aircraft structure and then applying a load or stress. The level of stress applied need not reach general yielding, nor does the stress generally need to be of a specific type. Bending stress can be applied to beamed structures, torsional stress can be applied to rotary shafts, thermal stresses can be applied with heat lamps or blankets, and pressure-induced stress can be applied to pressure-containment systems such as the aircraft fuselage. The materials emit sound and stress waves that take the form of ultrasonic pulses that can be picked up by sensors. Cracks and areas of corrosion in the stressed airframe structure emit sound waves (different frequencies for different size defects) which are registered by the sensors. These acoustic-emission bursts can be used both to locate flaws and to evaluate their rate of growth as a function of applied stress. Acoustic-emission testing has an advantage over other NDI methods in that it can detect and locate all of the activated flaws in a structure in one test. Acoustic-emission testing does not now provide the capability to size flaws, but it can greatly reduce the area required to be scanned by other NDI methods."

Thermography

AC 43.13-1b, section 5-120 [24]:

> „Thermography is an NDI technique that uses radiant electromagnetic thermal energy to detect flaws. The presence of a flaw is indicated by an abnormal temperature variant when the item is subjected to normal heating and cooling conditions inherent to the in-service life, and/or when artificially heated or cooled. The greater the material's resistance to heat flow, the more readily the flow can be identified due to temperature differences caused by the flaw."

Holography

AC 43.13-1b, section 5-127 [24]:

> "Holography is an NDI technique that uses visible light waves coupled with photographic equipment to create a three-dimensional image. The process uses two laser beams, one called a reference beam and the other called an object beam. The two laser beams are directed to an object, between beam applications the component is stressed. The beams are then compared and recorded on film, or other electronic recording medium, creating a double image. Indications of applied stresses or defects are shown as virtual images with a system of fringe lines overlaying the part. Holography is most commonly used for rapid assessment of surface flaws in composite structures."

Shearography

AC 43.13-1b, section 5-134 [24]:

„Shearography was developed for strain measurements. The process now provides a full-field video strain gauge, in real time, over large areas. It is an enhanced form of holography, which requires the part to be under stress. A laser is used for illumination of the part while under stress. The output takes the form of an image processed video display. This technique has been used effectively in locating defects, such as disbonds and delaminations, through multiple bondlines. It is capable of showing the size and shape of subsurface anomalies when the test part is properly stressed. Shearography has been developed into a useful tool for NDI. It can be used easily in a hangar environment, while meeting all laser safety concerns. Other applications include the testing of honeycomb structures, such as flaps and control surfaces. Shearography offers a great increase in the speed of inspection by allowing on-aircraft inspections of structures without their removal, as well as inspections of large areas in just seconds."

Tap testing

AC 43.13-1b, section 5-105 [24]:

"Tap testing is widely used for a quick evaluation of any accessible aircraft surface to detect the presence of delamination or debonding.

a. **The tap testing procedure** consists of lightly tapping the surface of the part with a coin, light special hammer with a maximum of 2 ounces (see figure 5-22), or any other suitable object. The acoustic response is compared with that of a known good area.

b. **A 'flat' or 'dead' response** is considered unacceptable. The acoustic response of a good part can vary dramatically with changes in geometry, in which case a standard of some sort is required. The entire area of interest must be tapped. The surface should be dry and free of oil, grease, and dirt. Tap testing is limited to finding relatively shallow defects in skins with a thickness less than .080 inch. In a honeycomb structure, for example, the far side bondline cannot be evaluated, requiring two-side access for a complete inspection. This method is portable, but no records are produced. The accuracy of this test depends on the inspector's subjective interpretation of the test response; therefore, only qualified personnel should perform this test."

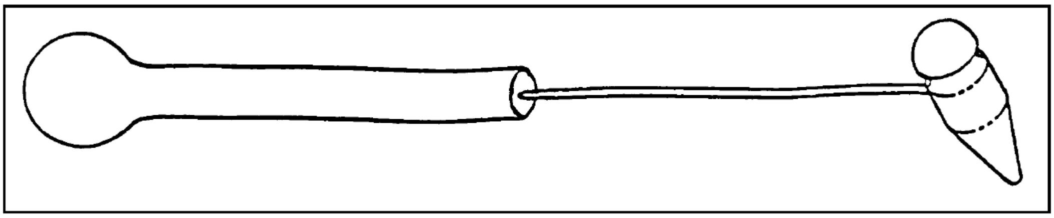


Figure 77: Sample of special tap hammer (source: AC 43.13-1b).

Appendix F – SHM projects funded by the European Commission

- **AHMOS** – Active Health Monitoring System, http://www.smartfibres.com/AHMOS.htm

  The project demonstrated an integrated health monitoring system for military aircraft and other military platforms using electrical, acoustic and optical sensing technologies. AHMOS delivered:

  - Advancement of the technology readiness level of 7 sensor technologies.
  - Development of an open architecture for integrated SHM systems.
  - Demonstration of condition monitoring and damage detection on three ground based aircraft test structures.

- **ARTIMA** – Aircraft Reliability Through Intelligent Materials Application, http://ec.europa.eu/research/transport/projects/article_3708_en.html

  Research on systems based on smart materials, defined as solid-state actuators activated by external fields. Expected results are:

  - Real-time structural health monitoring system for real aircraft parts with acceptable reliability (low rate of false alarms and missed defects).
  - Practical, robust active constrained layer damping treatment for aircraft.
  - Rotor blade icing detector capable of measuring ice thickness on the rotor blade, and the ice distribution and accumulation rate. PZT - based systems will be tested.
  - Feasibility study of applying encapsulated PZT actuators and Magnetic Shape Memory Actuators for wing vibration control.

- **TATEM** – Technologies and techniques for new maintenance concepts, http://www.tatemproject.com/pg11.html

  The goal of the project is to show how monitoring techniques and technologies can enable an integrated Health Management approach to significantly improve the aircraft operability and reduce maintenance related costs. In the main objectives of the project it is stated that "Integrated Systems for the detection of flaws can not only increase safety but also facilitate inspection of parts of the structure that are not accessible during normal aircraft operation or simple checks. These sensors can help to avoid dismantling parts of the aircraft to do the conventional inspection, to realise a considerable drop of maintenance costs. New structure concepts such as the CFRP fuselage need these sensor technologies because complicated multi-layer sandwich construction (that might be decisive part of the part of the design concept) cannot be inspected thoroughly without integrated systems. It is likely that these CRFP components will be crucial in the design philosophy."

- **AISHA** – Aircraft integrated structural health assessment, http://www.aishaproject.info/

  This European project explores the capabilities of ultrasonic Lamb waves as the basic sensing principle and by providing an integrated and multidisciplinary research path. Both active and passive (acoustic emission) Lamb wave inspection will be explored, using the innovative concept of selective and tuneable multimode wave generation/reception. Novel sensors/actuators will be developed which not only provide tuneable properties, but also potential for integration into aircraft structures. A specific research action will be devoted to structural integration of sensors/actuators. An extensive testing program using multiple materials and loading conditions will be devoted to the establishment of quantitative correlations between monitoring signals and the extent of damage.

This information, combined with the development of autonomous signal analysis routines and adequate models for remaining lifetime prediction, will ultimately be used in a full scale testing action during which the possibilities for large scale application of the developed technologies will be explored.

- **AERONEWS** – Health monitoring of aircraft by nonlinear elastic wave spectroscopy, http://www.kuleuven-kortrijk.be/aeronews

  Nonlinear Elastic Wave Spectroscopy (NEWS) and related acoustic and ultrasonic methods comprise a new class of innovative non-destructive techniques that provide extreme sensitivity in detecting and imaging incipient damage in the form of microcracks or delaminations, weakening of adhesive bonds, thermal and chemical damage, etc. The sensitivity and applicability of nonlinear methods to damage are superior to those obtained by currently used technologies. NEWS methods are in various stages of development and have not yet been applied to aircraft health monitoring. The project's goal is to examine, confirm and exploit the successful results of these techniques, using fundamental materials research on fatigue loading, and to apply them to the particular field of aeronautics. The project includes progressive microdamage and fatigue monitoring of aircraft components and structures, sensor engineering, development of NEWS-based imaging methods, and fundamental research on the modelling of meso-scale damage phenomena. We aim to investigate the relation of these studies to the macroscopic behaviour of progressively fatiguing materials, and formulate the design of a unique system for microdamage inspection, including remote control and communication tools, and the completion of a full-scale model validation. The long-term goal of the project (5-10 years) is to monitor while in operation, the integrity of airframes and aircraft engines, and helicopter rotor systems. The development of this innovative NEWS-based technology and its engineering applications to aeronautics will result in an enhanced, reliable and integrated measurement system and protocol for microcrack diagnostics of aircraft components and structures. We expect this development to result in a significant increase in aircraft and passenger safety while contributing to a substantial cost savings through a decrease in maintenance and operating times.

- **SMIST** – Structural monitoring with advanced integrated sensor technologies, http://ec.europa.eu/research/transport/projects/article_3710_en.html

  The objective of the proposed project is to allow the best and most advanced sensing technologies to become an integral part of the aircraft structure and so thus implement Structural Health Monitoring (SHM) into aircraft structural design with respect to maintenance cost reduction, increased aircraft availability and significant weight savings.

  The main project target is to develop and validate monitoring technologies that are able to deliver the expected cost savings for maintenance and enable innovative structural design for metals and composites.

The project includes nine sensor and monitoring technologies of different natures, which, at the end of the project, have to prove their applicability with regard to the objectives and specifications set. The monitoring technologies to be proved are:

- Fibre Optic Bragg Gratings
- Sensitive Coatings
- Environmental Degradation Monitoring Sensors
- µ-wave Antennas
- Acousto-Ultrasonics
- Comparative Vacuum Measurement
- Acoustic Emission
- Imaging Ultrasonics
- Eddy Current Foil Systems