Non-destructive testing methodologies on helicopter fiber composite components challenges today and in the future

Reinhold Oster
Center of Excellences Air Vehicles - Laboratory Materials and Processes - Laboratory Tests
81663 Munich Germany; Eurocopter Deutschland GmbH
Phone: +49 89 6000 2570, Fax +49 089 6000 8585
Mail: reinhold.oster@eurocopter.com

Abstract

Eurocopter helicopter structures are composed of fiber composite materials. Helicopter rotor blades consist of very complex monolithic CFRP laminates, like the main rotor blades of EC135 helicopter or the fuselage of NH90 helicopter made of CFRP laminates and sandwich structures. Design and production processes are adapted to the characteristics of the high performance FRP structures to reach the specified requirements on functionality, quality and safety. With various NDT techniques, defects could be detected inside the structures. The efficiencies of the NDT techniques will measure how well individual defects can be detected and characterized according to defect type, location and size. NDT techniques like ultrasonic testing, X-ray computed tomography, thermography and shearography or are in strong demand. This lecture describes aspects of NDT inspection on helicopter components, methodologies such as NDT techniques, Design to NDT, process optimization and monitoring, material and defect characterization and the “effect of defects”.

Keywords: ultrasonic, computed tomography, thermography testing, air-coupled ultrasonic, aerospace, helicopter, carbon, glass fiber composite, process monitoring

1. Introduction

Founded in 1992, the Franco-German-Spanish Eurocopter Group [1] is a division of EADS, a world leader in aerospace, defense and related services. Eurocopter confirmed its position as the world's number one helicopter manufacturer in the civil and parapublic market. Eurocopter offers the largest civil and military helicopter range in the world.

Eurocopter helicopter structures like helicopter rotor blades and fuselages are made of fiber composite materials. Helicopter rotor blades consist of very complex monolithic GFRP laminates, such as the main rotor blades of the EC135 helicopter or the fuselage of the NH90 helicopter, which are made of CFRP monolithic and sandwich structures.

Design and production processes of FRP structures are adapted to the high performance characteristics to reach the specified requirements on functionality, quality and safety. Production processes should be performed reliably and optimized so that no manufacturing defects can occur. Nevertheless, various defects such as delimitations, porosity and voids or undulations can occur inside the laminates during the production process.

Figure 1: History
In this paper we look at the importance of NDT and its methods used in the development, production and inspection of helicopter structures made of fiber composite materials. In the course of making a component there are a large number of detailed processes required in order to guarantee the component’s functionality, quality and safety. This paper will provide a summary of some of the key processes that are defined by the use of NDT methods, beginning by taking a look at the entire process chain of component realization. This will show how NDT is used in the process chain of component realization in order to guarantee the quality and safety of the helicopter structures made of fiber composite materials.

2. NDT in the process of component realization

The realization of a component made of fiber composite materials consists primarily of the four main stages design, manufacturing, QA testing and approval. Each of these stages can be broken down into a large number of individual steps, which include the process steps of quality assurance. One of these steps is conventional NDT testing of the finished component, for example, ultrasonic pulse-echo testing of the CFRP frame or computer tomography of the rotor blade in order to detect relevant defects such as undulation, porosity or delamination. The table below provides an overview of the most important process steps with reference to aspects that are relevant to NDT.

<table>
<thead>
<tr>
<th>Process of Component Realization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and Stress</td>
</tr>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Definition of inspection areas</td>
</tr>
<tr>
<td>Types of Defects</td>
</tr>
<tr>
<td>Limits of Defects</td>
</tr>
<tr>
<td>Design to NDT</td>
</tr>
<tr>
<td>Testability</td>
</tr>
<tr>
<td>Qualification Process</td>
</tr>
<tr>
<td>Industrialisation</td>
</tr>
<tr>
<td>Production</td>
</tr>
<tr>
<td>NDT for Process optimization</td>
</tr>
<tr>
<td>InLineNDT for Process controlling</td>
</tr>
<tr>
<td>QA Inspection</td>
</tr>
<tr>
<td>NDT on the produced component</td>
</tr>
<tr>
<td>Release</td>
</tr>
<tr>
<td>If no defect limit has been exceeded</td>
</tr>
<tr>
<td>If the limit has been exceeded answer the questions of “Effect of Defect”</td>
</tr>
</tbody>
</table>

NDT is often seen as a testing method that is only used to inspect a finished part or component for defects, but the methodological approach of NDT actually impacts the process chain of component realization at a much earlier stage (Table 1). If you look at the entire process chain of component realization, NDT affects the process chain at a number of points, in different ways and with varying significance, beginning with the definition of the areas to be tested, the permissible types and sizes of defect by the Design and Stress Engineering departments. The questions raised by “Design to NDT” such as the testability, the accessibility of the component for the NDT sensors and not inspectability zones can have a major impact on component design.

In the very early stages of development of the component, samples and prototypes are made. If inspection methods such as ultrasonic testing and/or computer tomography are used at this stage, it is possible to identify and correct the impact of design, semi-finished parts, cutting and draping, and the tooling on the emergence of defects. If this is then carried out in combination with the approval-related calculations and the associated destructive tests, it is possible to arrive at better answers to the questions concerning the “effect of defects” (evaluation of safety-critical defects). This leads to more in-depth understanding of the types of defect and the causal factors that play a role in their development and their effects on the strength of the component. This then makes it possible to transition from a global perspective of the permissible defect sizes to local, permitted defect sizes. Not all porosity or undulation is “harmful” for the component, but only those types of defect that initiate delamination or fiber cracks in highly stressed structural elements.

New, highly automated processing techniques of semi-finished parts made of CFRP fabric into preforms, which are then infiltrated with resin using the injection processes used in the RTM or VAP processes call for inline testing methods for quality monitoring. This is referred to as InLineNDT [2] at Eurocopter. Quality features such as the fiber orientation, lay-up and stitching defects, and injection defects can thus be prevented at an early stage, reducing or completely preventing porosity and undulation in the finished component. The InLineNDT testing methods are currently under development at Eurocopter and are therefore not described here.
3. Eurocopter helicopter composite structures

3.1 Rotor blades made of glass fiber reinforced composite materials

As long ago as in the 1960s, MBB was already developing helicopter main rotor blades made of glass fiber reinforced plastic, which were first used by the BO105 in 1967. The rigid rotor head was born. Further development aimed to simplify the rotors. This led to an ever increasing number of functions being integrated in the rotor blade structure. These monolithic/sandwich structural components, which are highly complex in terms of their design, like the rotor blades for the EC135, can be tested very effectively non-destructively by computer tomography (CT). CT played a major role in the development of the rotor blade, being used as a development tool [3, 4].

3.2 Helicopter fuselages made of carbon fiber reinforced frame and sandwich components

Eurocopter developed and manufactured the entire cell structures for the military helicopters Tiger and NH90 (First flight 1995). The combination of monolithic frame structures and the CFRP/Nomex honeycomb construction method results in especially light and stiff CFRP cells. The proportion of fiber composite structures is over 90% in both of these helicopters. The TIGER and NH90 helicopters also have rotor blades made of glass fiber reinforced plastics [5].

A particular challenge for NDT testing is the novel design of the tail boom for the EC145 T2. The CFRP sandwich structure is made integrally from a single piece, as described in [6]. Air-coupled ultrasonic testing is used to inspect the sandwich component, see chapter 5.1.2 for details.
4. Description of the types of defect

The types of defect (porosity, delamination, undulation) that can arise during the production process can have a serious impact on the strength properties of the component, with the type, size and position of the defect in the component, in relation to the local strength required from the component, being of crucial importance.

Table 2 gives an overview of the most important types of defect that can occur in monolithic composite laminates. The pictures represent a characteristic selection of defects, which can vary in type and size depending on the construction method, the semi-finished fiber part and the production methods used.

Table 2. Manufacturing defect types in monolithic fiber composite materials

<table>
<thead>
<tr>
<th>Types of defect</th>
<th>CT</th>
<th>PE-UT</th>
<th>TT-UT</th>
<th>IRT</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Porosity</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Undulation</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Fiber crack</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>o</td>
<td>-</td>
</tr>
</tbody>
</table>

++ very well, + well, o conditionally well, - not possible or unknown

Various other conditions, such as the materials used, the construction methods, the size of the components and their accessibility, determine the choice of NDT method used. Eurocopter Deutschland therefore makes use of various inspection methods in order to solve various inspection issues in the best possible way. To give an example, the use of the NDT methods used to test helicopter rotor blades and cell parts are described below.

5. NDT methods

The purpose of using NDT methods is to detect the type and position of defects in components. This is important in order to be able to maintain component quality in serial production by monitoring error tolerances. In the development of the prototypes, the various NDT methods are used to study the causes of the emergence of defects and to remove them.

According to the current state of the art, the types of defect described above can be detected and characterized using the inspection methods such as ultrasound testing (UT), thermography testing (IRT), shearography testing (ST) and the inspection methods based on X-ray techniques like 3D computer tomography (CT) and laminography [8, 9]. The physical process technologies used by the various testing methods are all very different, meaning that the testing quality for detecting different types of defect varies, too.

Table 3. Detectability of defects in monolithic laminates

<table>
<thead>
<tr>
<th>Types of defect</th>
<th>CT</th>
<th>PE-UT</th>
<th>TT-UT</th>
<th>IRT</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Porosity</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Undulation</td>
<td>+</td>
<td>o</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Fiber crack</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>o</td>
<td>-</td>
</tr>
</tbody>
</table>

++ very well, + well, o conditionally well, - not possible or unknown
5.1 Ultrasonic testing
5.1.1 Conventional UT testing

The large components used for the helicopter structures, as described in chapter 3.2, are tested using the conventional ultrasonic inspection methods such as the pulse-echo technique (monolithic laminates) and the through-transmission technique (squirt technique for sandwich inspection). For PE-UT testing, everything from individual oscillators up to multi-element phased array probes are used. As part of the production ramp-up for CFRP component production for the helicopters NH90 and TIGER it was necessary to automate the UT inspection. UT sensors, are used, with the help of robots, to traverse the complex curved sandwich components. The TWIN robotic inspection system [10] is capable of tracing the component contours with squirters centered with high precision for TTU testing. The test patches and the associated scan tracks are programmed in advance in the CATI environment and prepared for ultrasonic testing in a simulation environment.

5.1.2 Air-coupled ultrasonic testing

The air-coupled ultrasonic testing technique [11] has been qualified for testing CFRP honeycomb sandwich structures for the integral sandwich tail rotor boom for the EC145. The air-coupled inspection system for automated testing of the tail boom is in operation since 2011.
2 Computer Tomography (CT)

5.2.1 Macro CT
Non-destructive computer tomography has become an important development and quality assurance process for Eurocopter. As long ago as the late 1970s, CT was already being used in helicopter component testing for fatigue testing of GFRP rotor blade, and for crack detection and crack measurement. Eurocopter has also used computer tomography as a quality assurance tool in serial production of rotor blades since 1993, and it is also used in production process optimization. Over 3000 components are tested using a medical CT scanner each year. This quality assurance procedure for the main rotor blade of the HS EC135, made using a highly integrated process, thus also contributes to maintaining the production quality of the component and guaranteeing the lifetime of the rotor blade determined in the acceptance processes.

Figure 1. Medical CT scanner  
Figure 2. Tomograms of an EC 135 GFRP rotor blade

The large number of fiber composite tomograms that are generated in the course of CT serial inspection call for a powerful visualization and image processing tool. The program VGStudio is used for this purpose. It is important, for example, to be able to identify and characterize the local fiber orientation and their distributions. Using special image processing algorithms it is possible to carry out automated evaluation. The step from the qualitative analysis of the tomograms to quantified defect characterization has been realized here [12].

Figure 8: Reference-analysis of fiber orientation  
Figure 9. Histogram of fiber orientation

Figure 8 shows the results of a target/actual comparison of a local fiber orientation at the voxel level. Using the analysis software it is possible to compare any number of material-specific structural characteristics such as the fiber-volume content or the porosity distribution.

5.2.2 Micro-CT
The medical CT is augmented by a micro-CT testing system. This is designed in such a way that small material samples and large components can be scanned with a voxel resolution of up to (10 µm)³. There are several measurement and reconstruction modes available for use. The measurement modes 3D-CT, ROI-CT, Transversal CT (type of laminography method) and HELIX-CT [13] can be selected depending on the task at hand and the component configuration. The material and defect characterization is performed with VGStudio as described above.
5.2.2.1 Micro-CT as a referencing method

As described above, CFRP cell structure components are tested using ultrasonic methods. Ultrasound indicates delaminations with very high sensitivity using defect echoes, and reveals porosity by way of a reduced back-wall echo. Correct interpretation of a defect-echo (whether it is an instance of delaminations or a small pore) when performing radius testing or of the back-wall echo to deduce the actual volume porosity is not directly evident from the ultrasonic signal. Here micro-CT testing is used to support ultrasonic inspection. This makes it possible for the test engineer to interpret the echoes, meaning that micro-CT is used for the qualification of ultrasonic inspection methods at Eurocopter. Figure 12 shows an example of this comparison process. On the left is a tomogram with clearly visible delamination. On the right there is an S-scan in which the defect-echo of the delamination is clearly shown at the right depth. Micro-CT makes an important contribution in the process of developing new NDT testing methods and evaluation methods as a reference method.

5.3 Optical non-destructive testing methods

The inspection methods based on optical processes such as thermography and shearography have the advantage that components with large surface areas can be inspected quickly. Another advantage is the fact that these methods, depending on the application conditions, are capable of performing selective defect detection.

5.3.1 Thermography

The full range of testing methods that use active thermography, like OLT, ULT and PT, is used at Eurocopter. Methods for the inspection and repair of helicopter structures made of fiber composites have been qualified and formalized in inspection instructions.
Thermographic methods are not yet used in the serial testing of CFRP components. However, various studies have shown that these methods indicate porosity in CFRP laminates at high sensitivity. Eurocopter is working intensively to unlock the potential of thermographic methods.

The images below show a small selection of thermography results from this work.

5.3.2 Shearography
The potential of shearography has not yet been fully exploited. An interesting use case is the fact that undulations in fiber composite laminates can be detected by shearography. Studies have shown that out-of-plane undulations can be detected with very high sensitivity. Intensive studies are currently underway in order to be able to characterize undulations using shearography.

6. Effect of defects
The question of the “effect of defects” always arises when the permissible defect sizes need to be defined as well as when a finished component fails to meet the permitted limits when inspected using NDT methods. Then the question arises as to whether the NDT method is capable of accurately quantifying the defect in terms of its type, size and position in the component cross-section? The NDT method should be capable of this, if possible, so that a structural engineer can get a precise idea about the type of defect and thus make appropriate decisions about the effect of the defect on the component quality.

To achieve this, it is also important to have the corresponding material and defect characterization parameters that make it possible to describe any decrease in the strength of the material due to the defect. Figure 17 shows such a
characterization and validation process, taking a porosity defect as an example. The schematic diagram shows how the two methods work in parallel: NDT characterization and strength characterization. The qualification of the ultrasound pulse-echo method used to characterize the porosity of a CFRP laminate is shown on the left and the determination of how the effect of porosity on strength affects the material parameters is shown on the right. Micro-CT testing was validated as a reference method for porosity quantification in the samples [14, 15].

Another method used for the evaluation of defect types and sizes on the failure behavior of the component is the introduction of defects such as impacts and artificial delamination in critical component structures that are being subjected to a limit-load test. Before the limit-load test, which is obligatory for the strength approval of the component, the component is inspected by air-ultrasonic testing to determine the position of the defect. During the limit-load test, optical measuring methods such as image correlation, are then used to measure the deformations and the local tensile stresses [Figure 18].

The combination of the defect-describing NDT with the destructive testing methods helps the structural engineer to improve his calculations of the failure behavior of the component.

![Figure 17. Defect characterization of porosity supported by PE-UT](image)

![Figure 18. Component test of a CFRP sandwich tail boom](image)

### 7. Conclusion

This report has provided a summary of the current state-of-the-art of NDT methods used by Eurocopter. The potential performance of these methods is far from being fully exploited. Future development work on NDT aims to exploit this potential performance and to develop new methods. These will then help to realize novel, efficient fiber composite design concepts, which also call for new approaches, which will lead to a change in attitude regarding NDT processes. NDT is in demand due to its holistic approach in the application in the process of “component realization”. Ranging from aspects of design to NDT, the demonstration of compliance of aircraft components, the use of InlineNDT for process monitoring to achieve robust production processes, conventional NDT testing of serial components, the aspects of the effect of defects, all the way to its use in maintenance, the range of NDT applications is very broad.
Acknowledgements

I would like to take this opportunity to thank the members of the team as well as the manager of the “Laboratory Testing” department, and express my recognition of their excellent work. I would also like to thank the departments in the “Laboratories, Processes and Materials” organizational unit at Eurocopter Deutschland GmbH for their support, as well as all of the QA departments for their kind cooperation.

References

[1] www.eurocopter.com


[11] W. Hillger, (Hillger Ing. Büro, Braunschweig; Germany); NON-CONTACT ULTRASONIC IMAGING TECHNIQUES FOR COMPOSITE COMPONENTS, WNDT 2004


[13] Jochen HILLER, Stefan KASPERL, Tobias SCHÖN, Stefan SCHÖPFER+; Daniel WEISS**,+Fraunhofer IIS, Development Center for X-ray Technology, Fürth Germany; **Carl Zeiss Industrielle Messtechnik, Oberkochen, Germany; COMPARISON OF PROBING ERROR IN DIMENSIONAL MEASUREMENT BY MEANS OF 3D COMPUTED TOMOGRAPHY WITH CIRCULAR AND HELICAL SAMPLING; 2nd International Symposium on NDT in Aerospace 2010

[14] R. Oster1, J. Schuller1, G. Oelrich1, R. Meier1 1 Eurocopter Deutschland GmbH; 2 Universität der Bundeswehr München, 3IntelligeNDT Systems&Services GmbH KLASIFIZIERUNG VON POROSITÄTEN IN CFK-LAMINATEN MIT HILFE VON ULTRASCHALL BASIEREND AUF MIKRO-CT UNTERSUCHUNGEN; Poster; DGZFP Dachtagung, Salzburg, Mai 2004.