FATIGUE SUBSTANTIATION AND DAMAGE TOLERANCE EVALUATION OF H145 FIBER COMPOSITE COMPONENTS

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Abstract

Helicopter rotor systems are dynamically loaded structures with many composite components such as main and tail rotor blades and rotor hubs. The EC145 T2, first flown on 18th of March 2011 (shown in Figure 1) is a light twin engine helicopter in the 4-ton class. The T2 is the latest upgrade of the EC145 with increased take-off weight, stronger engines, next generation avionics and a new tail boom including a Fenestron™ tail rotor. It takes the advantages of the broad experience gained on Gazelle, Dauphin, EC120, EC130 and EC135 aircrafts with similar technologies.

In parallel to technology evolutions, new substantiation requirements have been followed during the certification of the newly designed parts. The most significant modification to notice in the new fatigue and damage tolerance evaluation rules compared to the old rules is the separation of the evaluation of metallic and composite structures in §27/29.571 and 573 respectively. Another important feature of the new rules is the strong flaw tolerance requirements and subsequent introduction of a requirement for the residual strength demonstration up to limit or ultimate load after repeated loading of the structural parts.

The composite parts of the H145 Fenestron™, tail rotor drive system and main rotor system are certified according to the new fatigue evaluation rules supported by 'Special Conditions for Primary Structures Designed with Composite Material' of the German airworthiness authority LBA.

1. Introduction

In 1967 the BO105, a product of the former helicopter division of MBB, now Airbus Helicopters, flew for the first time. The hingeless main rotor system was a key element of this helicopter, using the advantages of the newly developed fiber glass technology. Thus the flapping and lead-lag hinges could be eliminated. The rotor design included new materials such as titanium for the rotor hub and fiber glass epoxy for the main and tail rotor blades. The substitution of hinges was a great progress with regard to weight reduction and cost saving due to the reduction of parts. The pitching motion, however, has still been carried out using roller bearings.

The helicopter family BO105, BK117, BK117 C-2 (EC145) and the newly developed BK117 D-2 (H145) (see Figure 1) is equipped with this hingeless main rotor system and D-2 is additionally equipped with the new Fenestron™ tail rotor system. The H145 is the newest aircraft with the latest Fenestron™ technology including the carbon fiber reinforced plastic blade with integrated tension-torsion element. It takes the advantages of the broad experience gained on Gazelle, Dauphin, EC120, EC130 and H135 aircrafts with similar technologies.

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Figure 1. BK117 D-2 (H145) first flight on 18th March 2011 - figure showing the main rotor blades and Fenestron™ anti torque system

Over the past 40 years, new materials and continuous improvements in detail design have been introduced in recent developments. In parallel to technology evolutions, substantiation requirements have been changing as well. The most significant modification to notice in the new fatigue and damage tolerance evaluation rules compared to the old rules is the separation of the evaluation of metallic and composite structures in §27/29.571 and 573 respectively [1]. Another important feature of the new rules is the strong flaw tolerance requirements and subsequent introduction of a requirement for the residual strength demonstration up to limit or ultimate load after repeated loading of the structural parts.

For the dynamically loaded fiber reinforced composite parts of the H145 aircraft, the Flaw Tolerant Safe Life methodology is used for the substantiation. The main rotor and Fenestron™ blades and the Tail Rotor Drive Shaft (TRDS) with material and design changes were substantiated according to the FAA rules and the Special Conditions of the LBA concerning the damage tolerance requirements. The substantiation of these parts is presented in detail to describe the improved design features and to demonstrate the compliance with the new rules. The flaw tolerant characteristics are explained as well.

2. Fatigue Substantiation Approach for H145 Composite Parts

This chapter summarizes the approach of strength substantiation of “BK117 D-2 Primary Dynamic System Parts Designed with Composite Material” with respect to FAR 29.571 Amendment 40 and the “Special conditions No. SC1 of the Luftfahrtbundesamt LBA”.

It shows how the requirements are fulfilled for the following primary composite parts:

- Main rotor blades
- Fenestron™ blades
- Tail rotor transmission drive shaft

These parts are designed according to the damage tolerance approach by taking into account the allowable manufacturing and in-service defects under fatigue loading. For the main and Fenestron™ rotor blades, several fail safe features were incorporated into the design in order to ensure a sufficient residual strength capability after flaw growth.

Firstly, the Principal Structural Elements (PSE) are identified in the course of the substantiation according to § 571. Then the possible manufacturing and in-service damages are identified based on previous development and in-fleet experience. Allowable manufacturing and Barely Visible Impact Damages (BVID), which can realistically be expected from production and during operational service shall not grow under fatigue loading to such an extent that the structural strength will be reduced below Design Ultimate Load.

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Both main and tail rotor blades consist of attachment area (i.e. either loop or laminated attachment design) and airfoil section similar to sandwich design. The sizing of the blades is mainly defined by stiffness requirements in combination with strength limitations. Additionally, the whole design is typically optimized to a light weight design. This means that at airfoil area rather thin skins (app. 1 mm) with core thicknesses between couple of millimeters up to couple of centimeters. Hence, an impact which is above BVID level is very likely to produce clearly visible damages in the skin. Further increasing the impact energy will produce a hole in the structure. However the structure remains intact. Thus, a categorization up to five levels of impact damages is technically not practical for such structures.

As next step, size and location of these damages is selected with respect to the quality assurance and inspection program. Several areas were pre-damaged with impacts. For the herein treated structural parts, the maximum impact energy that could happen during the life of the composite element was determined to be 25 J. Usually these impacts are applied with the help of a cylindrical impactor with a spherical tip diameter of 25.4 mm (1 inch). Figure 2 shows the investigation results with different impact damages on different areas of the main rotor blade.

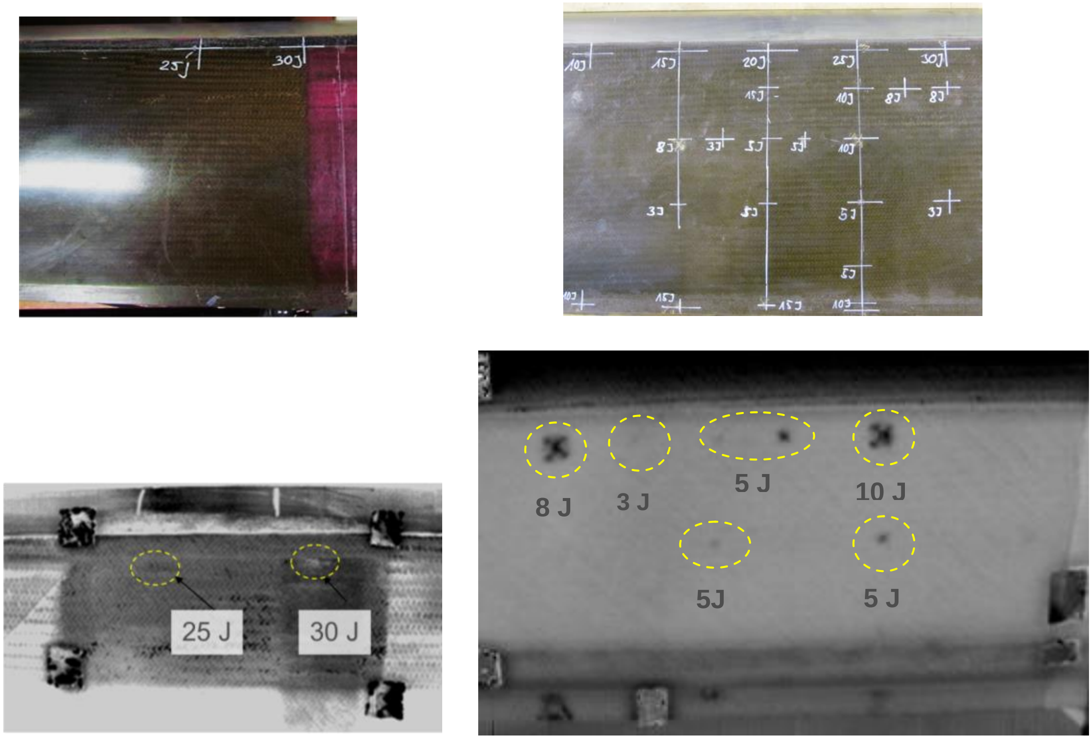

Figure 2. Airfoil section of the main rotor blade with BVID and Clearly Visible Impact Damages (CVID) impacts at different energy levels along the chordwise length (i.e. above the spar and at the trailing edge) and the corresponding ultrasonic photos of the resulting damage shown below

Visible damage resulting from obvious discrete sources shall not reduce the structural strength below Design Limit Load level. Impact damages that could reduce the strength below Design Ultimate Load have to be detectable. The strength reduction caused by local damage is determined by test or calculation supported by test. The final strength of the structure is checked by analysis and/or test.

Finally, the safe life is determined from:
- Fatigue curves derived from tests on specimens.
- Fatigue tests on parts till a crack nucleation, the propagation of a flaw or an unacceptable stiffness loss.

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The safe fatigue limit is derived from the mean fatigue limit, determined by a well-established statistical procedure as described below:

- Strength tests at coupon level taking into account the environmental effects are performed to determine the material stiffness and strength properties
- Strength tests at full-scale level with BVIDs were performed to validate the no growth approach taking into account the environmental effects in the residual strength test.
- Strength tests at full-scale level with manufacturing defects were performed to validate the slow growth approach taking into account the environmental effects in the residual strength test.

After the fatigue tests, a static test up to ultimate load has been performed for the transmission shaft and main rotor blade including an additional factor simulating the environmental effects. The Fenestron™ blade Tension-Torsion-Strap was tested in fatigue and residual strength under elevated temperature.

At the end, detailed inspection procedures based on the results of the damage tolerance evaluation have been established. The inspection program for visible damages defines e.g. the inspection methods, areas of interest and inspection intervals. Inspection requirements are defined in the Aircraft Maintenance Manual (AMM).

3. Main Rotor Blade

The main rotor blade of the H145 is a full composite rotor blade with a loop attachment. The rotor blade includes the hinge less rotor system technology, similar to BO105 and BK117. [3] This results in a design with reduced number of parts and low maintenance costs. The virtual hinge in the neck area of the rotor blade induces high strains, thus this is realized as glass fiber laminate. In the following the damage tolerance aspects of the rotor blade are shown.

Figure 3. Cut of a rotor blade interface (loop embedded within a titanium fitting)

The rotor blade interface of the H145 is realized as a loop design embedded in a titanium fitting. The loop area of the rotor blade reacts both, the loads induced by centrifugal forces and the loads resulting from dynamic behavior of the rotor, the lead-lag and flapping forces. Especially the lead lag forces induce high stresses within the loop. The destructive component tests of the rotor blade interface are performed with combined load cases taking all three loads, centrifugal, lead-lag and flapping into account. During component test lead-lag intensive load cases show a crack growth within the loop area.

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Figure 4. Test set-up for destructive component testing of H145 main rotor blade attachment

Cracks introduced within a unidirectional laminate induce high interlaminar shear stresses resulting in delamination. This effect results in a very slow crack growth within the laminate. On the other hand it can be shown, that change within stiffness induces dynamic effects resulting in an intensive dynamic imbalance of the hinge less rotor system. Based on the destructive tests the loop is substantiated as a safe life component.

The neck area, the transition from the interface to the airfoil and the airfoil of the rotor blade are prone to impact damages. These can result from ground handling or foreign object damage during flight. Within the fatigue substantiation BVID are taken into account. The energy level for barely visibility of the impacts is defined within impact pretesting. For all destructive component tests of the rotor blade several impacts are applied on the critical zones of the blade. The locations of impacts for a rotor blade interface specimen are shown in Figure 5. The rotor blade is substantiated as a safe life component based on the S/N curve derived from the tests with damages.

Figure 5: Impact locations on a rotor blade specimen. Different energies are applied on thin (marked by crosses) and thick (marked by dots) zones of the laminate [3]

4. Fenestron™ Blade

The Fenestron™ blade of the H145 is the latest evolution step of the [2] long development of Fenestron™ blades. The first Fenestron™ blades were aluminum blades with separated tension torsion elements manufactured from steel applied first on the SA340 Gazelle. With increasing size of the helicopter and thus chord of the blade, the weight of the blades and the resulting centrifugal and control loads increase. The reduced mass of the composite Fenestron™ blade leads to a significant reduction of centrifugal forces and mass of the anti-torque system. The current blades show a fully

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integrated composite design with a one shot manufacturing of blade and tension torsion elements. The overall design of the blade is shown in Figure 6.

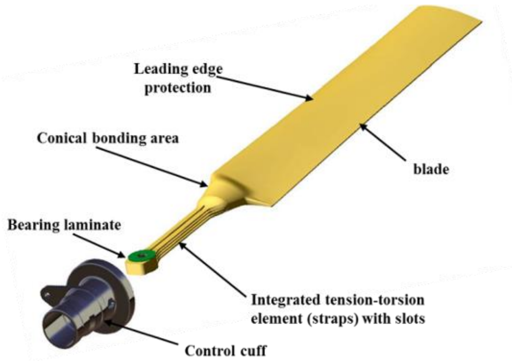

Figure 6. H145 carbon composite Fenestron™ blade with its main components [2]

The major load path of the centrifugal forces through the interface with the center hub is realized by a flat bearing laminate at the inner end of the tension-torsion element. The design is realized as a stacked laminate without fiber loops. The unidirectional fibers go straight from the bearing laminate through the tension-torsion element into the airfoil section. This design offers a low height-to-width ratio allowing an efficient integration of the blade within the system. The bearing laminate provides a manufacturing tolerant design, thus saving effort within the blade manufacturing. Further details of the sizing approach for the bearing laminate can be found in [2]. One of the more complex components required for the fully integrated manufacturing of the blade is the tension torsion element.

The tension-torsion element is the link between the blade attachment, the bearing laminate, and the airfoil section. It has to transfer the centrifugal forces and works as a torsional hinge. Within the preliminary design phase it was designed as a stack of four tension-torsion straps made of 0° unidirectional layers to fulfill the stiffness and strength requirements as shown in Figure 7.

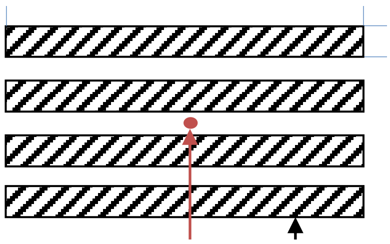

Figure 7. Sketch of the tension-torsion element cross section with four straps [2]

The tension torsion element is loaded by a combination of centrifugal loads of the blade and large torsional deformation resulting from control movements. The high twist in combination with the centrifugal forces leads to a significant geometrical nonlinearity. The definition of the main sizing parameter, the width of the straps, was defined, based on a numerical optimization. The optimization was performed using HyperStudy as optimization algorithm and MSC Marc as solver, being able to cope with the nonlinearities. The target for optimization was the minimization of the torsional stiffness. The boundary condition, beside geometrical restrictions, was the maximum stress under a combined loading with maximal centrifugal forces and torsional angle. The qualitative stress level and stiffness in dependency on the design parameter are shown in Figure 8.

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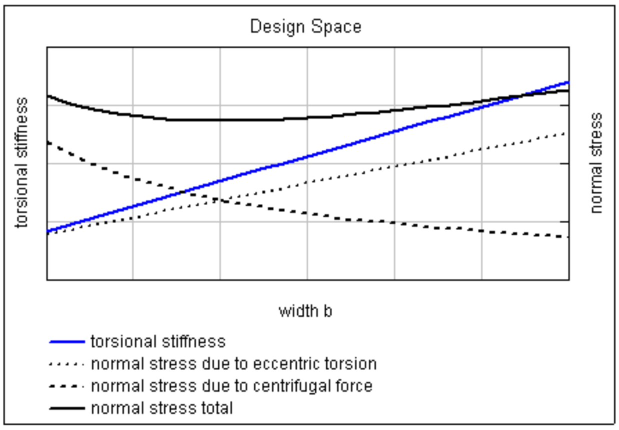

Figure 8. Torsional stiffness and normal stress distribution with respect to width of the strap

The result obtained by optimization, fulfilling all boundary conditions leads to high torsional stiffness. In a further step the design was enhanced by splitting each tension- torsion strap in two fingers via the introducing a slot. This design change leads to a significant reduction of the control loads of the Fenestron™. The stress distribution of the final design under combined loading is shown in Figure 9.

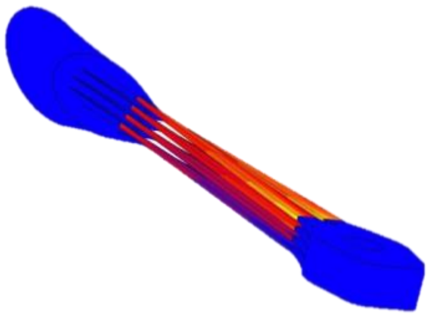

Figure 9. Stress distribution along the tension-torsion element under combined loads of tension, torsion and bending moments

The composite laminates such as used for the Fenestron™ blade are prone to erosion and small impact damages. Therefore the leading edge of any composite blade has to be protected by an erosion protection. The exact geometry of the erosion protection influences strongly the vulnerability of the blade. Within the development of the blade an impact test program on the erosion protection was performed. Corresponding to this experimental investigation a numerical simulation of the impact was developed and validated, based on the gained test results. The goal of this hybrid experimental and numerical approach was the minimization of the penetration depth within the erosion protection shell by optimization of its geometry. Based on this result a robust erosion protection shell with varying thickness was developed for optimal impact behavior.

The static strength substantiation is mainly based on finite element analysis. The fatigue and corresponding damage tolerance substantiation is based on full component testing and subcomponent testing. The fatigue curves, providing the basis for lifetime calculation and definition of inspection intervals are derived from the fatigue tests**.** As realized for the main rotor blade, the derived fatigue curves are based on components with inherent flaws.

The damage tolerance of the Fenestron™ blade is shown by artificial damages and flaws within fatigue testing. Within the blade attachment and the transition area delaminations and local debonding were simulated by the application of a separation foil during manufacturing. Furthermore several levels of porosity and fiber misalignments were investigated during testing. In parallel NDT

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investigations have been performed in order to identify the detectability of the flaws and identify thresholds for the acceptable variation within the manufacturing. Typical flaws during component testing are shown in Figure 10. Furthermore impact damages were introduced in the critical areas. The energy level for impact was chosen to achieve barely visible impact damages. The energy level for the different areas was derived by a previous impact test series.

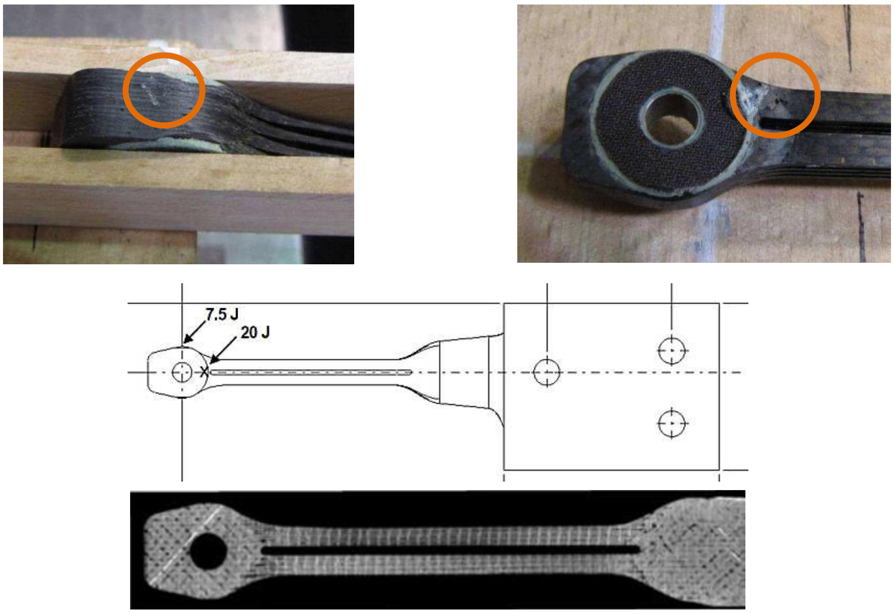

Figure 10: Tension-torsion fatigue test specimens with BVIDs at different energy levels (on top and middle) and manufacturing flaws, i.e. porosity (on bottom)

The component test was performed with combined tension and torsion loads. The test was performed at elevated temperature to simulate surrounding environment. As mentioned, fatigue testing is followed by ultimate load testing to substantiate the residual strength.

5. Tail Rotor Drive Shaft

As can be seen in Figure 11, the chain of the complete Fenestron™ drive shaft consists of one long steel shaft and two short composite drive shafts and 4 flexible couplings. High strength carbon fiber fabric, impregnated with high temperature epoxy resin system, was used for the design with a 0°/90° and ±45° lay-up in order to optimize the strength and the stiffness features and to achieve a high impact resistance.

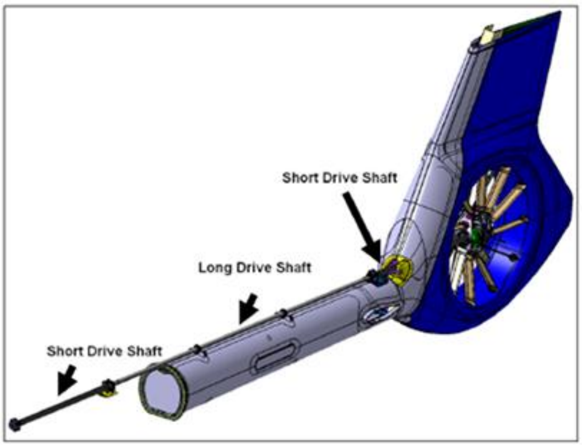

Figure 11. H145 Fenestron™ Drive Chain with long and short drive shafts

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As explained in chapter 2, manufacturing flaws and impact damages are considered as well in fatigue test program. Test specimens are manufactured by introduced foil in the middle of the shaft to simulate the possible manufacturing flaws such as disconnected fiber layers or delaminations.

Several specimens are tested with impact damages at positions L/4, L/2 and 3L/4 on the shaft to substantiate the damage tolerant design. Additionally one impact is placed between the rivets (see Figure 12). The impact energy is defined by previously performed tests in order to determine the threshold for barely visible impacts. 25 J impacts with 25.4 mm impactor are applied. As the impact damages caused by the applied 25 J cannot be detected by in-field inspections, the 'Flaw Tolerant Safe Life' approach is used to calculate the life of the drive shaft. By tests a stress-load cycle curve with impacted specimens without test failure is established to prove fatigue strength of the shafts.

In accordance with the Special Condition of the German certification authority LBA, a knock-down factor of 1.3 is considered for taking into account hot and humid environment. After the fatigue tests without failure, the ultimate static strength, considering an additional ageing factor was demonstrated.

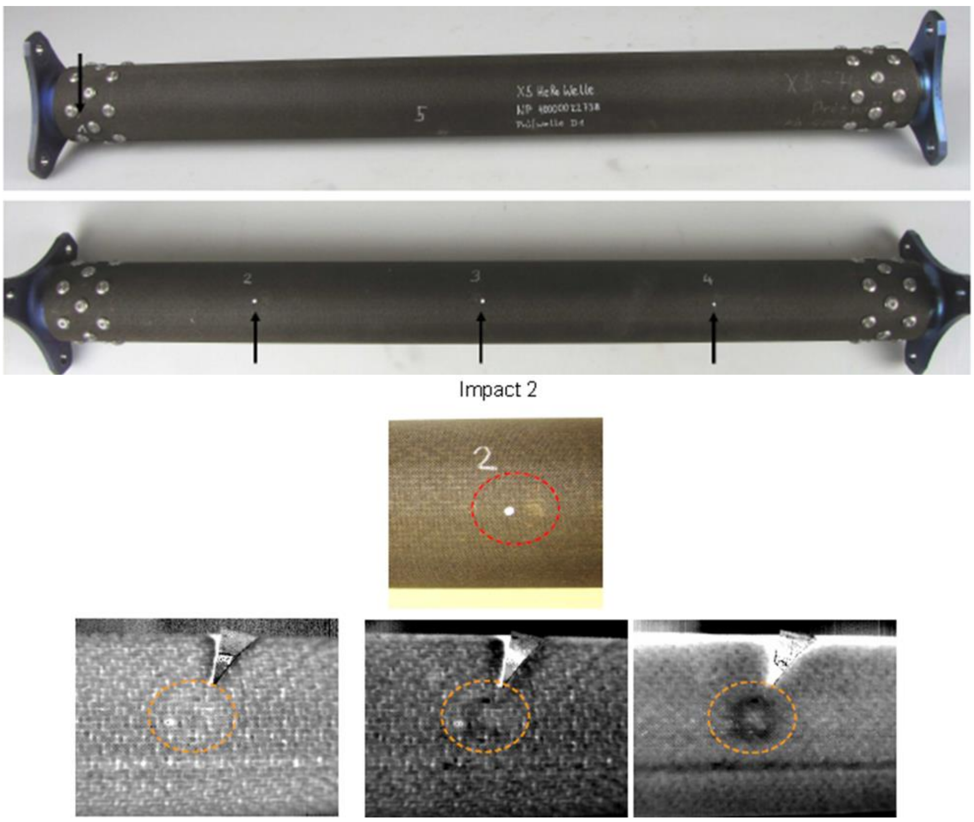

Figure 12. H145 composite tail rotor drive shaft with impact damages at three different locations (on top) and the ultrasonic photos of the impact damages (bottom pictures)

Figure 13 shows the fatigue test set-up and test specimen with impact damages and final fatigue damage. Each point which is considered in fatigue S/N curve represents a specimen tested until certain number of load cycles with the capability of sustaining ultimate load including temperature and moisture effects. The final lifetime calculation shows infinite life for carbon composite drive shaft.

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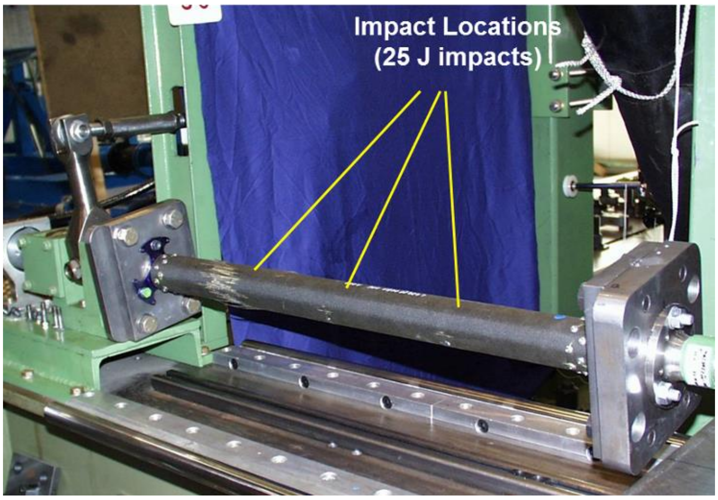

Figure 13. H145 tail rotor drive shaft test set-up and test specimen with impacts and fatigue damage

6. Conclusions

Within this paper the damage tolerant substantiation of different composite components of the dynamic system of the H145 is shown. The particularity of a helicopters dynamic system in contrast to the majority of applications is the dominating fatigue loading. Furthermore composite components are prone to damages during operation. Especially impact damages can cause barely detectable flaws. For a save and efficient operation of composite components within aircraft, these damages have to be taken into account during substantiation. – Thus the major effort is spent on design and substantiation of a damage tolerant fatigue behavior of the components. The substantiation of the components is based on flaw tolerant fatigue curves derived by testing, taking into account possible non-detectable damages suffered during operation and flaws within manufacturing. Based on this approach a fulfillment of the certification rules is achieved. On the other hand this approach allows a robust design providing a high reliability of the dynamic system while preserving a save and lightweight composite design.

7. References

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