DESIGN OF AIRCRAFT STRUCTURES UNDER SPECIAL CONSIDERATION OF NDT

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Abstract: The present paper takes a critical view on aircraft development, design and operation as a complex exercise with many different disciplines involved. To understand the background of requirements to NDT technology, an overview is given over design drivers and design criteria. An important activity in the aircraft development phase is the establishment of a structure inspection program. In this context, a strong relationship between damage tolerant design and non-destructive evaluation is shown. Some examples of NDT usage in today's practice are shown, including quality assessment of welded joints and application to semi-finished products. Finally, an outlook on the expected future of Structural Health Monitoring (SHM) is given.

Introduction: The continuous growth in air traffic has placed an increasing demand on the aerospace industry to manufacture aircraft at lower cost, while ensuring efficiency in operation, friendliness to the environment and high safety. To meet these objectives it is essential to consider the complete product life cycle including

- Development (e.g. Design),
- Manufacturing,
- Operation and
- Disposal.

The development and design of aircraft structures is a complex, multi-disciplinary exercise. The demand for maintenance and NDT becomes clear when reflecting to long life and extensive usage of civil aircraft structures. For example, a typical short-range jet aircraft may be designed to reach a design service goal of approximately 50.000 flights. It can be derived easily that such aircraft will travel about 400.000 km / 250.000 miles on ground – only during take-off, landing and taxiing. Consequently, such aircraft will make more miles on ground than any conventional car! This example also illustrates the excessive loading history, which the structure has to withstand during its operational life, including many accidentally as well as operationally induced damages and cracks.

Within the last years, the development of aircraft structures has lead to a competition between composite and metallic structures. This competition has proved to be inspiring for composite technologies as well as for metallic technologies. However, this paper focuses mainly on experiences gained from metallic structures.

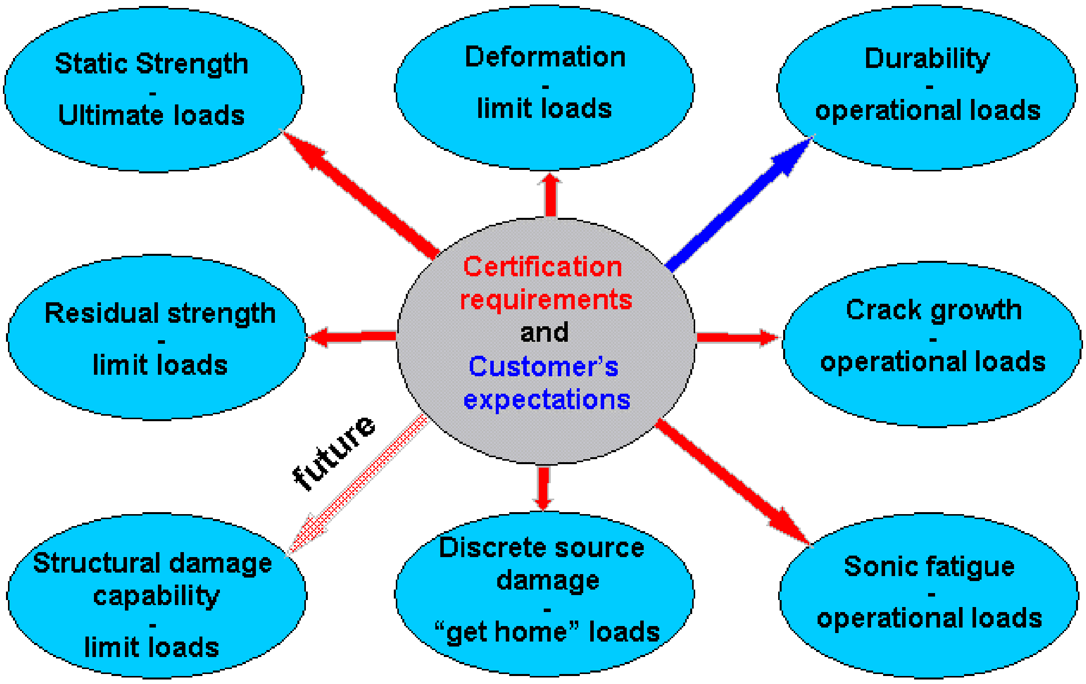

Figure 1: Major design criteria applied to metallic civil aircraft structure [2]

Design Aspects: The design of civil aircraft structures is heavily influenced by several drivers, the major of those are considered to be:

- Airworthiness regulations and requirements
- Available materials / material data
- Required structural details
- Environmental considerations
- Production / manufacturing capabilities
- NDI / NDT capabilities

The variety of drivers, which have to be considered, lead to the design process being a complex iterative procedure, finally leading to an optimized design regarding weight, cost and aircraft performance.

Design Criteria: In order to design a structure, which is able to fulfill all requirements from static, durability and damage tolerance point of view, it is necessary to consider a large range of design criteria. Figure 1 illustrates the most important design criteria, which are today applied to civil aircraft structure. The structure must satisfy all design criteria in all structural locations. However, designers need to have a look on the dimensioning criteria in certain structural areas, because the dimensioning criteria are finally driving the dimensioning and the design/weight of the structure.
It is not possible to give a generic answer to the distribution of dimensioning criteria over the aircraft structure, since this distribution depends on many factors, including:

- Material scenario chosen
- Loads (relevant load cases)
- Size and configuration of the aircraft
- Mission profile of the aircraft (e.g. differences between long- and short-range aircraft)
- etc.

However, it is possible to show an example: Figure 2 shows a typical scenario of dimensioning criteria on a long-range aircraft fuselage structure. The knowledge about dimensioning criteria influences and drives the selection of materials. For example, GLARE® (Glass Fiber Reinfoced Aluminum) material has excellent properties regarding crack growth. Consequently, this material is a recommended choice for the upper fuselage panels, where the crack growth criterion is typically dimensioning to the structure. On the other hand, the low-cost stringer-to-skin-welding is mainly used in the lower fuselage, where static and stability are typically the dimensioning criteria.

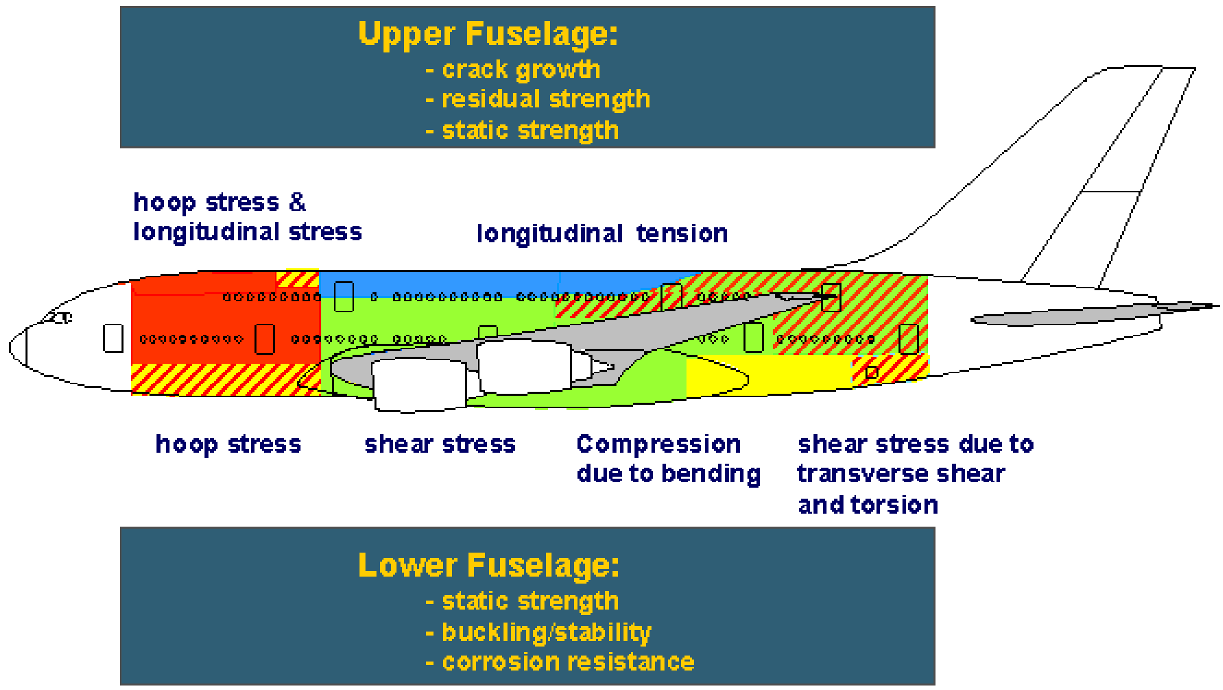

Figure 2: Example for dimensioning design criteria on metallic fuselage structure [3]

Development of structure inspection program: For any new developed aircraft, it is necessary to demonstrate that the safety and airworthiness will be given throughout the whole lifetime of the structure. Any initial manufacturing damage as well as any service-induced damage may not affect the safe operation of the aircraft.

To provide such high level of safety, a structure inspection program is developed for every new aircraft. Figure 3 shows (in a simplified way) the establishment procedure for such program. The analysis of damage tolerance behavior (e.g. crack growth and residual strength) plays an important role in the establishment of this program. However, also the damage detectability provided by the NDI/NDT methods available has significant influence on the structure inspection program.

The structure inspection program finally provides information about

- Inspection threshold: time of first inspection in flights
- Inspection interval: period between the repeated inspections in flights
- Inspection method: information of the method to be used, for NDI methods the detailed description of the method is given in a special handbook

Large parts of the metallic aircraft structure are today designed according to a damage tolerance design philosophy. Figure 4 shows an example for a damage tolerance investigation: In this case, a crack in a metallic fuselage skin is investigated. The upper part of Figure 4 shows schematically a skin crack above a broken stiffener (the assumption of a broken stiffener has to be made because there are no sufficient internal inspections to guarantee the integrity of the stiffener under the skin). The lower part of Figure 4 shows a crack growth analysis for this configuration: the crack growth behavior is calculated assuming operational loads. At some point the curve crosses the detectable crack length, which is significantly depending on the inspection technique used. After a certain period of growth the curve crosses the critical crack length (defined as the longest crack, which permits the structure to carry limit load). The interval between the detectable and the critical point, divided by a scatter factor, sets the required inspection interval, which has to be compatible with the aircraft's inspection program. Therefore, the panel dimensioning has to be chosen according to the crack growth criterion: The crack growth under operational loads must be sufficiently slow in order to meet the inspection plan. This illustrates that there is a strong link between the sensitivity of inspection methods/technology and the dimensioning (weight), which finally determines the performance of the structure.

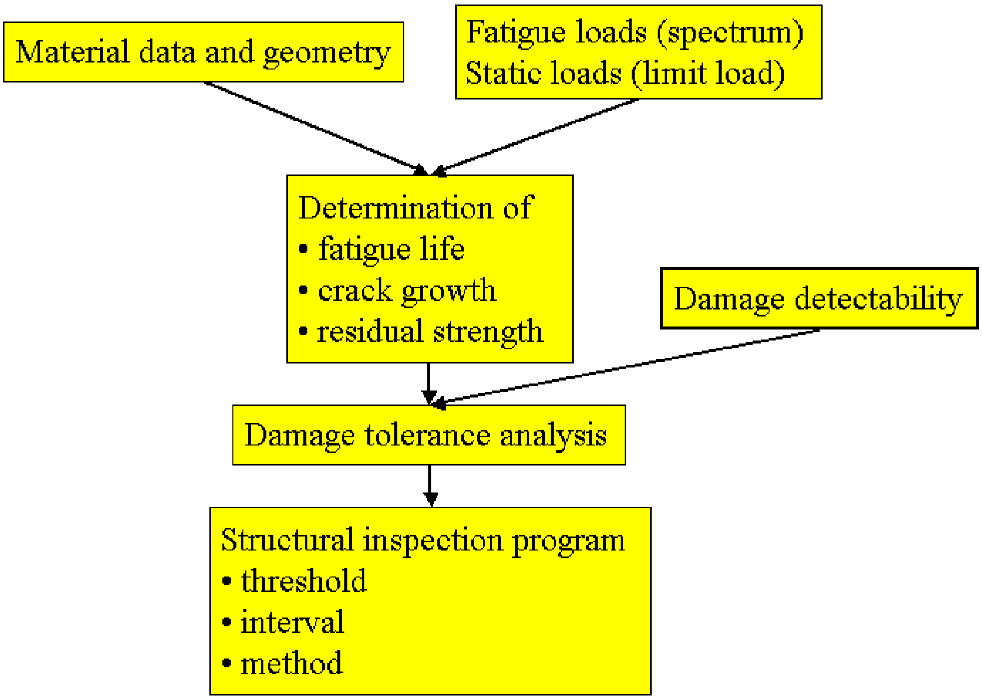

Figure 3: Development of structure inspection program (simplified)

The structure inspection program covers different types of inspection activities, classified in three inspection levels. These are:

- General visual inspection (GVI):
  A visual examination to detect obvious unsatisfactory conditions and discrepancies. The inspections are performed in frame of the so-called zonal inspection program where the complete aircraft, divided in zones, is inspected in regular time intervals.
- Detailed visual inspection (DET):
  An intensive visual examination of a specified detail or assembly searching for evidence of irregularity.
- Special detailed inspection (SDET):
  An intensive examination of a specific location similar to the detailed inspection but requiring special techniques, mostly NDI.

The method chosen in the individual case depends on many factors. If for example the designers accept a higher stress level in a special component, the result will be a shorter critical crack length combined with an accelerated crack growth behavior. This puts higher requirements to the inspection method chosen, in order to meet the inspection program. Again the link between inspection technology and structural performance becomes visible.

When looking on a major structural component of an aircraft (e.g. a stiffened fuselage or wing panel), it can be stated that normally a combination of the inspection levels is applied: in many cases, a GVI is mandatory for the whole component, while in specific areas DET and SDET/NDI have to be applied.

The NDI/NDT methods currently applied at Airbus are mainly:

- Visual Inspections
- X-Ray
- Ultrasonic Testing (UT)
- Eddy Current Testing (ET)
- Resonance frequency method (manly metal bondings and composite structures)

However, Airbus is also looking at (and partially already using) some newer methods, e.g.:

- Shearography / Mobile Shearography
- Eddy Current Arrays
- Ultrasonic Phased Arrays
- Thermography / Lock-In Thermography / Pulse Thermography / Ultrasonic Excited Thermography
- Laser Ultrasonic
- Air Coupled Ultrasound

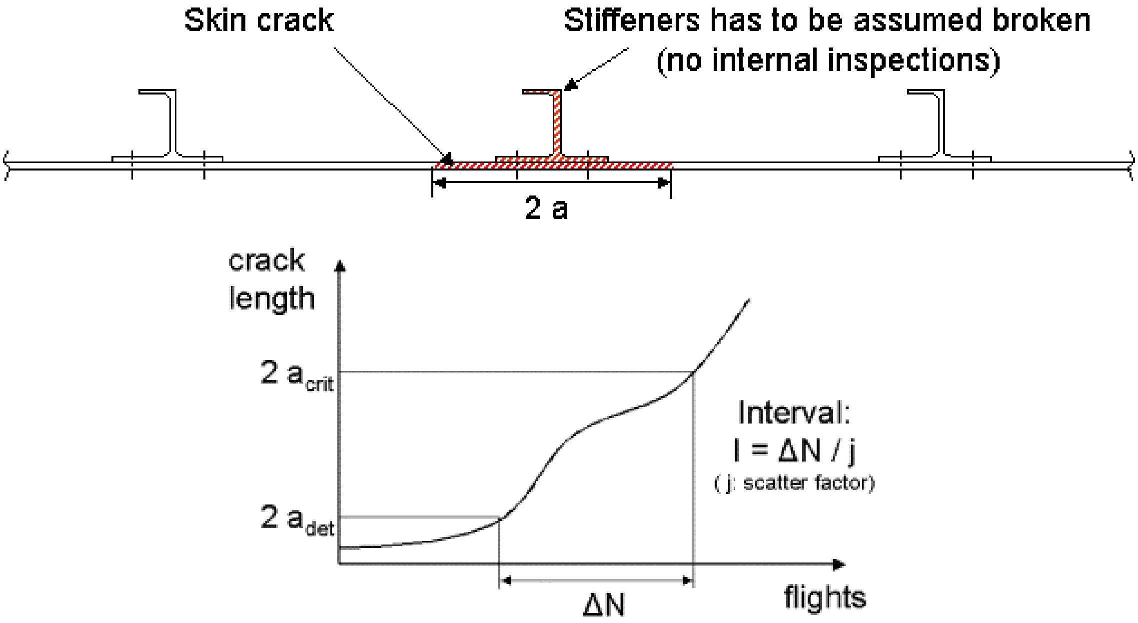

Figure 4: Example for damage tolerance investigation: skin crack over a broken stiffener

In the field of Structural Health Monitoring (SHM), some additional methods are applied, e.g.:

- Acousto Ultrasonic Patches
- Comparative Vacuum Method (CVM)
- Optical Fibers, specially: Fiber Bragg Gratings
- Acoustic Emission (AE)
- Embedded Eddy Current Sensors

1st example for NDT application – Monitoring of Friction Stir Welding (FSW): In order to build aircraft primary structures that are less expensive than currently riveted structures new advanced joining techniques are being developed. Friction Stir Welding (FSW) is a promising technology, which is expected to deliver cost savings, weight reductions, and higher mechanical properties.

FSW is based on rotating tool moving along the joint, the frictional contact generated by the tool heat the material, the softened plastic material consolidates to form a solid phase weld. Although the FSW process is stable and robust the occurrence of defects due to incorrect process parameters or unexpected events has to be taken into account.

Assurance of high quality of the weld is of paramount importance in order to provide consistent mechanical properties.

Currently both online and offline NDT methods are investigated for application during manufacturing.

- Online methods for process supervision
  Analysis of process data, thermographic temperature measurement, optical measurement of surface shape / deformation
- Offline methods for quality assurance
  Ultrasonic testing (conventional and phased array), Eddy current arrays, X-ray and penetrant testing, Lock-in / pulse thermography

Figure 5 shows an example of defects in the weld line. Tunnels and lack of penetration have a major impact on the mechanical properties but can be detected with conventional as well as with phased array ultrasonic testing. Most challenging is the root flaw detection but its significance on mechanical properties is also not yet clear.

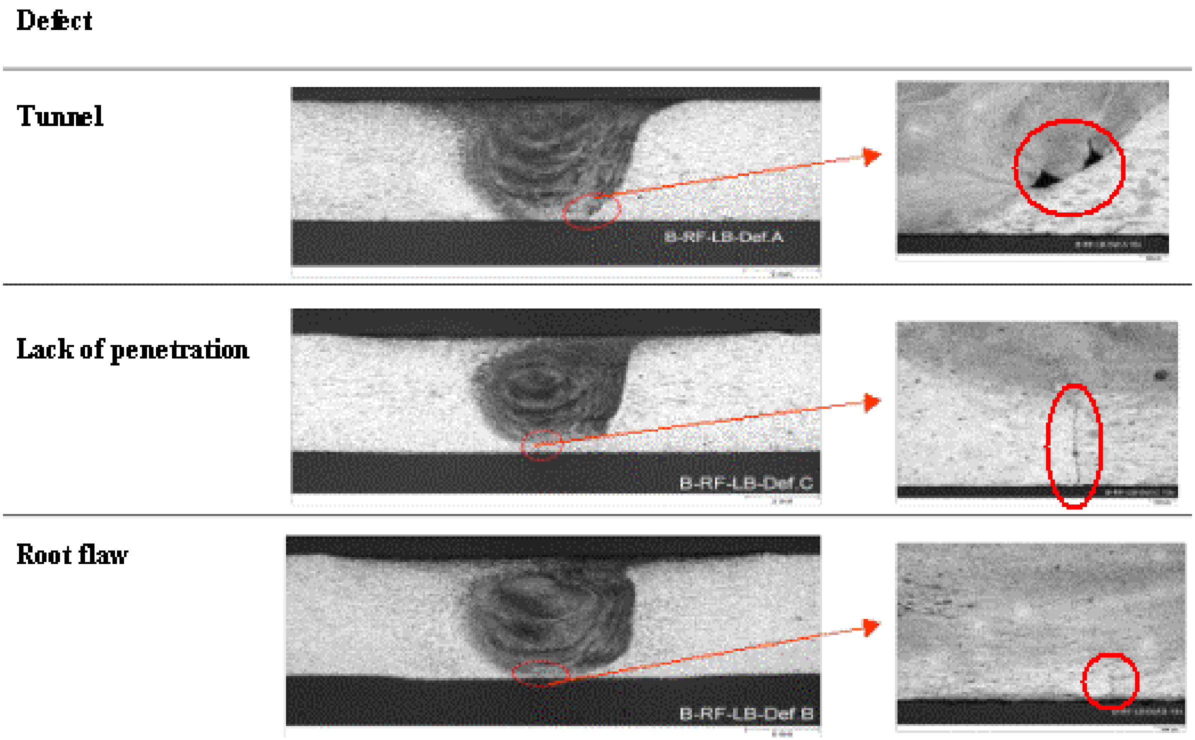

Figure 5: Example of defects in FSW welded weld line

2nd example for NDT application – Semi-finished products (GLARE®): GLARE® Material is a fiber-metal-laminate, a lay-up of aluminum layers and glass fiber / adhesive layers, as illustrated in Figure 6. It is considered a metallic material, mainly because in can be processed and machined like monolithic metallic materials. However, GLARE® has significant advantages over monolithic materials, especially regarding its damage tolerance (crack growth and residual strength) properties.
Figure 7 illustrates an application for testing of GLARE® sheets by the application of the Squirter Ultrasonic method. This method uses the ultrasonic transmission through a water beam in order to check the integrity of the sheets. Specially, the method is able to identify de-lamination voids within the GLARE® sheet.

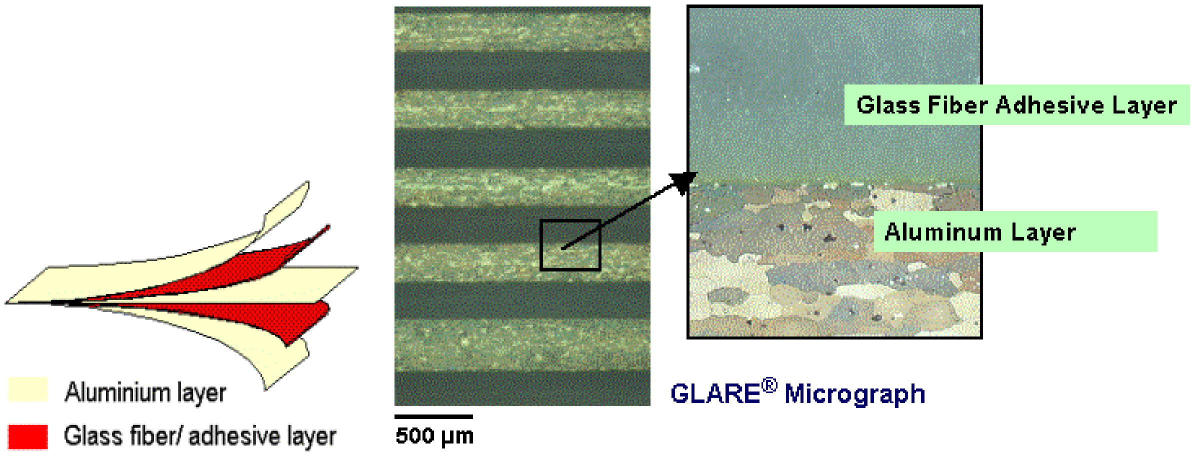

Figure 6: GLARE® principal lay-up and micrograph example

Regarding the GLARE® material's use in aircraft structures it is emphasized that there is a possibility that less (or no) inspections will be needed throughout the operational life of these structures. This reduction of inspection effort should be possible for the skin field as well as for specific areas like e.g. lap joints. The reason for this development is that the growth of cracks in GLARE® material is extremely retarded, compared to monolithic metallic material. The reduction of inspection effort will make aircraft more attractive to customers, since it reduces operational cost and downtimes.

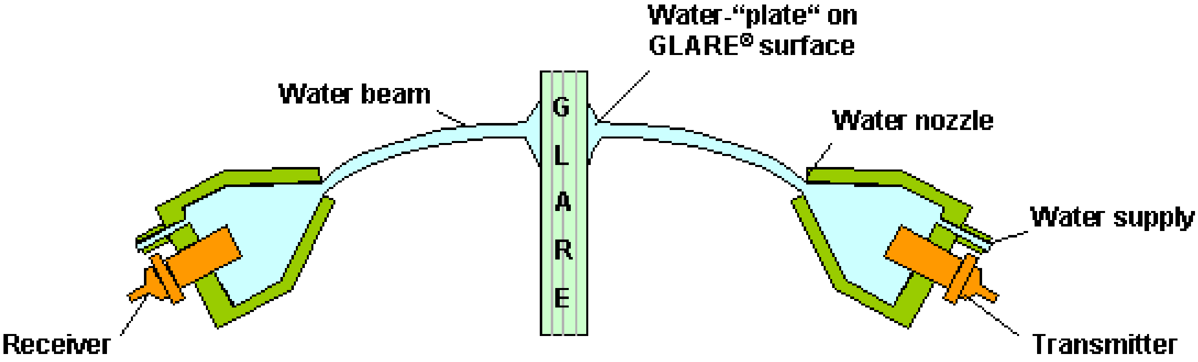

Figure 7: Squirter Ultrasonic method for testing of GLARE® sheets

Expected future developments: For the future, an increased use of Structural Health Monitoring (SHM) is expected. Short-term benefits to aircraft manufacturers as well as operators will mainly result from monitoring of known hot-spot areas of the aircraft type under consideration. Furthermore, short-term benefits may also result from monitoring of cracks in the aircraft structure.

On the other hand, there are also long-term benefits, which need some more development time before they can be achieved. These benefits will in future result from consideration of the SHM system already in the aircraft design phase. By this philosophy, the Damage Tolerance design criteria like crack growth and residual strength (metallic structures) or the compression after impact criteria (composite structures) can be applied in a different way, compared to structure design without SHM systems. The criteria mentioned will then be released regarding their impact on the dimensioning of the structure, compared to today’s design philosophy. Therefore, the design will be optimized, offering the possibility to save weight on metal and composite structures while maintaining airworthiness and fulfilling current and future regulations.

Figure 8 contains an example of SHM application to fuselage structure. It is assumed that the fuselage stringers are permanently monitored by SHM, whereby the skin is visually inspected from outside, according to the intervals given in the aircraft’s inspection program. The advantage gained by this modification results from the fact that in traditional design philosophy, the stringer under a skin crack (see Figure 4) has to be assumed broken, since there is no monitoring of this internal member, and also no sufficient scheduled internal inspection. With the modified design philosophy – using SHM – the stiffener will be monitored throughout the aircraft life and may therefore be assumed intact in the calculations. The assumed crack scenario is the less stringent damage scenario, i.e. a skin crack above an intact stringer. The figure shows a significant slower crack growth resulting from SHM application. The crack growth period (in terms of number of flights) between 2a = 75 mm, which is detectable by general visual inspection, and the critical crack length is increased by a factor of roughly 2.5. This would on the one hand allow an increase of the intervals for general visual inspection by this factor. On the other hand, it may also be used to increase the allowable stress level by more than 15 percent, while keeping the inspection interval constant. This significant improvement is not possible for areas dimensioned by other design criteria, e.g. static strength.

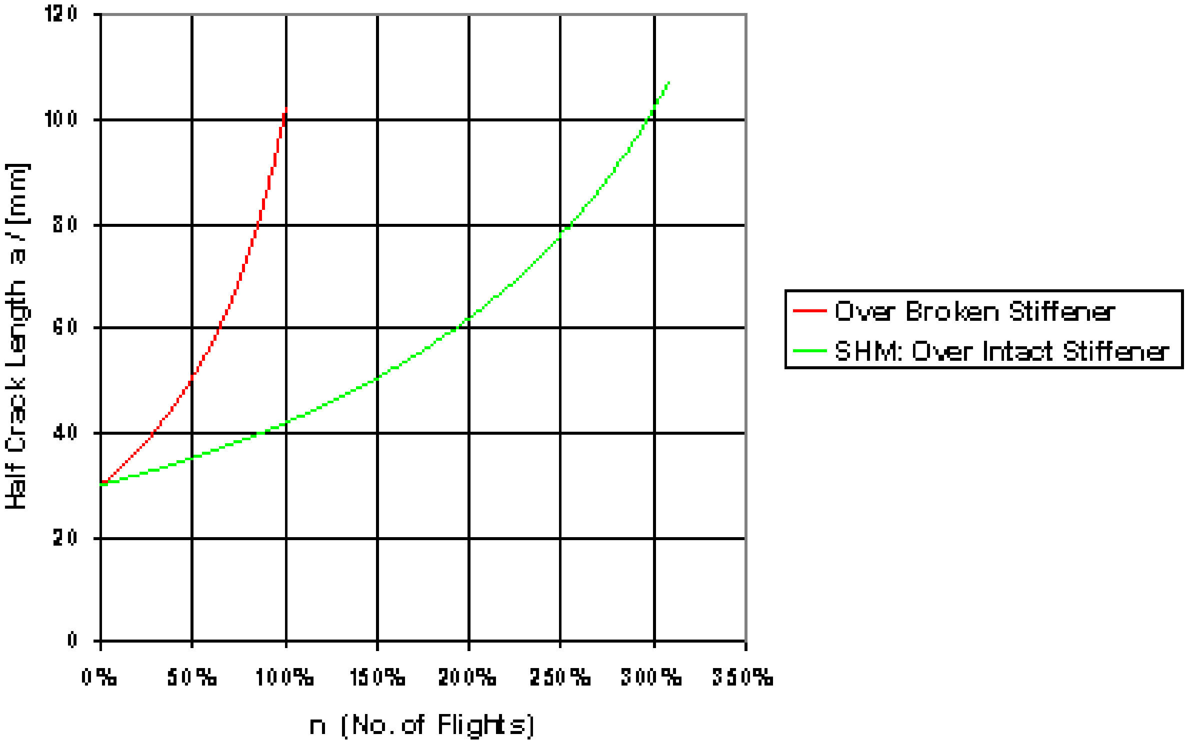

Figure 8: Modified crack growth design philosophy, using SHM to monitor stiffeners on fuselage structure

Conclusions: The design of aircraft structure is a complex issue. New materials (e.g. GLARE®) and new technologies (e.g. Laser Beam Welding and Friction Stir Welding) offer new degrees of freedom, but simultaneously increase the complexity of the process.

The NDI/NDT technologies play an important role through all phases an aircraft's life cycle. It is evident that aircraft maintenance and NDT technologies are strongly linked. However, there is also a strong link of NDT to the aircraft design and dimensioning. This is illustrated above on the examples of damage tolerance and crack growth criteria, which play an important role in the dimensioning of aircraft structure. Therefore, the requirements to NDT technologies are in the process of steady change and extension.

It is important to emphasize that a close cooperation of different involved disciplines will be needed to be effective with future NDT technology developments and improvements. These disciplines include:

- A/C Architecture & Design Principles
- Materials & Protections
- Design & Analysis Methods
- Sizing & Certification Approaches
- Manufacturing & Assembly Processes
- Operational Support

In addition, close co-operations between aircraft manufacturers, material and technology suppliers and aircraft operators need to be established!

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