Structural Integrity Management System for enhanced aircraft availability

Christian Stolz
Manfred Neumair
EADS Defence & Security, Military Air Systems
Structural Integrity Management & SHM
Rechliner Straße, 85077 Manching, Germany

christian.stolz@eads.com

ABSTRACT

Due to high development cost of new flying weapon systems operators rely more and more on existing aircraft systems by upgrading these systems with modern equipment and avionic systems. Nevertheless the aging of the airframe becomes more and the key player with respect to reliability, operability and maintainability.

New ways of managing the structural integrity of these aging aircraft are required to ensure the operability and to maintain or reduce the life cycle costs. Therefore a Structural Integrity Management System (SIM System), which combines the assessment of different degradation effects (surface protections, corrosion, delamination, fatigue, repair effects), the results of the usage monitoring and the in-service experience in order to

- *increase safety,*
- *ensure the qualification requirements,*
- *enhance operations (availability, reliability, performance) and*
- *reduce maintenance costs*

is considered as a new approach to manage the fleet of aging aircraft.

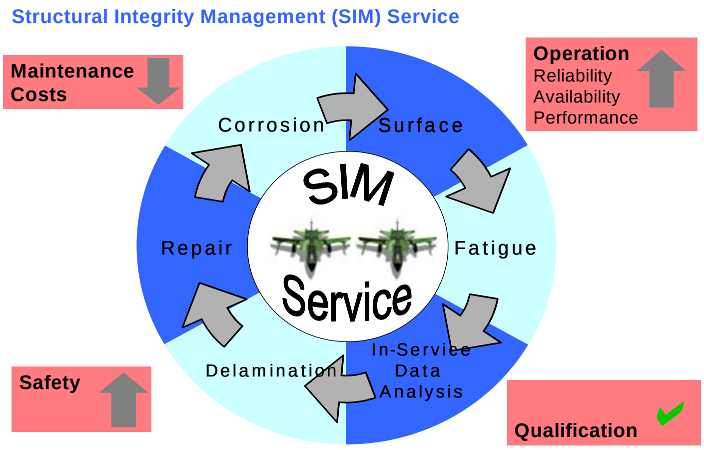

Figure 1: Overview of the Structural Integrity Management Service

The paper will give an overview of the approach and developed models, which are the basis for a Structural Integrity Management System.

All platform data (qualification, usage, maintenance,…) have to be collected, combined and consolidated to specific critical platform information.

Models for the assessment of different degradation effects were developed, validated and trimmed to handle real in-service events. For instance, corrosions effects are covered by an engineering approach which is based on the fatigue and damage tolerance philosophy.

Alternatively, a stochastic lifing method is developed to cover all degradation effects with the input of in-service inspection data in a probabilistic way. Hereby the concept of reliability-based design is introduced. Historically based scatter and safety factors are getting less reliable with highly optimised structures and new materials and design concepts. Therefore a direct access to the knowledge of reliability is needed and provided by the stochastic lifing method. Further, the method will support future Prognostic Health Monitoring systems.

Risk assessment for in-service A/C is based on the probabilistic analyses of the combination of corrosion in-service data and fatigue screening.

Usage monitoring on IAT basis helps to estimate the variability of operation and to define on the local loading spectra. Usage severity is the important factor to ensure the structural integrity. Usage data are used for prognostics.

Effect on improvement of operability and life cycle costs will be raised.

1.0 SITUATION AND BACKGROUND

Due to high development cost of new flying weapon systems operators rely more and more on existing aircraft systems by upgrading these systems with modern equipment and avionic systems. In consequence, the aging airframes are becoming the major limiting factor, in case of reliability, operability, maintainability. And this will further increase fleet costs, if no enhanced fleet management systems are introduced.

Over the last years, the reasons for replacing platforms have changed. As stated in the RTO-Workshop "FUTURE AIRFRAME LIFING METHODOLOGIES": "In the past, aircraft performance obsolescence was the primary factor in removing an entire platform inventory from operations and replacing it with a new type or model aircraft. All past service/agency-specified fatigue life limits never really constituted overall controlling limits in fleet life management. Fatigue almost never became the primary factor justifying the removal of an entire platform inventory. In essence, fleet life management functioned mostly in terms of planning inventory removal versus the need for new acquisition." For example, the EA-6B Prowler fleet is one case where fatigue has become a critical factor in deciding when to retire the aircraft.

"Today, fatigue life has become a primary factor for the removal of a platform inventory, not aircraft performance obsolescence. The critical question now is - what constitutes end of fatigue life? This question can only be answered in terms of tolerable risk as specified by the risk takers, the aircraft owners-operators-managers. In essence the next evolutionary step in fleet management is the incorporation of reliability engineering management concepts. A clear quantitative risk assessment must state the probability of failure, or conversely the reliability, associated with critical structural components."

[1] RTO-TR-AVT-125, "Future Airframe Structural Lifing: Methods, Applications and Management", NATO Research and Technology Organisation, Pre-Release July 2008

2.0 VISIONS

In times of shrinking military budgets, lifecycle costs are one of the key parameter for fleet management. The requirement to limit the cost increase of aging aircraft fleets can be satisfied by optimizing existing processes to manage fleets. For maintenance, this means an optimisation in planning (optimal timing and securing the high safety level) based on enhanced forecasts of structure integrity. Managing structural integrity means to satisfy the following requirements:

- Safety
- Performance
- Reliability
- Availability

The defined high level of all four requirements have to be ensured continuously, even beyond design life where unexpected degradations are one of the main problems of aging aircraft. The latter two requirements focus mainly on the optimisation of maintenance planning. This can be reached by using degradation forecasts based on individual usage and maintenance history.

The vision is to develop a management system which satisfies all the named requirements by combining all effects of different structural degradation. This system uses engineering analysis tools which interact with usage and maintenance data to proactively predict trends as a basis to manage fleets, and to perform maintenance planning.

3.0 PROCESS OF THE MANAGEMENT SYSTEM

Starting from the qualification requirements and the qualification results the structural integrity management process has to cover the following aspects:

- increase safety,
- ensure the qualification requirements,
- enhance operations (availability, reliability, performance) and
- reduce maintenance costs

to meet the aim of a condition and usage based maintenance.

As this process itself could be complex and cost consuming, there is the need to perform a dedicated selection of the components or parts where this process promises the expected benefit.

There are two possibilities to apply this process on an aircraft type:

- Process will be considered during design and starts from entry into service. In this case the process can provide the most benefit, as the selection of the relevant components, gathering of the relevant usage data and environmental data including the continuous and detailed recording of maintenance data. But this is not the case for most (or nearly all existing) platforms.
- Therefore this process has to be adapted on an existing structural integrity philosophy / process like a safe life or damage tolerance based approach. As the relevant parts of the structural integrity concept like usage monitoring, maintenance processes inspection requirements are focused on the original approach, specific adoption / changes are required to start a new structural integrity management process. The following figure shows that a detailed selection of the components and parts is required, which will feed into the structural integrity management process.

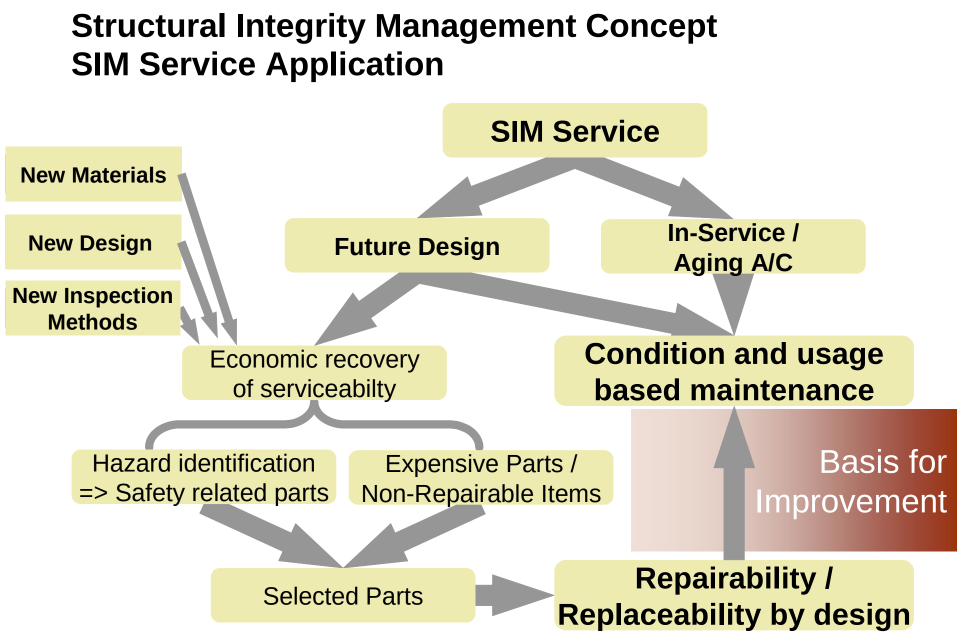

Figure 2: Application of the Structural Integrity Management Concept

The relevant parts are:

- Safety Related Parts
- Parts or Components with a high value or which are unrepairable and unreplaceable in case a damage exceeds a certain limit

Before transferring these parts into a condition and usage based maintenance a risk assessment phase including the identification of the relevant hazard values needs to be performed to clearly identify the risk using a condition and usage base management approach.

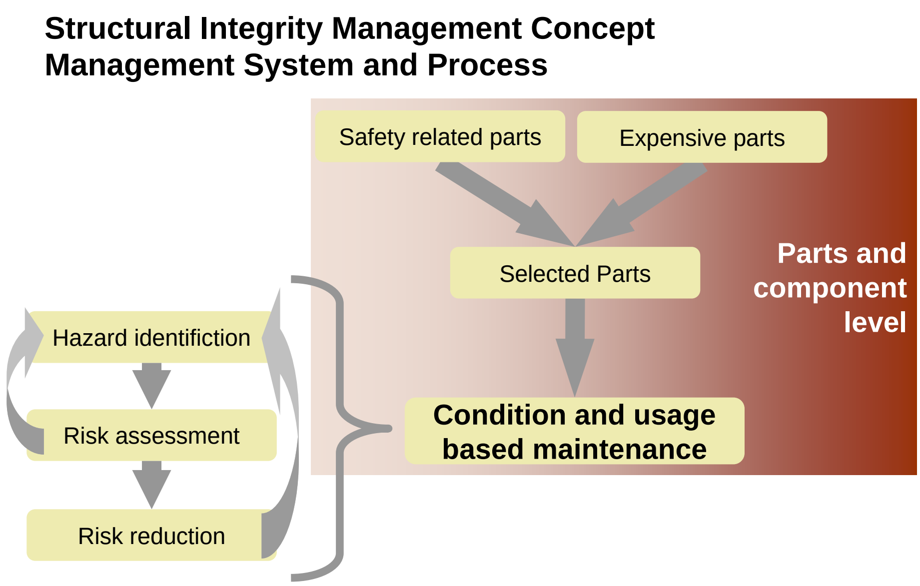

Figure 3: Process of the Structural Integrity Management Concept

After selecting the relevant parts the gathering of the required information is the next important step. Figure 4 shows the relevant levels of information and the relationship between these levels. For in-service aircraft the usage history on a component and parts basis is mainly limited to the data which have already been recorded during the in-service operation. The amount of data and accuracy of data is dependent on the existing data acquisition systems. The interpretation of these data by intelligent methods of superposition of loads and environmental data will provide a dedicated description of the current condition supported by (dedicated) inspection results. The interpretation of the current condition including the usage history allows the calculation of degradation factors and therefore of life consumption trends tailored for the various in-service usage scenarios. This factors and trends combined with design assumption and qualification results will allow a dedicated prediction of the forecast for the structural integrity capability.

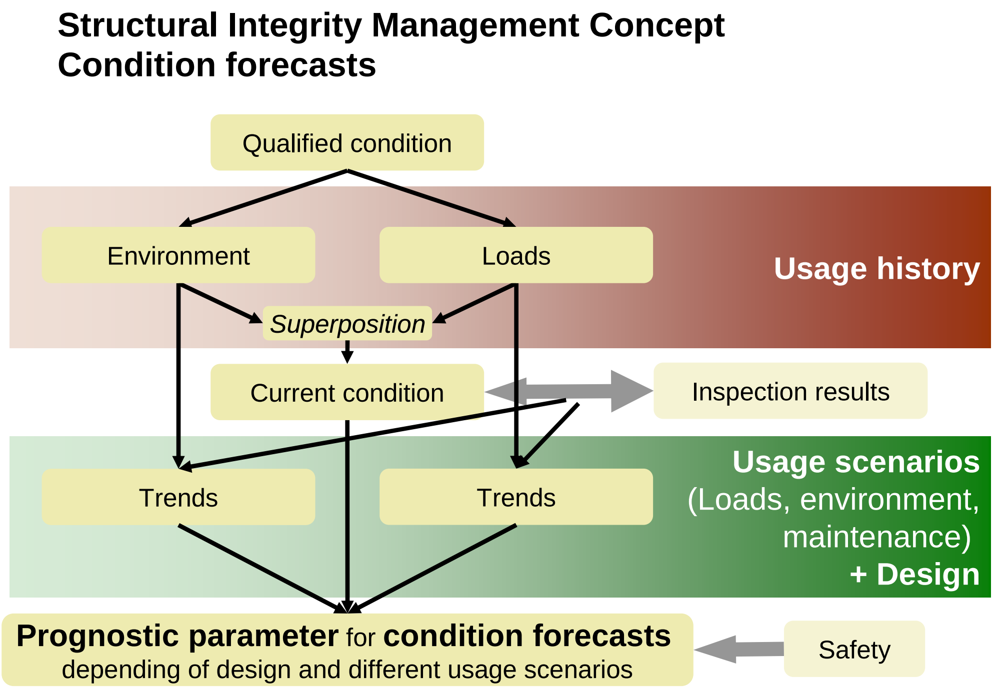

Figure 4: Derivation of condition forecasts

The process is a living process and needs to be performed in a continuous way to support in an efficient way the operational and maintenance planning.

4.0 METHODS

The main function of the system management lies in the several methods to assess the different degradation effects, which are combined in this approach. The combination is realised in an engineering analysis tool which interact with usage and maintenance data. The result of this tool is to proactively predict trends depending on different scenarios.

In order to assess the degradation effects data from design, test, research and maintenance data are used. All necessary data were taken into consideration to perform an individual trending. Hereby the predictions are based on the usage data together with data from the degradation model which are extended and verified by inspection data.

4.1 Prediction methods for remaining life of corroded structures: simple + enhanced

Maintenance and repair activities to mitigate the effects of corrosion are in many cases over-conservative due to the absence of technology to predict the impact of corrosion on structural integrity. An additional problem with corrosion is that its plain existence itself is not predictable. If we would know where corrosion occurs, proper protective measures could be taken in advance. Maintenance is therefore primarily reacting to the corrosion problems that surface during depot or other inspections. A strategy known as “find & fix”. The only action taken to a clear benefit of the fleet management program of a given weapon system (aside from a complete rework), is to improve and optimize the maintenance processes itself. This can be achieved by increasing the ability in planning and scheduling of corrosion related maintenance work. The key is to establish a prediction tool to determine the remaining life of a structure, which was developed within EADS MAS. The advantages of such a lifing analysis are diverse. The ability to predict the remaining structural life leads from a “Find & Fix” to a “Assess, Predict & Manage” approach. Thus, the severity of corrosion damage can be judged, and the extent and severity of corrosion that should not be overseen or neglected can be determined.

During their service life, military aircraft typically experience corrosion between flights when exposed to aggressive atmosphere or due to practical reasons such as that condensed water remains in the structure after landing, promoting corrosion. Aircraft thus experience comparably little fatigue-corrosion interaction and the consequences of prior corrosion on the remaining life become of interest.

To predict the remaining life of precorroded structures two methods were developed within EADS-MAS:

1. The first prediction model is simple and quick as it is based on existing fatigue calculation routines (Miner's linear damage accumulation) with special S-N material data representing the corrosion degradation effects. The corroded S-N data were defined by extensive testing for different material, manufacturing methods and stress concentrations. A brief overview is shown in Figure 5. A further development of this method was to express the corrosion degradation as a damage-equivalent increase in stress concentration. Several damage-equivalent stress concentration factors $k_{t,equi}$ were defined.

2. The second prediction model is more sophisticated, which results in more accurate predictions, but also in more calculation effort. The corrosion degradation can be categorized in three types which can be analysed with static and fracture mechanics calculations, as shown in figure 6. The fatigue life degradation due to pitting corrosion is predicted with the linear-elastic fracture mechanic

[2] M. Lang, C. Stolz, T. Hack, V. Holzinger, "Technology for Corrosion Management of Aging Aircraft", presented at ASIP 2001, US Air Force Aircraft Structural Integrity Program Conference, Williamsburg, VA, USA, 11-13 Dec. 2001

approach with an equivalent crack length for the corrosion pits, taking into account an estimated extend of intergranular corrosion.

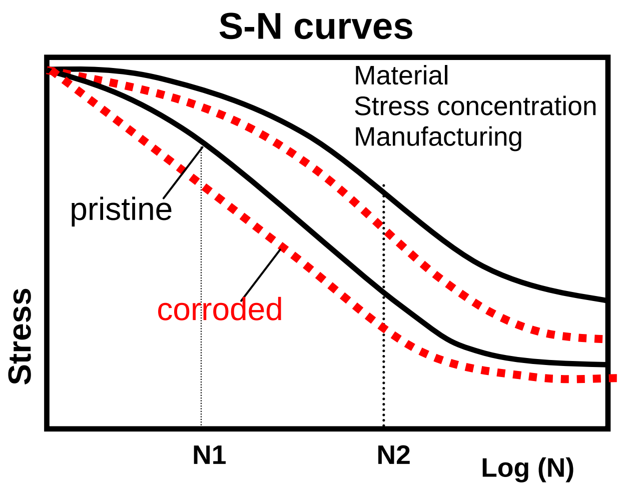

Figure 5: Conceptual approach for the corrosion damage assessment of using fatigue S-N data.

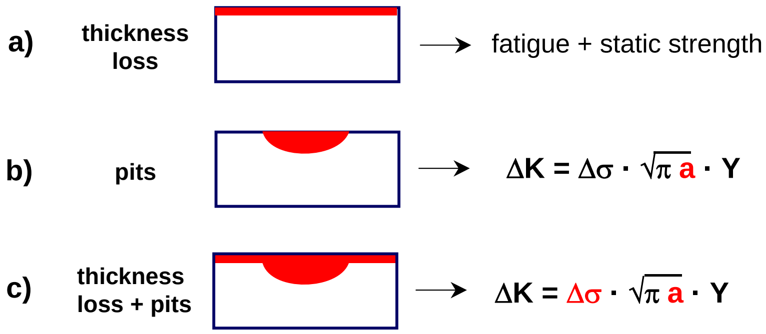

Figure 6: Categorization of corrosion degradation and conceptual treatment using fracture mechanics

Several tests to verify both methods were conducted using corroded specimen.. An example of a corroded specimen representing a splice joint and its analysis results are shown in Figure 7. The predictions using the "Equi-k_t" method show a high level of safety compared to the crack growth predictions, which fit quite well to the test results.

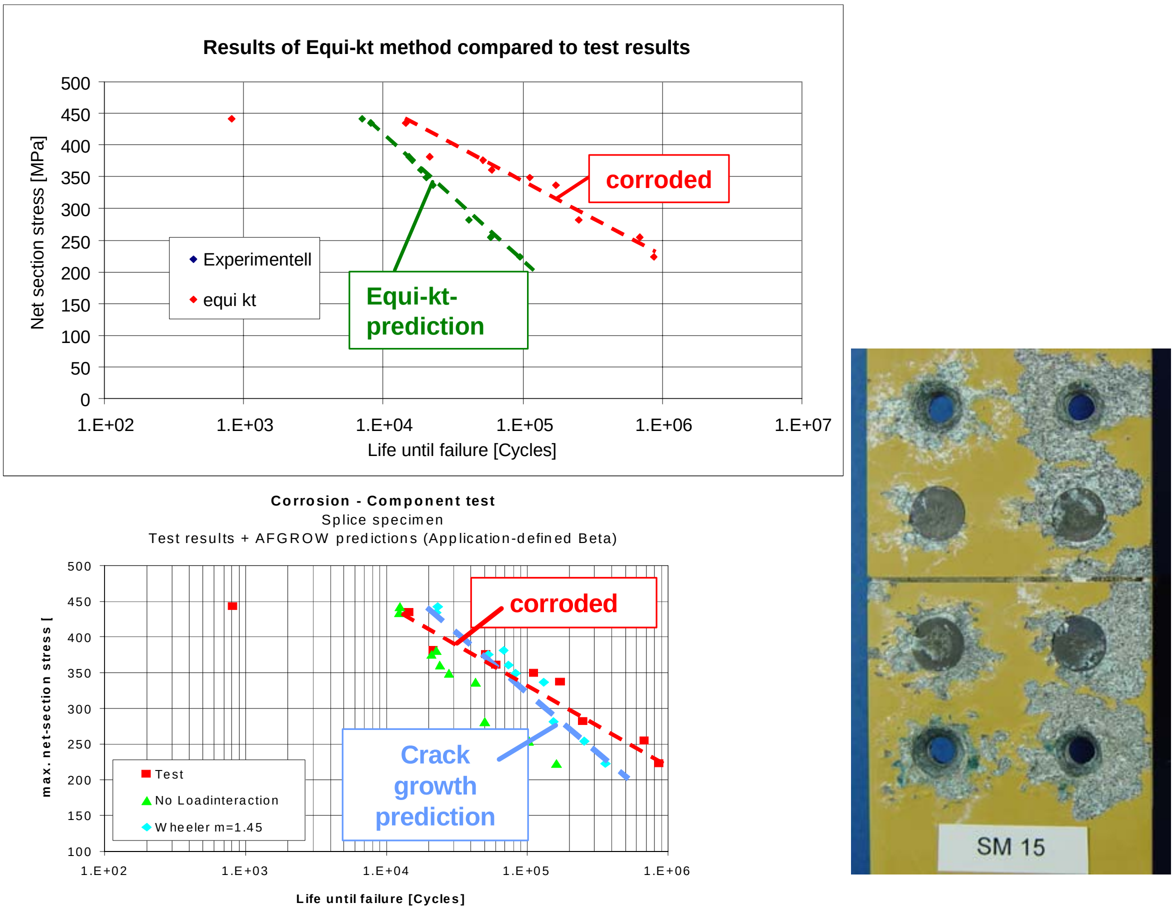

Figure 7: Comparison of remaining life predictions and test data for corroded splice specimen

4.2 Usage Monitoring

The usage monitoring is mainly dependent on the limitations of the usage monitoring systems which are available in each individual aircraft. Especially for older aircraft types the usage monitoring is related to manoeuvre loading based on g-counts or some additional flight parameters or strain gauges. The monitoring of environmental data has normally not been performed. Detailed usage data are often only available for a short range. Nevertheless the process allows to combine the high level short term data with the long term low level data supported by inspection results to determine the relevant usage consumption for the various components and parts.

The following few items are required for a high level short term usage monitoring

- Dedicated flight by flight usage recording including hot spot measurements
- Development of high level algorithms to recalculate the low level historical data based in tuning factors derived from the high level short term usage monitoring
- Dedicated monitoring of environmental data incl. assessment of low level historical data.

4.3 Stochastic Lifing Approach (SLA): Benefits

The interest and technology effort in stochastic fatigue analysis has intensified during the last years. The driver is the trend to introduce more attributes of reliability-based design. As an alternative to deterministic analyses of aircraft structures, stochastic approaches are promising. The basic deterministic analyses for the safe life and damage tolerance philosophy have not considered the variability of parameters used in the analyses. Instead, the variations of parameters are covered by scatter and safety factors. In general, such deterministic analyses result in over-conservative (short) life estimates and short inspection intervals. As a result, the reliability (safety level) of the structure and its components is not properly known. With continuing aging and the extension of service life, beyond the designed and tested basis, the unknown level of conservatism is diminishing. Therefore, a strong need developed to introduce stochastic approaches with the ability to assess the reliability level.

The Stochastic Lifing Approach used in this Structural Integrity Management System is based on the work of Frank Grooteman. The analysis can be started at end of the service life or some time before . A sufficient number of inspections data are essential because they form the basis for a service life failure distribution that represents the probability of failure for a certain component life. From this failure distribution, the crack size distribution at any time can be determined by means of a reversed stochastic crack growth analysis. With these reverse calculations, a resulting crack size distribution can be calculated for the initial inspection time. Or for a defined detectable crack length the initial inspection time can be calculated. To determine an optimal repeat inspection scheme which fulfils the allowed Probability Of Failure (POF), the crack size distribution is used in an upward stochastic crack growth analysis together with the corresponding Probability Of Detection curve. With the results of several in-service inspections, the calculated failure distribution can be verified and if needed the inspection scheme can be updated with the same analysis process.

This adaptive approach will lead to an optimized inspection scheme with an accessable knowledge of the safety level.

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[3] F.P. Grooteman, “A fully stochastic approach to determine the lifetime and inspection scheme of aircraft components”, NLR-TP-2004-131, April 2004

5.0 FORECASTS AND GLOBAL MEASUREMENT

5.1 Trending and forecasts

The basics for an optimized fleet management are realistic forecasts and trends for the future structural capabilty of the airframe. As described above, this Structural Integrity Management System tries to integrate every degradation and describe the behaviour in an overall capabilty.

In figure 8 the linkage between the structural condition data of a fleet based on inspections and the operational usage data coming from the usage monitoring is shown. Together with basic design data, information generated by certification tests and reseach data the structural degradation and the strucural remaining life is determined.

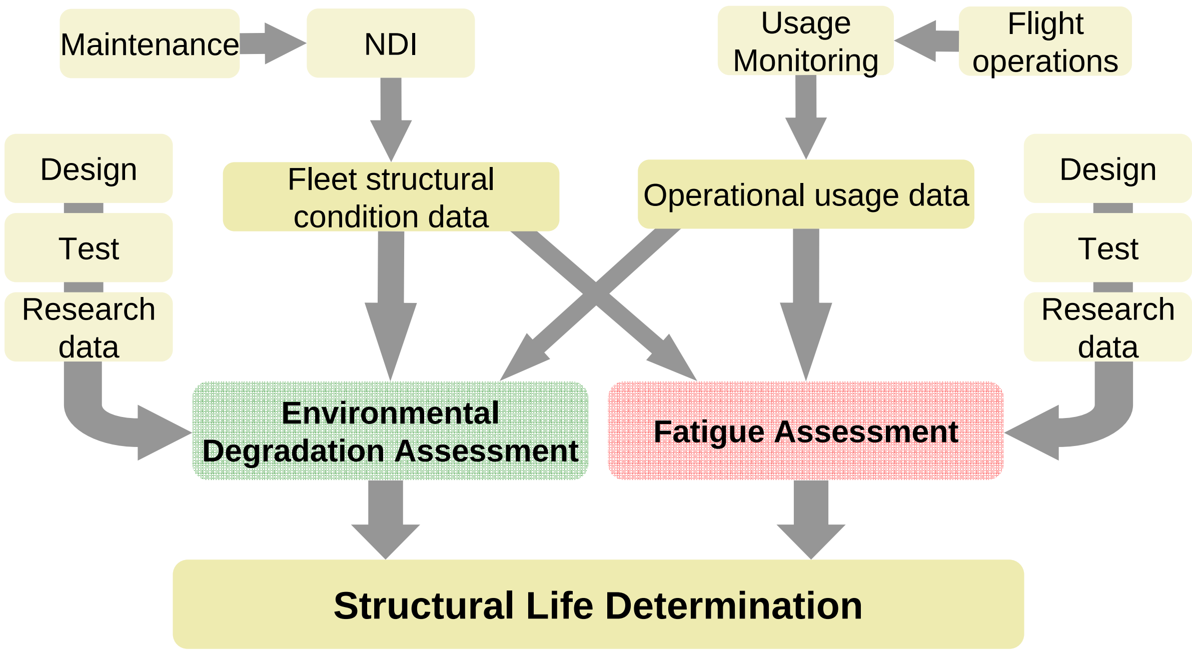

Figure 8: Framework of Structural Life Determination

5.2 Criticality index as a unique measurement parameter

In order to asses, compare and rank the structural capabilty of different components and even airframes with differnt degradation effects a unique measurement parameter is needed. This parameter has to represent the criticality of a combined degradation damage. In figure 19 the combination of environmental damage (ED) and fatigue damage (FD), resulting in the combined damage (CD) curve is shown exemplarily. The environmental damage is derived from equivalent crack length used for the assessment of the corrosion pitting degradation. The fatigue damage represents the number of fatigue loading cycles. The shown failure curve is resulting from predictions of the remaining life as described in chapter 4.1. and verified by tests.

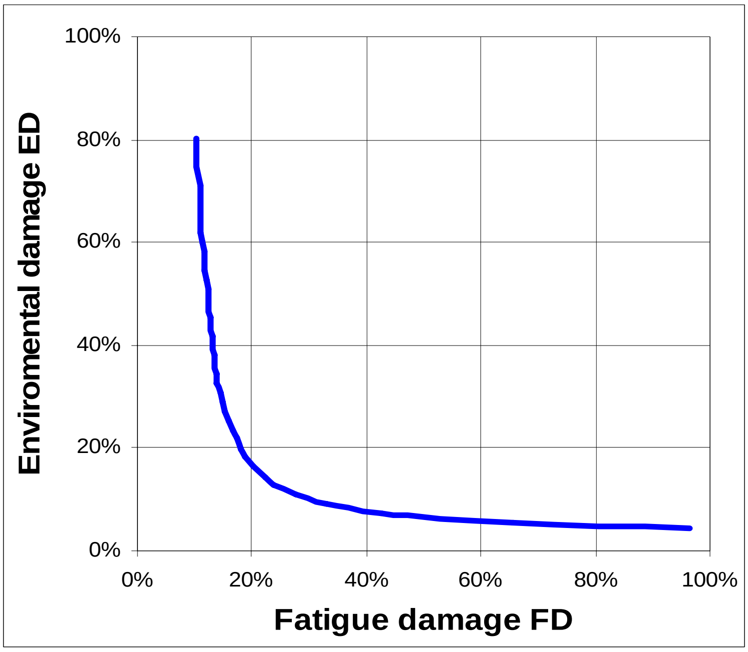

Figure 9: Combined damage and failure curve

In order to describe the criticality of a combined damage, the Structural Integrity Criticality (SIC) is defined as the combined damage divided by the critical combined damage derived from the failure curve. Figure 10 is showing exemplarily a detail area of figure 9 with an combined damage at time t_1 ($CD(t_1)$) and the critical damage. For time t_1 the probality of the combined damage is shown here as a box. Furthermore the area of trending is shown in shaded colour. The trending area is derived from forecasts as described in chapter 3. The prognostic parameter used in the trending analysis are based on

- initial design
- inspection results
- individual damage scenario
- superposition of various degradations
- risk assessment
- usage experience

Based on this prognostic, trends are calculated for the critical combined damage size. This will result in a failure distribution based on the combined damage, the individual degradation and usage scenario.

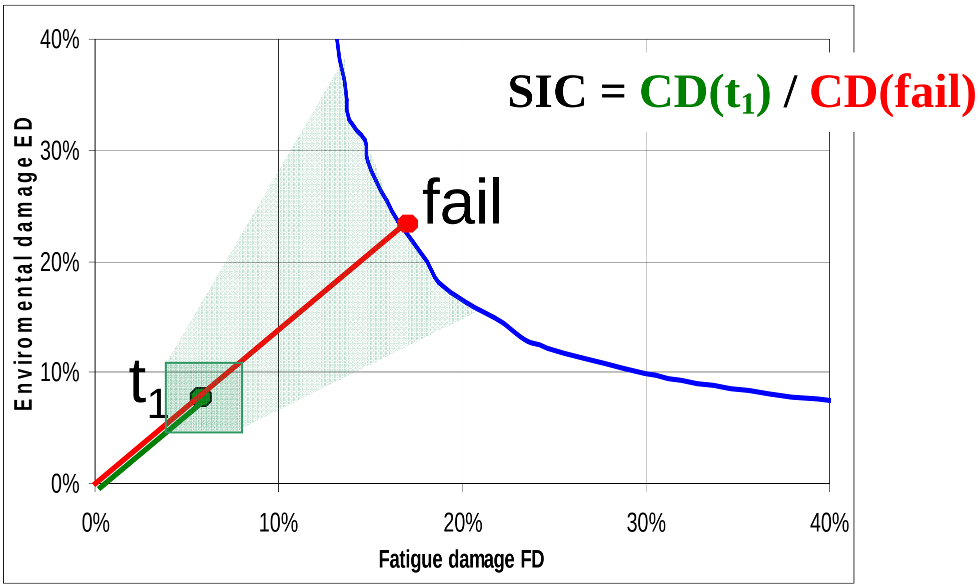

Figure 10: Trending for the combined damage and Structural Integrity Criticality.

6.0 BENEFITS AND OUTLOOK

The here described Structural Integrity Management System focus on the following topics:

- Enhancements of the life estimation methods
- Improvements for the inspection definition
- Development of advanced methods for the selection of high-value or structural critical items

All leads to an increased understanding of structural degradation behaviour of in-service. This will result in a beneficial manner in the reduction of risks and costs. And it will provide at the same time an enhancement of reliability, availability and performance.

For the future, more experience must be gained, stored and analysed with this management system, its methods (e.g. Stochastic Lifing Approach) and its tools. But with every step of advanced structural knowledge the system will benefit and the effectiveness and accuracy will improve.