ROSA

Reliability Oriented Optimization of Structural Replacement Strategies for Aircraft Structures

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1 Executive summary

The optimization of maintenance schemes for aircraft structures is a major technical and economic issue in the aerospace industry. There is a strong interest to further optimise and customize maintenance activities, aiming at reducing costs directly and indirectly associated with unnecessary inspections and replacement actions. Recent technical developments in Structural Heath Monitoring (SHM) have provided new possibilities for inspecting engineered structures in general. Knowledge of the “damage level” of the structure and forecasting of its development on a probabilistic basis allows the intelligent system to plan removal from service of the aircraft when the requirement for maintenance is specifically justified

The methodology and the corresponding codes developed in the ROSA project facilitate the quantification of the impact of SHM information on maintenance planning and the optimization of the life-cycle costs. The framework developed enable the quantification of the effect of changes in the design of the structural components as well as the SHM design on the inspection / maintenance cost and consequently the overall life-cycle cost. All relevant models for the problem description have been presented, developed and implemented into a code. Main achievements of the ROSA project are summarized as follows:

- A mechanical meta-model for the description of the damage growth on stiffened composite material due to different impact scenario has been identified and implemented.
- A procedure for the inclusion of the monitoring system has been investigated. Models for the probability of detection and the receiver operating characteristic have shown to be essential in the perspective of the Bayesian damage update, at the basis of this report.
- The method for the evaluation of the capacity loss due to the damage detected by the monitoring system can be extended in order to include an alarm system for decision support.
- Complex structures, as the aircraft wing in final report, can be easily handled by the method, accounting for simplified structural effects on the element capacity.
- The ROSA strategy has been implemented for specific models but it can easily be adapted to more complex models, due to the modularity of the methodology.

Sensitivity analysis has been made by changing the most relevant parameters. It has been shown that the quality of the monitoring system, expressed by the Receiver Operating Characteristic (ROC) curves is central to the optimization of the optimal interval between consecutive inspections.

The expected life-cycle cost analysis has been presented. The analysis evidenced that the probability of false alarm of the structural health monitoring systems plays an essential role in the total expected maintenance element cost.

2 Project context and objectives

The project is part of the Clean Sky Joint Technology Initiative, whose mission is to make research and development to increase the performance of airplanes and air transport in general. The scope of the project is in particular in line with the main theme (called Integrated Technology Demonstrators (ITD)), Green Regional Aircraft (GRA). Aim of the GRA is to deliver low-weight aircraft using smart structures.

Smart structures are structural components built with advanced materials which have mainly two characteristics:

- They are constituted by layers of composite materials (fibers, matrix) such that their performances are tailored to suit specific load conditions with extreme reduction of weight with respect to standard structural metal;
- They are provided with built-in automated systems able to perform a check on the integrity of the material condition, indicated as structural health monitoring system (SHM).

SHM techniques, which have been developed in the last decades, play an important role in the change from metals to composite materials, especially carbon fibre reinforced polymer (CFRP), in the aircraft industry. Important parts of aircrafts like fuselage, cockpit and wing structures will be built as smart structures thus increasing the airplane efficiency.

Unlike metals, composite materials show brittle behaviour in case of impacts which often cause barely visible damages. The typical failure modes of the composite materials relevant to the safety of the aircraft structures include matrix cracking, fibre failure and puncture. These can be caused abruptly during in-flight and on ground operations as well as in the course of maintenance work. On the other hand, occurrences of failure modes such as fatigue common in the metals are less likely.

The unique advantage of built-in SHM systems in comparison with classical inspection techniques such as Non Destructive Testing (NDT) is that built-in SHM systems in aircraft structures enable real-time monitoring of the states of the structures in service. Hence, the SHM's unique property of the real-time monitoring is best exploited with structures consisting to a significant part of composite materials.

The adoption of smart materials influences and completely change the way aircraft structures are maintained and inspected. At present, the practical applicability of SHM techniques for the inspection of aircraft structures and their inclusion in the maintenance strategy are subject of extensive research and testing. Indeed, one of the major technical and economic issues in the aerospace industry is the optimization of maintenance schemes for aircraft structures. In principle, operators of aircraft structures undertake maintenance campaigns in compliance with regulations on safety such as the EASA rules, and optionally Inspection Service Bulletins provided by manufacturers of aircraft structures, ensuring that the operations satisfy the safety requirements. Compliance with the safety levels in the regulations must be ensured at all times. By built-in SHM systems, the damage level of the structure is continuously monitored (or after inquiry) and this allows forecasting and management of the structural health condition. Efficient strategies and tools are needed to optimize and customize maintenance activities, aiming at reducing costs directly and indirectly associated with unnecessary inspections and replacement actions.

The goal of the project is development of a methodological framework and its implementation for optimizing the life-cycle cost of a smart aircraft component under the constraint that the overall probability of structural failure of the aircraft does not exceed a target probability p_T of 10^{-9} per flight hour. The smart aircraft component includes a structural health monitoring system which potentially enables the detection of damages that are caused by impacts from objects both in flight operation as well as during ground operations.

Optimization of the maintenance scheme for engineered structures requires consideration of costs over the entire service life time of the structure with possible renewals of the structural components. From a mathematical point of view it is formulated as a constrained optimization problem. The problem undertaken in this project has two optimization levels, roughly described as:

- the design of the SHM system itself is subject to an optimization, the characterization of the SHM performance and the statistical test to assess them;
- the interpretation of the results of the SHM system , and its inclusion into a maintenance strategy.

This approach is a damage tolerance approach, and the detection thresholds must be such, that the conditional probability of structural failure given any undetected damage must not be larger than $p_T = 10^{-9}$ per flight hour. The damage tolerance approach ensures that damages will not lead to failure before they are detected and repaired. Here, inspections must be planned at intervals that ensure the timely detection of relevant damages, i.e., the probability of a critical damage (one that can cause system failure) not being detected on time must be less than the target probability p_T.

The methodology and the corresponding codes developed in this project facilitate the quantification of the impact of SHM information on maintenance planning and the optimization of the life-cycle costs. It enables the quantification of the effect of changes in the design of the structural components as well as the SHM design on the inspection / maintenance cost and consequently the overall life-cycle cost. In this way, the outcomes of this project are relevant for the enhancement of the design of tomorrow's smart aircraft structures.

3 Description of the main results

A theoretical framework for the optimization of the re-placement strategy of aircraft structure components subjected to reliability constraints has been developed. Figure 1 shows the conceptual scheme for the integration of the many influencing factors under consideration for the optimization of the re-placement strategy.

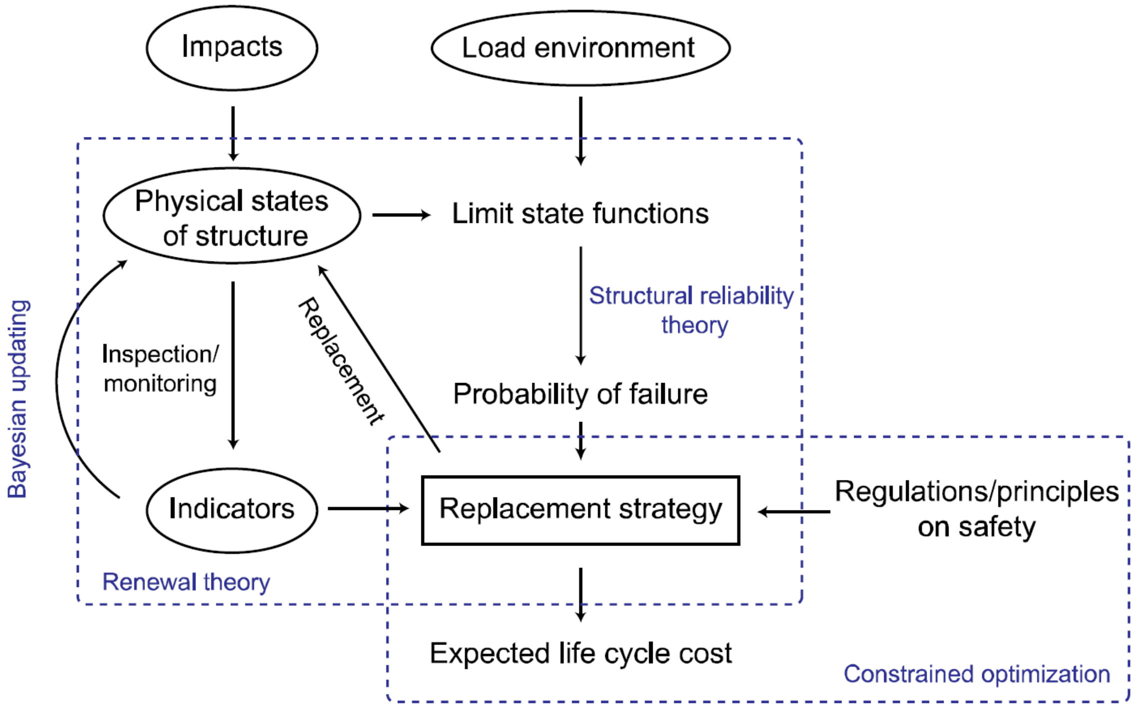

Figure 1

The modules represented by ellipses in the framework above are input models for:

- The physical state, e.g. the mechanical model of the aircraft component under consideration
- The quality of the structural health monitoring and the indicators for the state of the structure
- The impact occurrence in time and its magnitude
- The load environment

The links between the inputs are set in a probabilistic setting under the Bayesian updating:

- The impacts produce a change in terms of the physical state of the structural component, causing an accumulation of damage and consequent degradation of the mechanical properties of the material. Under normal load conditions this causes a change in the limit state function and consequently a change in terms of probability of failure of the structural component.
- The indicators, the SHM, quantify the change the material properties, causing a change in the structural capacity, which estimate an updated limit state function and consequently probability of failure.

The constrained optimization phase is formed by different contributions:

- Adapt the replacement strategy with the information on the residual capacity, the reliability of the monitoring system information and the regulation on safety for aircrafts
- Evaluate the expected life cycle cost
- Minimize the expected life cycle cost selecting the optimal inspection interval of time

The main achievement of the project was development of the strategy and its practical implementation by proposing the necessary models and interfaces between them.

3.1 Models

Models for the description of the post-impact strength, for the monitoring system, for the load and impact environment have been selected after examining the existent most relevant literature. Aim of this section is to specify the basic models used for implementation, and, most relevant, their interfaces.

3.2 Physical State of the structure

A mechanical meta-model has been included in ROSA, after extensive literature review. It allows to evaluate the damage growth on stiffened composite material and the post-impact capacity. The inclusion of the stochastic nature of the impulse is straightforward and leads to clear results. More sophisticated models based on multi-scale analysis, can be included in the present strategy quite easily, due to the modularity of the methodology developed.

Mainly, the method expresses the internal damage as a region of reduced elastic stiffness considering the most representative parameters which influence the capacity. The evaluation of the failure stress of a laminate after the impact is based on three categories of parameters which significantly affect the impact damage resistance and the consequent damage tolerance:

- Material parameters which comprise the strength of the undamaged laminate, the toughness of the material system, the laminate thickness, layup and geometry.
- Impact parameters, such as the impact energy which in ROSA is selected as the most representative parameter to characterize the effects of low velocity impacts.
- Structural parameters, which account for the location of the impact and the position of the stiffeners.

In its original formulation, the model does not include the effect of multiple impacts, neither contextually occurring at different locations on a bay, nor occurring at different time but in the same bay. In the ROSA project the mechanical model has been modified to include multiple damages due to impacts occurring at different time in the same panel.

3.3 Impacts Model

Impacts occurrence and magnitude are uncertain quantities that can be described as stochastic process. Many source of impact in aircrafts wings may occur:

- during in-service operation at ground during maintenance, such as equipment drop and stepping on tools, bolts or other impulsive contacts
- during in flight operations, for example due to the projection of stones and debris in the runway, or due to environmental events like hail.

Different types of damage, which cannot be detected by direct observation, indicated as Barely Visible Impact Damage (BVID), can occur in the laminate after impacts in different forms. More frequent consequences of low velocity impacts are indentation, matrix crack or delamination which can cause a decrement of loading capacity of the laminate.

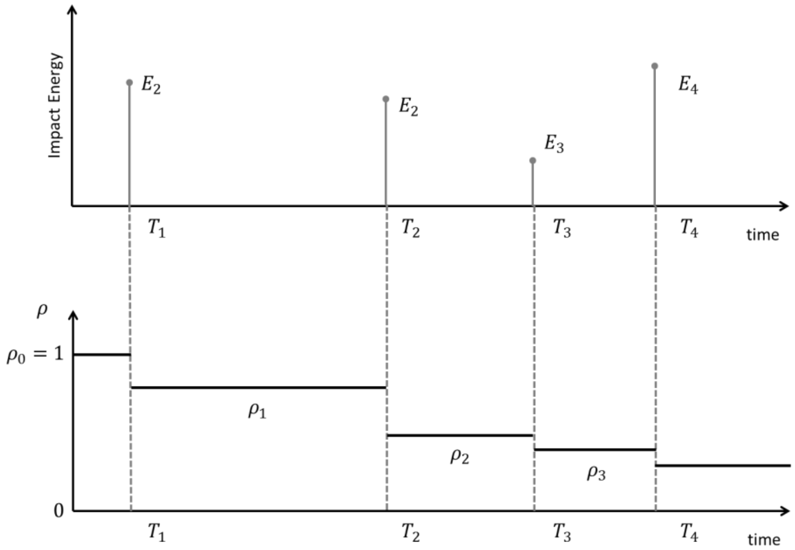

Figure 2

Damage resistance and damage tolerance of composite laminate in the aerospace field has been extensively studied in the past through experimental survey on civil and military aircraft structural parts. The main parameters influencing the damage in composite laminate evidenced in these studies are the impact location and energy as well as the impactor mass, size and velocity.

The stochastic nature of such parameters, which characterize the impact on aircrafts during their life, has been connected to a measure of damage in the structure through a mechanical meta-model in order to provide the post-impact strength of the laminate.

Statistics have been used to characterize the stochastic model of the impacts due to hail. Figure 2 shows an abstract scheme of the Poisson process which models the impact energy, where the time interval between consecutive impacts are exponentially distributed and the magnitude is a known probability density function.

3.4 Impact threat zoning

Impacts during the service life of an aircraft may occur due to many circumstances. Moreover, different parts of the airplane are differently exposed to impacts. A simple way to differentiate between locations of the airplane has been adapted from literature, including a relation between the occurrence of in-service impacts and the locations by the concept of threat zoning: 3 different threats distributions have been associated to different parts of the wing, in accordance with experimental tests conducted on aircrafts metal wings. The data on impact threats was collected under a Northrop/MCAir IRAD program on different in-service military aircraft types and was expressed in terms of dent depth on metal wings. This information has been applied to composite laminates by expressing the data in terms of equivalent impact energy.

3.5 SHM Indicators

The ability of Structural Health Monitoring (SHM) systems to identify and size defects in composite laminate is influenced by many parameters. Some of them are random in nature and might lead to false damage detection, a false alarm, with consequence on the maintenance operations and inspection planning. The discrimination between damaged and not damaged structural components based on SHM outcomes is part of a decision process, in which the optimal discriminating threshold must be selected. The optimum is influenced by the cost and the risk associated to the decision whether the structure is damaged or not. In this section we introduce some conceptual tools to model the inherent uncertainties of health monitoring which affects the damage identification and the consequent life-cycle cost.

Firstly the statistical characterization of monitoring systems is developed heuristically, to highlight the concepts be-hind models of SHM systems and to show how these models can be practically implemented from monitoring data. Then, these concepts will be discussed in mathematical framework, and the most significant models for SHM quality will be introduced.

Models for the probability of detection and the receiver operating characteristic have shown to be essential in the perspective of the Bayesian damage update. Moreover, in ROSA, the method for the evaluation of the capacity loss due to the damage detected by the monitoring system can be extended in order to include an alarm system for decision support. Complex structures can be easily handled by the method, accounting for simplified structural effects on the element capacity. Sensitivity analysis, by changing the most relevant model parameters has shown:

- The importance of the structural health monitoring indicators, such as the Probability of Detection (POD), the Receiver Operating Characteristic (ROC) and the Probability of False Alarm (PFA). Economical assessment on the effect of the SHM on the expected life cycle cost needs to be based on such, or equivalent, quality index.
- The estimation of the optimal interval between consecutive inspections and of the optimal time between successive monitoring runs also depends on the quality of the SHM;
- The detection threshold y_T, which discriminates between the damage and the not-damage event, strongly influences the optimal inspection time.
- The PFA, which in many works and literature is neglected, shows to be a key factor in the expected life cycle cost.

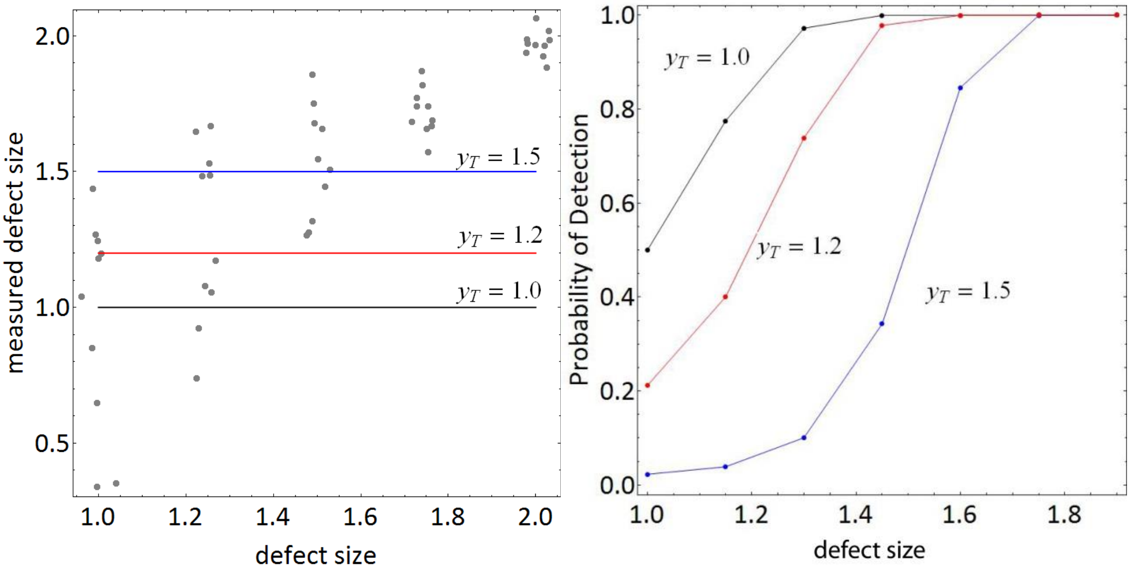

Figure 3

In ROSA, models that can be used either to fit the output data or to represent a generic SHM performance have been provided, presenting a survey on the statistical meaning of the quality indicators of the monitoring system, jointly with the most important parametrical model to represent the POD (Figure 3) and the ROC curve (Figure 4).

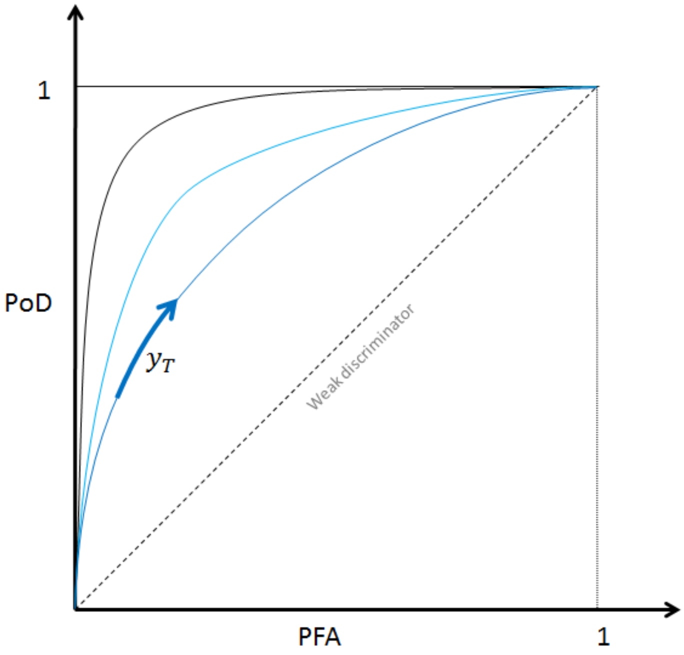

Figure 4

A particular role in the expected life-cycle cost is played by the discriminating threshold of the monitoring system, which, roughly speaking is a separation between the case which is classified as of damaged and not-damaged structural element. It is indicated by y_T and as it can be seen from Figure 5 it identifies the Probability of Detection (blue area in the figure) and the Probability of False Alarm (red area in the figure)

This quantity depends on the threshold y_T and on the noise which affects the SHM performance.

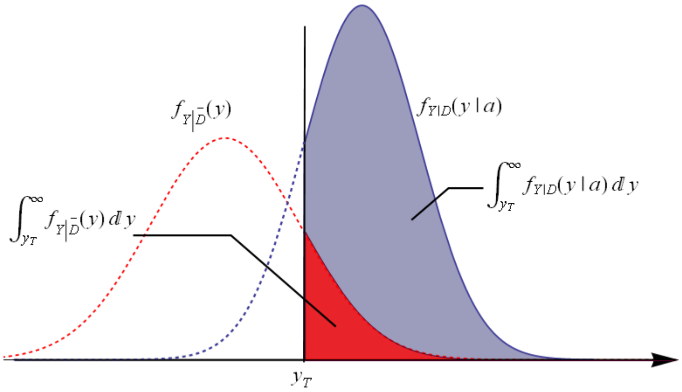

Figure 5

By varying the defect size, keeping fixed the threshold y_T, different values of the PoD can be found and the resulting PoD curve can be defined.

In the project, the difficulties in estimating the qualities of the SHM are evidenced. PoD curves do not depend only on the SHM systems, but also on material parameters, flaw type, structural geometry and environmental condition, such as temperature and humidity. In other words, SHM systems applied to structural parts with different properties might be characterized by different PoD curves depending on the location. Moreover, random instrumental and ambient noises, as well as model uncertainty are responsible for the stochastic nature of PoD curve. Following, for clarity's sake the factors which contribute in the uncertainties of PoD curves can be classified as:

- random noise that affects the SHM signal;
- statistical uncertainty due to the limited set of trials in the experiments;
- model uncertainty coming from the empirical nature of the parametric model;
- model uncertainty coming from omitting all possible influencing factors other than defect dimension.

Absence of uncertainty in characterization of the SHM performance through PoD curve would imply a PoD curve which takes only the value 0 and 1 (above some defect size threshold). Due to model uncertainty, noise and data scatter, in reality the PoD curve is defined as the mean rate of detection obtained by integration over uncertain parameters. Figure 5 shows a typical PoD curve, the thick continuous line, which can be thought as the mean of the density of the measured defects by the SHM.

3.6 Bayesian Updating using monitoring data

One of the most important S&T foregrounds of the project is the updating of the physical state of the material using the data provided by the monitoring system. This is achieved by the Bayesian updating approach. The combination of the meta-models describing impacts, material and SHM follows the scheme in Figure 6.

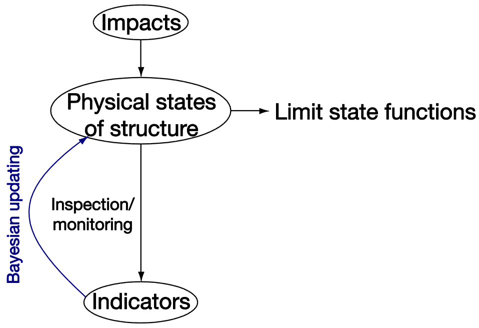

Figure 6

The combination of these components is based on the maintenance strategy: the SHM system installed on the aircraft components is called on ground at selected interval of time and might or might not give an output which indicates some geometrical characteristic of the detected defect area.

With this acquired data, the failure probability of the component is updated by using the quality (POD) of the monitor system by Bayes' formula. This phase is the core of the cost optimization addressed as last part of the ROSA project.

3.7 Cost optimization

In ROSA, the models described above are combined to deliver a methodological framework and its implementation for optimizing the life-cycle cost of a smart aircraft component. The constraint that the overall probability of structural failure of the aircraft does not exceed a target probability p_{T} of 10^{-9} per flight hour, has been adopted. The project considers that the aircraft component includes a structural health monitoring system which potentially enables the detection of damages that are caused by impacts from objects in the air as well as during ground operations. This SHM system provides an instruction to the operator of the aircraft on whether or not detailed inspections are necessary. False alarms are detailed inspections triggered by the SHM, which do not lead to damage detection and repair. It has been shown that the PFA (probability of false alarms) is essential in the overall. The objective function of the optimization is the minimization of the life-cycle cost. To calculate this, the models and model interfaces provided in the previous sections have been used.

The probabilistic models of impacts and loads, the mechanical model for the post-impact strength of the laminate and the SHM performance model (PoD, PFA, ROC) are necessary to determine the evolution of probability of failure overb time. Based on these models and on the inspection strategy, a tool has been implemented, which gives the optimal SHM threshold that minimize the maintenance cost per year.

Inspections on the airplane are performed in regular intervals $\Delta T^{in} = T_{k+1}^{in} - T_{k}^{in}$. By installing a SHM system to the stiffened panel, it is possible to optimize the life-cycle cost with respect to the cost of inspections. When monitoring data from the SHM system is available, unnecessary inspections may be avoided and the optimal length of the inspection interval ΔT^{in} can be found through the optimization process. The SHM system is assumed to be build-in in the stiffened panel and to let run regularly at every ΔT interval of time, e.g. every 10 Flight Hours. This value depends on: i) the airline maintenance resource location, such as specialized hangar and maintenance manpower; ii) the specific airplane mission. The SHM interval between consecutive runs should be selected optimizing the repair costs in case the SHM finds a damage and the airplane is not allowed to flight back to the main airline hub. In this section, we assume that Δt is constant in time; a time dependent case being a simple and possible extension of the model discussed below.

In case of <u>no</u> SHM system, ΔT^{in} will be calculated by regulation codes on airworthiness selecting that the probability of failure of the damaged component must be lower than $p_T = 10^{-9}$ per FH. This value will depend only on the load, mission and impact model.

The effect of the SHM system running at every Δt is that, due to more frequent repairs of small extent, the damage increases more slowly in time. This behavior depends on the probability of detection.

The case study performed shows that the inclusion of a build-in SHM allows for less frequent general inspections ΔT^{in} with consequent reduction of costs.

The inclusion of the costs associated to the false calls of the SHM is slightly more complicate but can be easily done including the life-cycle costs, which are defined in ROSA as costs related directly and indirectly to maintenance operations on the structure.

In ROSA, a tool for calculation of the optimal SHM threshold has been delivered, assuming:

- The cost of a regular inspections at the most convenient airline main hub c_I;
- The costs in other airports are expressed as c_{II};
- Interest payments and inflation are neglected.

Figure 7 shows the decision tree for the procedure following the output of the SHM system. As long as the SHM system shows a green sign (g) no inspection becomes essential. With increasing time, the failure probability will mount due to increasing number of impacts in time. For the red (r) signal the airplane has to be repaired or inspected immediately on-site, but after the repair, the failure probability takes a lower level again, corresponding to the probability of failure of the intact aircraft. In ROSA, it is assumed that the inspection method is perfect, which means that any damage can be excluded. Therefore, the airplane is approved to continue its air traffic.

The probability of damage detection depends on the ROC curve. If the monitoring system has produced a false call, the associated cost will be also c_{II}, assuming that the repair costs are negligible. Then, by the ROC curve, it is possible to quantify the best choice of the discriminating threshold y_T between $Z = z_g$ and $Z = z_r$.

The cost-based optimization problem is now to find the optimal levels for the limit y_T, subjected to the constraints on the safety given by the target p_T.

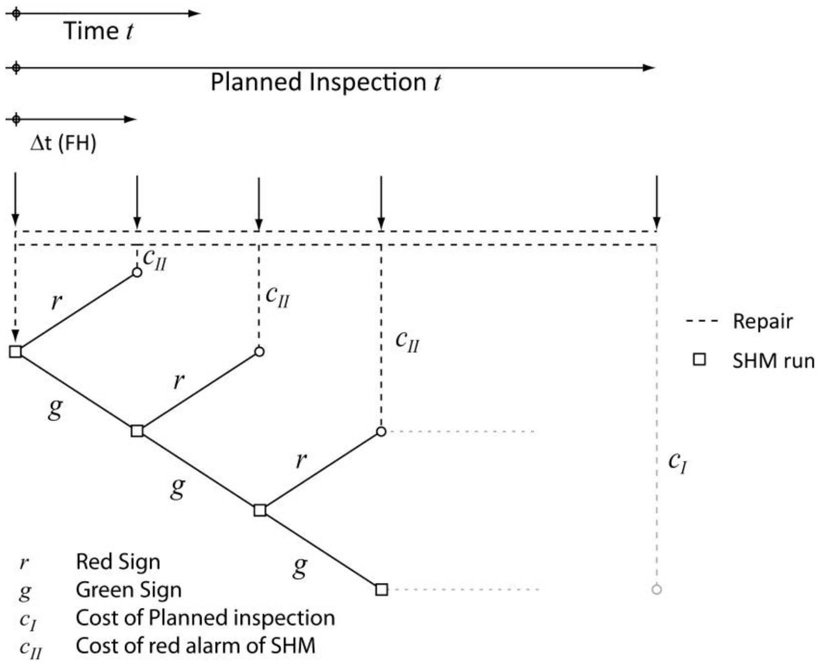

Figure 7

Models and tools have been demonstrated for a F/A-18A inner wing upper skin.