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Advanced Design Concepts and Maintenance by Integrated Risk Evaluation for Aerostructures

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Abstract: This paper presents an overview of the achievements of a research and development project sponsored by the European Commission in the general area of Key Actions and New Perspectives in Aeronautics. The project was coordinated by Alenia and involved partners from major European Aircraft and Helicopter manufactures as well as research institutions and universities. The project was in support of EU policies on energy and environment, in addition to those on transport, economic and social cohesion, industry and, of course, research and technology.
The overall objective of Advanced Design concepts and Maintenance by Integrated risk Evaluation for aerostructures (ADMIRE) was "to develop a probabilistic foundation for the application of damage tolerant design of metallic aircraft structures taking into account the innovative investigations on the initial flaw concept, crack growth evaluation improvements and residual strength in complex geometries".
The innovation provided by this project was the development of an overall approach capable of evaluating the damage tolerance of the structure on a probabilistic basis.
This global risk analysis took into account the stochastic nature of structural parameters, their variation and their effects on the design and response properties of aircraft structural components, in order to estimate structural safety on a probabilistic basis while providing information on the confidence to be given to the predicted behavior. It also incorporated the investigations on the initial flaw concept, crack growth evaluation improvements and residual strength in complex geometries.

keyword: Damage tolerance, Risk analysis, Initial flaw concept.

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1 Introduction

Since 1978 the damage tolerance philosophy (FAR 25.571 Amendment 45) has been the basis of the regulations concerning the prevention of in-service degradation of the structural integrity of fixed wing aircraft. The main objective of this philosophy is to ensure the continued airworthiness of aircraft by defining inspection programmes for the structure. These inspection programmes are characterised by an inspection threshold and repeat inspection intervals. The inspection interval for fatigue sensitive locations often follows from calculations based on the period for a crack to grow between a detectable size and a critical size, whilst, for the initial inspection threshold period two methods for its determination may be used, whatever the type of structure:

1. a conventional fatigue approach based on linear cumulative damage accumulation and scatter factors, corresponding to common European practice.

2. a crack propagation approach from an assumed initial flaw.

In a recent regulatory change (AC 25.571-1C, 29 April 1998) the damage tolerance requirements changed significantly, as embodied in the following extract:

"For single load path structure and for multiple load path and crack arrest fail-safe structure, where it cannot be demonstrated that load path failure, partial failure, or crack arrest will be readily detected and repaired prior to failure of the remaining structure, the threshold should be established based on crack growth analyses and/or tests, assuming the structure contains an initial flaw of the maximum probable size that could exist as a result of manufacturing or service-induced damage."

Thus for single load path structures and certain types of multiple load path structures a fatigue approach would no longer be possible to determine the inspection threshold. It would instead be replaced by a fracture mechanics analysis considering crack propagation from initial flaws to a critical crack length.

An initial flaw approach requires that a 'rogue' flaw and 'quality' flaw(s) must be used in a calculation to derive the threshold period. The rogue flaw represents the effect of manufacturing damage; the quality flaw represents typical manufacturing quality. Current SN fatigue data would normally be generated from test coupons manufactured with typical manufacturing quality.

Flaws of these types are already widely used in damage tolerance calculations, with rogue and quality flaws being placed in primary and secondary load paths of multiple load path structures. However, the dimensions of these flaws are normally 1.27mm and 0.127mm (rogue and quality flaw sizes respectively). These dimensions are well below likely in-service detection sizes and their precise values have a limited effect on inspection interval calculations, but, on the contrary, are crucial for threshold calculations.

There is scope for re-examining the determination of rogue and quality flaw sizes that are consistent with modern manufacturing processes and from what is known about typical manufacturing flaws in aerospace structures.

2 Improvements On Existing Deterministic Models

2.1 Introduction

From the review of the determination and use of the initial flaw concept a degree of common understanding has emerged. In particular, two different types of flaws are distinguished:

1. The Initial Quality Flaw, which is assumed to be a defect which exists in most of the structure locations and is representative of the initial quality of the structural item as produced in the manufacturing work shops.

2. The Rogue Flaw, which is assumed to be a defect which is created as a result of a form of manufacturing damage, e.g. due to errors in the manufacturing process, poor material (large inclusions, etc.), incorrect handling, corrosion, etc.

The rogue flaw size is dependent upon the area being investigated, the manufacturing process, the ability to detect the flaw at time of manufacture, and the susceptibility of the area to corrosion. The rogue flaw does not correspond to the typical manufacturing quality of the component, but rather to exceptionally substandard conditions. It is assumed to exist at a critical location, either at time of manufacture, in which case it is representative of inherent material or manufacturing damage (e.g. scratches, burrs or impacts), or as a result of the operating environment. It can be seen that the rogue flaw is not an "outlier" in the quality flaw population, but instead comes from a different population.

The requirement to derive the inspection threshold using damage tolerance (AC 25-571 1c and AC 29-2c for large transport aircraft and rotorcraft respectively) may lead to severe difficulties if the proposed methodology, named the Initial Flaw Concept or IFC (a fictitious defect is grown, with standard fracture mechanics tools, from a very small size to a critical size) is not able to model correctly the physics of the problem at all stages. Numerous research contributions (e.g. GARTEUR AG 26, and ADMIRE itself) have shown that this procedure is not robust in this case. The analysis becomes dependent on too many parameters (material, geometry, assembly procedure, load cases to name a few) to consistently and conveniently justify inspection thresholds. Using this methodology in the design phase is all the more problematic. These considerations, combined with the attractive potential of IFC as a basis of probabilistic analysis, lead the ADMIRE consortium to dedicate a significant effort to the improvement of deterministic analysis tools. For the effort to be worthwhile, all aspects of an IFC analysis had to be addressed, namely the derivation of the Equivalent Initial Flaw Size (EIFS), early crack growth, crack growth in complex structures under complex loads and final failure.

Research performed by the consortium ranged from the evaluation and improvement of existing models and tools, to the derivation of new analysis methods and tools. In addition to the goal of improving the IFC analysis, the assessment of all the models under investigation provided a basis for the probabilistic methodology to be applied.

2.2 The Initial Flaw Concept and Short Crack Models

Quality flaws, derived to be consistent with SN data representing normal manufacturing practice, are likely to be fictitious (i.e. not a simulation of real micro-flaws in a material) because of the inadequacy of short crack modelling procedures. Similarly, rogue flaw sizes may be fictitious, depending on modelling procedures and, particularly, if modelling manufacturing damage that is non-crack like.

All available applications of initial flaw concept in Europe are based on the determination of a hypothetical crack, the equivalent initial flaw (EIF), representing either the quality flaw or the rogue flaw. To establish the equivalent initial flaw size (EIFS), a 'back calculation' from existing fatigue test results is performed, where the data is regressed in time using a crack propagation law to obtain an equivalent initial crack size at time N = 0. In other words, the available S-N data is translated into a crack propagation period from an EIF to a critical crack. The basis for the inspection threshold is then calculated by a crack propagation analysis from the EIF to critical crack size.

The rogue flaw may be determined in precisely the same manner as the quality flaw, i.e. through the assessment of S-N test data. However, in this case the back calculation is based on S-N data from a fatigue specimen that includes artificial damage at the beginning of the test, representative of the manufacturing defect under consideration. In the absence of experimental evidence based on realistic damage scenarios, a conservative rogue flaw size of 1.27 mm is currently imposed.

2.3 Accounting for early crack growth

A good description of damage growth in the early stage of fatigue is key to an accurate prediction of the fatigue life by damage tolerance, regardless of the method. In the IFC framework, it is reasonable to expect that the better the model used for back extrapolation, the less sensitive the EIFS will be to parameters other than the material. In other words, ideally, if the fatigue damage leading to failure does initiate from a "flaw" (which is practically always the case, if flaw is taken in the sense of material discontinuity), an exact description of the full fatigue process would lead to a value depending on the material only. Therefore, it was the consortium's goal to improve the understanding of initial crack growth, and include the specific patterns of early growth in the EIFS methodologies. Although the EIFS methodologies did not necessarily include the short crack behaviour it is believed that the improved description of small crack growth is a mid-term objective to improve the IFC.

Specifically, the consortium investigated the following topics:

1. stress and fracture mechanics analysis of small cracks;
2. influence of residual stresses;
3. closure models for short cracks;
4. stress measurement.

Investigations have demonstrated new analysis capabilities for small cracks. It was demonstrated that refined models are available for a more accurate simulation of crack growth. In particular, the ability to simulate and take into account internal stresses is a significant improvement over the growth law empirical corrections currently in use.

However, it must be recognised that significant difficulties surround the reliable experimental assessment of short crack growth, particularly in real aircraft structure, and that the understanding of short crack growth is not complete. As such, care must be taken with the use of such short crack models.

2.4 Main achievements on the improvements of deterministic models

The main ADMIRE outcomes are the following:

- Methodologies for EIFS determination have been implemented by OEMs, universities and research institutions. This was a key objective of the project in order to close the gap with the US industry that has significantly more experience with these kinds of methods, now mandated by certification regulations.
- All the procedures developed to obtain the EIFS have demonstrated the sensitivity of the methods to "external parameters" (i.e. not intrinsic to the material or to the manufacturing process), like load level, load ratio, details of the geometry and assembly conditions. Efficient use of the IFC is thus very much a matter of know-how, reinforcing the interest of the ADMIRE project.

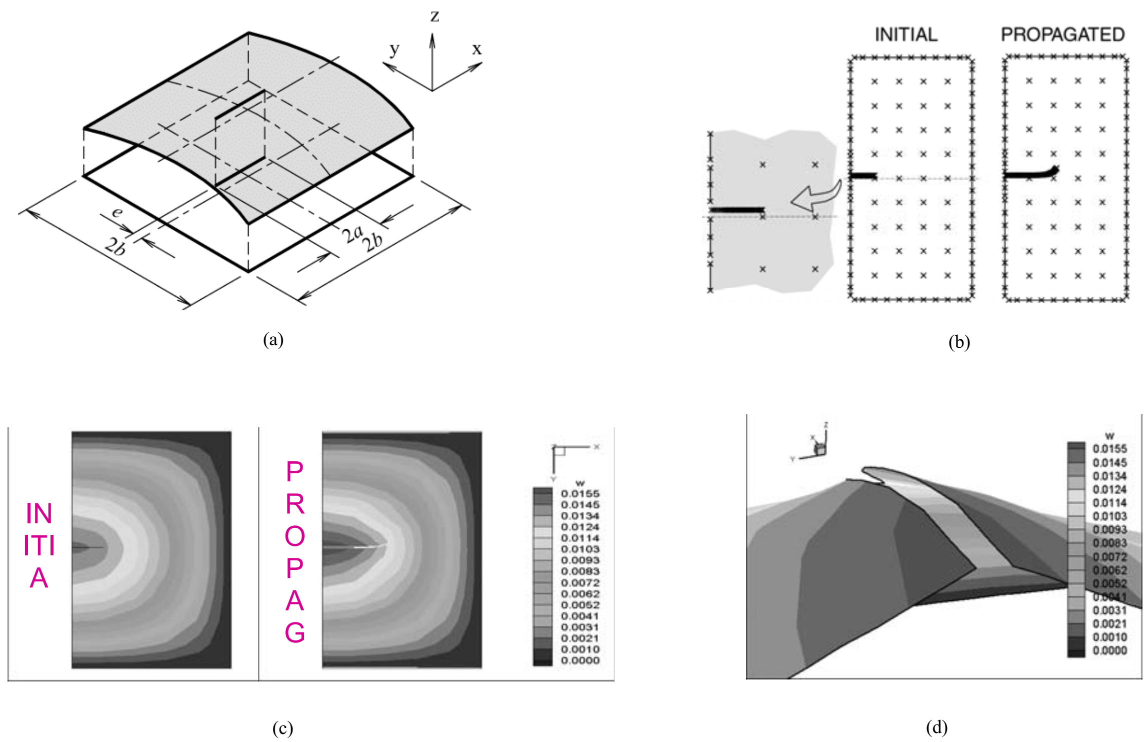


Figure 1 : (a) Cracked pressurized panel with eccentric crack; (b) BEM model and crack propagation simulation (eccentric crack); (c) Contour plot of BEM normal displacements with highlight of propagating crack; (d) Close up of the cracked area.

- Crack propagation analyses based on closure have been developed and implemented to assess the relevance of certain fracture mechanics parameters in the short crack range.
- Analysis techniques, based on weight function techniques or the finite element method, proposed to analyse the effect of manufacturing processes (e.g. cold expansion), have yielded good results.
- A powerful technique for stress, fatigue and fracture analysis of curved reinforced shells has been developed.

2.5 Some experimental and deterministic results

Queen Mary developed a Boundary Element Method (BEM) for fracture mechanic problems in curved shell (fuselage panels), taking into consideration the effect of large deformation and plasticity [1]. In particular a new BEM formulation involved geometric and material non linearity, with or without stiffeners. The results were validated against FEM results for several cases without the presence of cracks, showing a good agreement, and then the BEM results were also presented for crack cases. Several examples were presented to show the capabilities of the method (Figs. 1-2) that is based on a combined usage of Dual Reciprocity method (DRM) and Dual boundary element method (DBEM). In Fig. 2d, in particular, the importance of modelling the non linearity coming from the bending effects is highlighted: the mode I stress intensity factors (SIFs) would be underestimated in a simplified linear approach.

Another partner, IDMEC, produced results concerning residual stresses [2-5], being focused on experimental and numerical techniques used for the assessment of the residual stress field in a holed specimen undergoing a cold expansion process by an oversized tapered mandrel (Fig. 3a-b).

The X-ray technique was used to experimentally measure the residual stress field while the numerical work was based on the FEM code ABAQUS. Two- and three-dimensional FEM analyses were presented, using elastic perfectly plastic and hardening material behaviour. 3D FEM analyses were used to model the cold working process and compared with the simpler uniform (along the

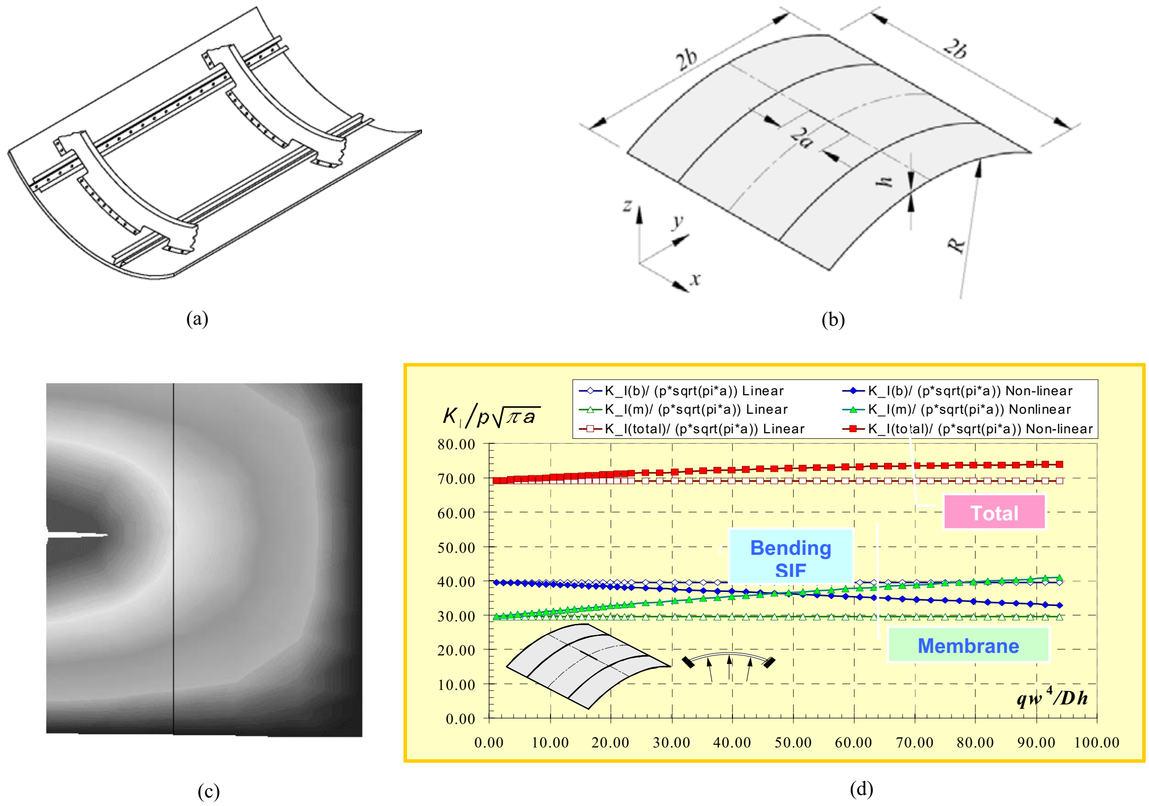


Figure 2 : (a) Stiffened fuselage panel; (b) Model of the stiffened fuselage panel; (c) Contour plot of BEM normal displacements in the stiffened cracked panel; (d) BEM results (SIF's) with linear and non linear approach.

thickness) hole expansion simulated by a 2d FEM. Experimental and numerical results were compared (Figs. 3c-d), showing that the residual stress field has the bigger stress gradients in a band of 5 mm from the hole surface. These stress gradients and the residual stress effect vanish with increasing distance from hole surface.

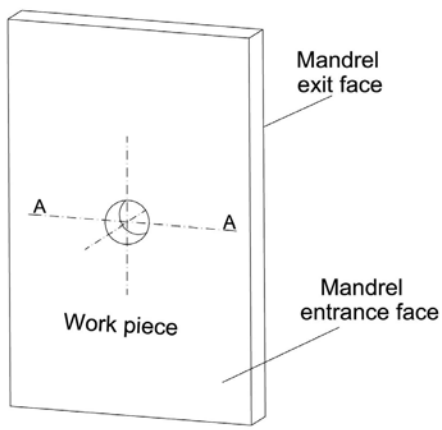
The same partner, IDMEC, also produced fatigue striations spacing measurements (Fig. 4a-d) on normal or cold worked open hole specimens [6-7], so that the effect of stress level and cold work on the fatigue striation spacing could be assessed, in terms of fatigue striation spacing along the length and depth of a fatigue crack (Fig. 4d). Fatigue striation spacing rise along with the crack length: this is comprehensible because as the crack length increases during the fatigue test the local stress field on the crack front increases and consequently the deformation field produces larger striations. For specimens with cold work a similar trend was found along the crack length but in this case with smaller values of striation spacing. Infact, cold work introduces a residual stress field that makes the effective stress field on the crack front smaller than without cold work. As a consequence the deformation field on the crack front is not so high as without cold work and smaller striations are produced. Along crack depth it was shown that striation spacing for specimens with cold work was also lower than for normal hole specimens.

Finally the crack growth rate (CGR) was calculated based on striation spacing.

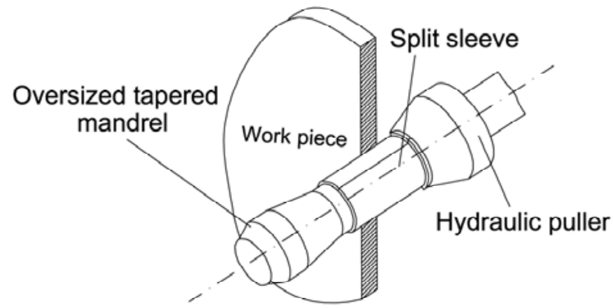
Another partner, University of Naples (UNF), realised a biaxial fatigue test (the applied load was static in one direction and cyclic in another) on a large scale fuselage panel (Fig. 5a), using an in house made advanced fatigue test machine (Fig. 5b) [8]. Unfortunately the final rupture happened in an unexpected area (Fig. 5c), too close to the gripping devices and not suited for results exploitation.

3 Probabilistic Analysis

The use of probability theory in airframe structural reliability analysis was considered with the goal of calculat-



(a)



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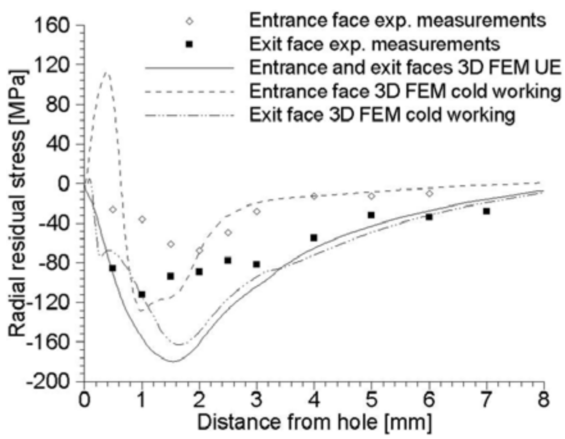

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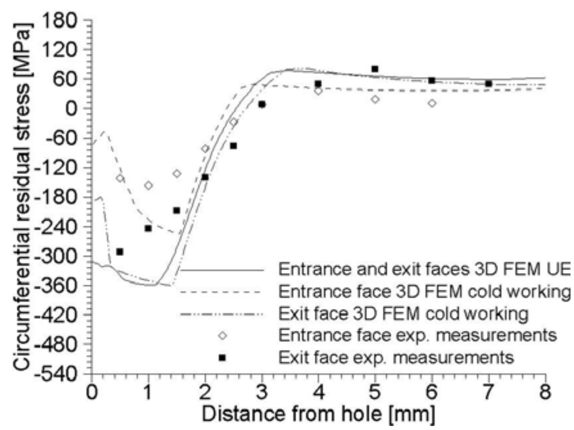

(d)

Figure 3 : (a) Work piece to be cold worked; (b) Schematic diagram of the cold working process; (c) Numerical (FEM) and experimental (X ray) results; (d) Numerical (FEM) and experimental (X ray) results.

ing a probability of failure or constructing a distribution function for a critical response, e.g. crack length at a specified service time.

The objective was to create a new design methodology to enhance the conventional single-point safety factor approach to a more general risk based structural integrity justification. This approach supports design by showing in a quantitative manner what the overall safety factor is composed from and where design has to be focused, as some parameters have more influence on reliability than others.

Specific advantages that this technique could offer were identified, including:

- The ability to accurately define the risk level: in other approaches, this important element is not known and the assumption of conservative values of the inputs can produce uneconomical designs.
- The possibility to know the “distance” from the critical condition in terms of probability of failure, for each design condition.
- The possibility to handle in a logical way aspects such as multi-site damage/widespread fatigue damage, considering the statistical distribution at each critical point without singular assumptions.
- The justification of criteria for a definition of the economic life based on the statistical distribution of the damage and its size at each time.

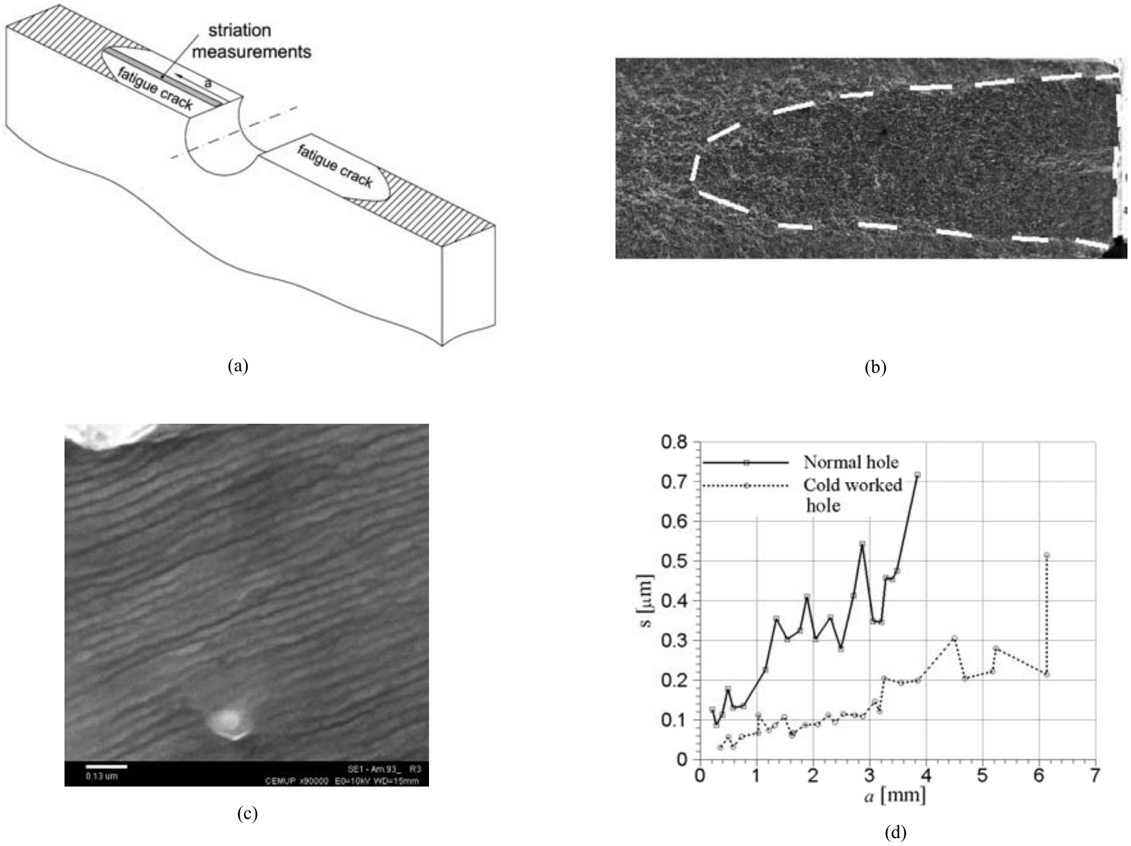

Figure 4 : (a) Fatigue striation spacing measurements; (b) Fractographic analysis; (c) Striation highlight by scan electron microscopy (d) Fatigue striations spacing results.

However, difficulties associated with this technique could also be identified:

- The use of this approach requires the accurate knowledge of the probability distribution of the parameters, whereas in the current approaches only some fixed values are needed.
- The requirement relevant to the consideration of the "rogue" flaw introduces a deterministic condition that reduces the advantages of the probabilistic approach. On the other hand, the knowledge of the statistical distribution of this initial damage is a complex problem.

3.1 General outcomes of probabilistic investigation

The current deterministic procedure forces the design to choose conservative safety margins in order to cover all uncertainties that have not been foreseen. These deficiencies were resolved in ADMIRE project and in particular:

- The quality of numerical results of failure probabilities is related to the exact definition of uncertain variables and their correct statistical representation. Those parameters important for damage-tolerant fatigue design were defined with their density type and coefficient of variation.
- One drawback which is connected to the statistical description of the initial flaw size remains unsolved: neither deterministic computation by back extrapolation technique nor randomised calculation of the IFS, using standard crack propagation laws for small/long crack development, are able to find realistic representations of the IFS distribution. The reason lies in the usage of incorrect material parameters and crack growth laws which are not representative of the physical fracture behaviour in the micro-crack region. Use of appropriate micro-crack laws promise to give a more realistic statistical description of the important initiation phase.

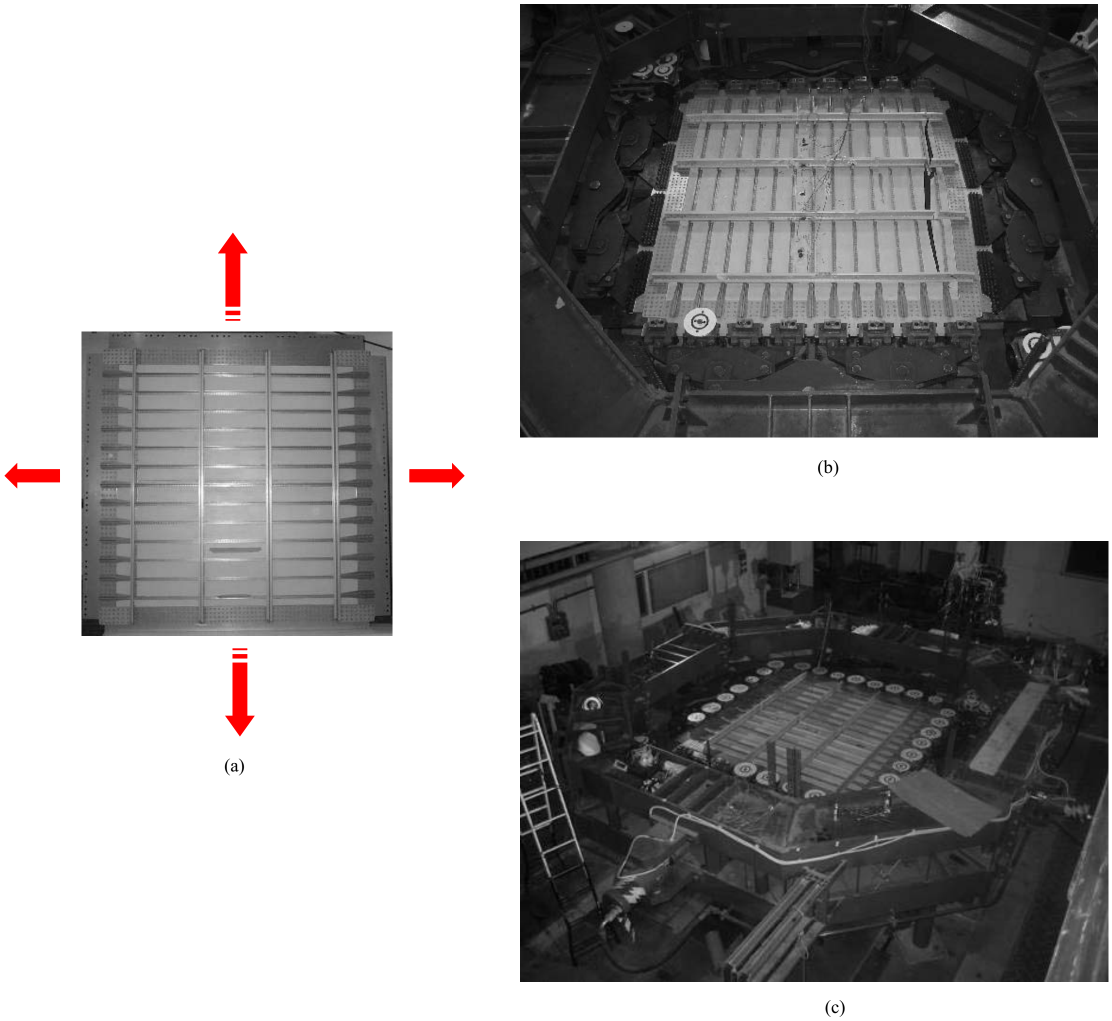

Figure 5 : (a) Large scale fuselage panel undergoing biaxial stress; (b) Fatigue machine with panel under testing; (c) Final fatigue rupture of the stiffened panel.

- Appropriate structural reliability methods have been derived which could handle implicit or explicit defined limit state functions used in damage tolerant design of aeronautic joints. Apart from well known updated FORM and SORM (First and Second Order Reliability Method) techniques, the development, by the National Aerospace Laboratory, of MonteCarlo (MC) methods using an advanced directional importance sampling (ADIS) technique is worth mentioning. Alternatively, an updated response-surface method (RSM) applying a regression technique was shown to be efficient together with a sophisticated SORM. A fast probability integration technique was applied to solve the joint density integral.

- Probabilistic design and justification in the frame of the certification process demands a step by step procedure which can easily be applied in industry practise. Several risk strategies were developed which are able to treat parallel and serial linked events (e.g. limit states). Inspection results and detection methods are taken into account in order to design an economic maintenance strategy. The inclusion of correlation between uncertain variables and limit states defining statistical dependencies between events was demonstrated. This feature has an impact on the achievable reliability level of the chosen design and is an indispensable prerequisite of probabilistic analysis.

- In order to provide a probabilistic model validation in the long crack region, the University of PISA (UP) agreed to perform 36 propagation tests on open hole specimens with artificial cracks. The crack growth data obtained by UP were used as basis for the validation of the stochastic procedure developed to define the statistical parameter C and m of the Paris law. By probabilistic prediction, quantile values of stress cycles N for defined crack sizes a were defined and compared with those derived from the 36 tests [9-10]. It was demonstrated by the ADMIRE partner DASA that, correctly modelling the statistical correlation of the parameters C and m of the Paris law as multivariate normal using the conditional probability between both, nearly eliminates the error in the stochastically simulated model [11]. Thus, the probabilistic model is able to predict realistically quantile values of cycles N depending on crack size a. Furthermore the simulation allows the extension of the density and distribution function far below the 5% quantile of the test data. Thereby a basis is created for realistic predictions of small failure probabilities. Results of this analysis can be used to demonstrate the applicability of the risk procedure for the definition of inspection intervals.

3.2 An example of Equivalent Initial Flaw Sizes (EIFS) distribution

Another ADMIRE partner (EADS CASA) worked on the determination of the equivalent initial flaw size (EIFS) from fatigue findings [12]. For this purpose, the associated initial flaw size is calculated for each one of some selected damages, found during full-scale fatigue tests on two aircraft (we will call them A and B). Such natural damages were localised in: wing, fuselage and Horizontal Tailplane (HTP) for aircraft **A;** HTP only for aircraft **B.**

The following fatigue tests and findings were considered:

- Aircraft **A**

  A total number of 120 000 simulated flights were applied.

  Fifteen natural damages, discovered during the test, were selected.

- Aircraft **B**

  A total number of 100 000 simulated flights were applied.

  Two natural damages, discovered during the tear down inspection, were selected.

3.3 Backward extrapolation

To obtain the equivalent initial flaw size associated to each one of the selected damages, a complete crack growth analysis was performed, starting from an initial flaw whose dimensions are chosen in such a way to reach the crack configuration discovered during the fatigue test (Fig. 6), in a number of cycles corresponding to those that had been applied when the damage was discovered (Fig. 7a).

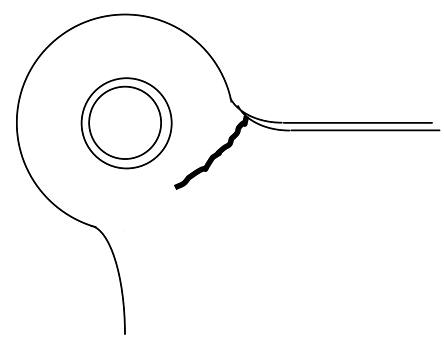

Figure 6 : Example of natural damage, located at the fillet radius of the upper rear fitting lug (2024 T351 plate, crack size a=55.00 mm, number of simulated flights SF=67202).

3.4 Crack propagation model

The crack advancement due to each individual cycle was calculated entering in the *da/dN* curves corresponding to the considered material, with the parameters that define the fatigue cycle (incremental stress intensity factor ΔK and valley-peak ratio R). These parameters had been previously modified according to the “Modified Generalised Willenborg Retardation Model”. A full “rainflow” counting process was applied on the stress sequence for analysis purposes.

In a multiple load path structure, the initial damage to be considered in a secondary member is a quality flaw. In such a case, short crack effect should be considered when simulating the propagations.

It is of the uttermost importance to use a crack propagation model as much accurate as possible in such a way to better approximate the real physical initial flaw size dis-

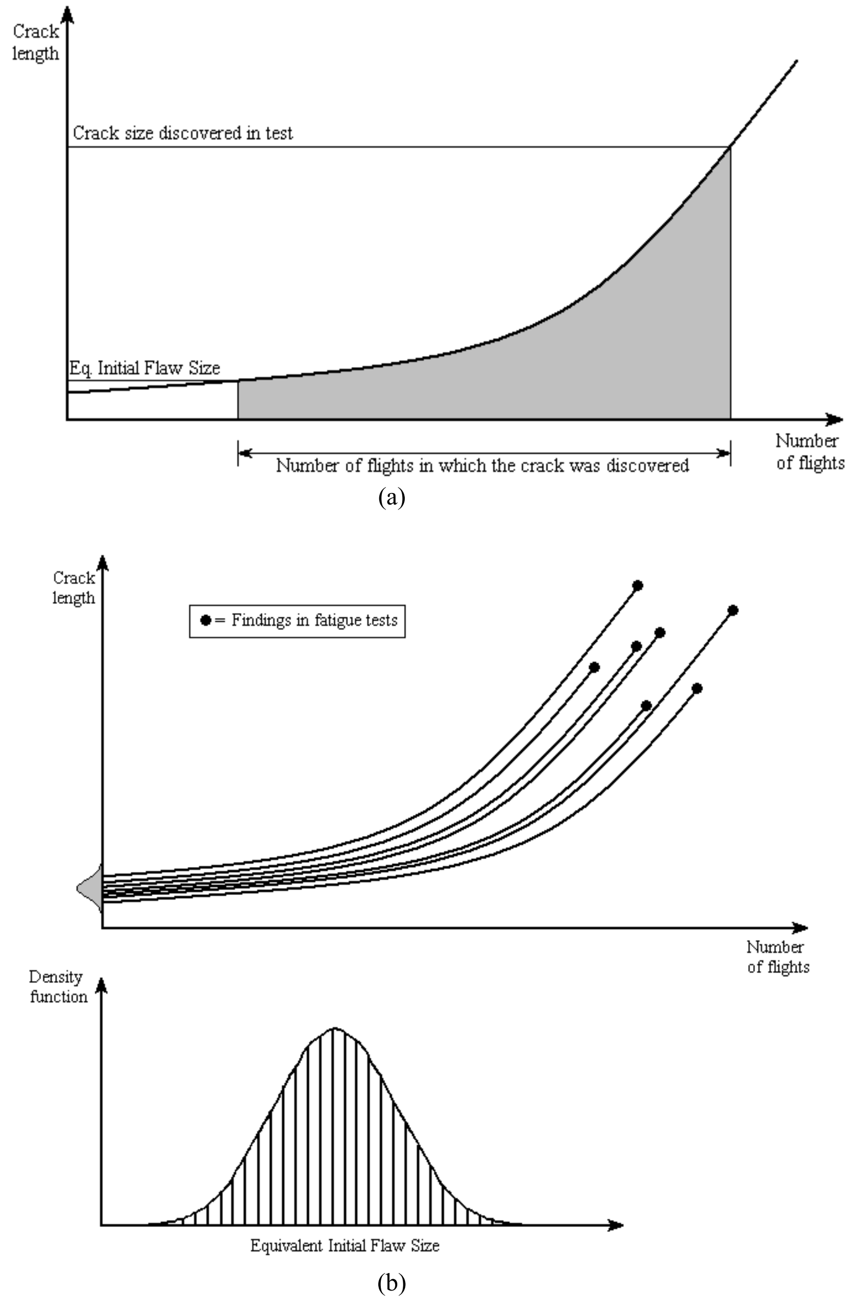

Figure 7 : (a) Backward extrapolation, e.g. from a=55 mm and for a number of simulated flights SF=67202; (b) Equivalent Initial Flaw Size determination (all the selected natural damages are back-propagated).

tribution and consequently guarantee the general applicability of the obtained results. More specifically, if the crack growth model include the allowance for short crack effect, load spectrum, riveting squeeze force, component geometries and so on, the distribution obtained can be utilised also for different values of the aforementioned parameters, otherwise a new EIFS is to be generated for each variation on the aforementioned parameters.

3.5 EIFS determination

After the determination of the equivalent initial flaw size, for each one of the considered damages discovered in tests, a statistical treatment was applied to obtain their distribution (Fig. 7b).

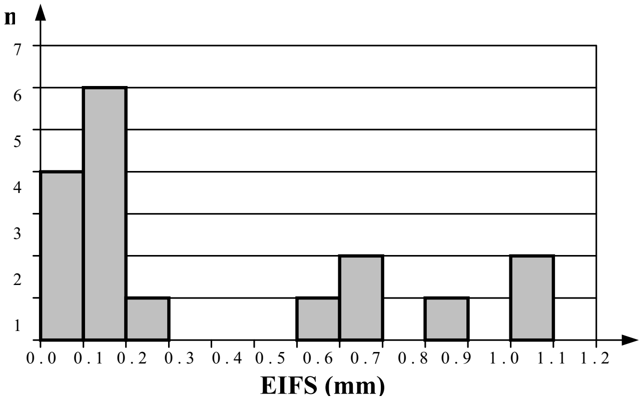

Figure 8 : Histogram representative of the initial flaws.

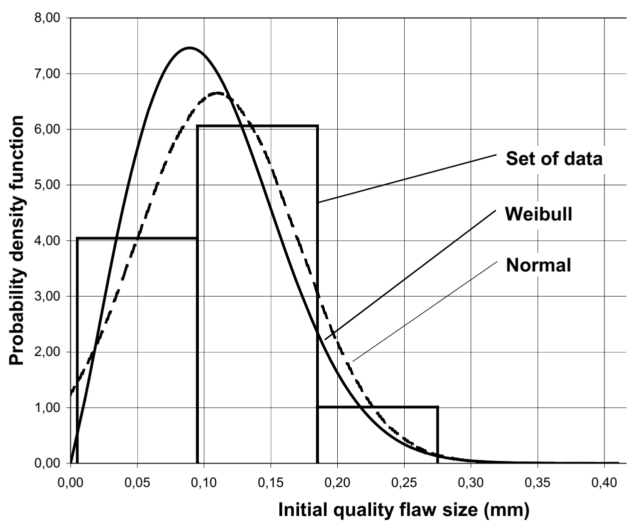

Figure 9 : Initial quality flaw distribution.

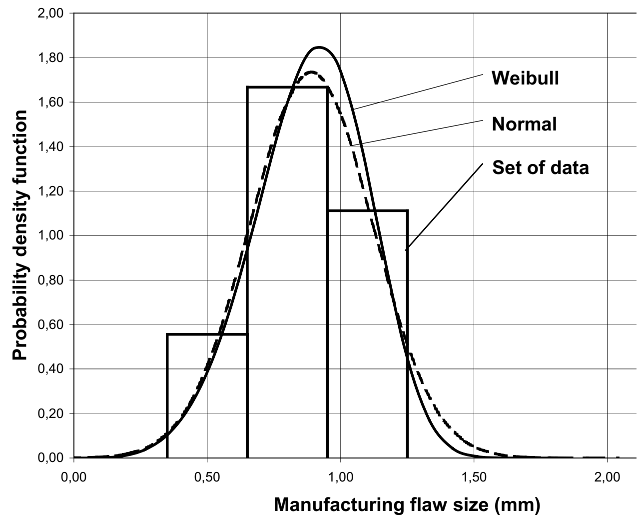

Figure 10 : Initial manufacturing flaws distribution.

The initial flaws, based on their size, were grouped in two sets of defects (Fig. 8):

Initial quality flaws: 11 equivalent initial defects, from 0.05 to 0.26 mm.

Manufacturing flaws: 6 equivalent initial defects, from 0.62 to 1.16 mm.

Both sets can be adjusted by a Weibull or by a Normal distribution (Figs. 9-10).

The equivalent initial flaw size can be obtained attending to different criteria. The considered ones are the following:

- Modal value: this can be considered as the most representative value of the population, but it does not provide any safety margin; for justification purposes, it must be used in combination with appropriate scatter factors for the inspection threshold calculation.

- Value for 90% of probability: the use of this value provides an acceptable safety margin to cover the scatter of the material.

- B value: this value covers the 90% of the population with a 95% of confidence level and is the most common accepted method to obtain allowable values. When the number of data points used to obtain the distribution is very small, this value can be very conservative.

Taking into account that the number of fatigue findings used for the EIFS determination is very small, (11 for quality flaws and 6 for manufacturing flaws) and that the Weibull distribution can be considered more appropriate (no negative values are allowed), the value of the 90% of probability in the Weibull distribution was considered, so as to obtain:

- Initial quality flaw size = 0.18 mm

- Manufacturing flaw size = 1.16 mm.

According to recent regulations, for single load path structures and certain types of multiple load path structures, the airworthiness authorities will no longer accept

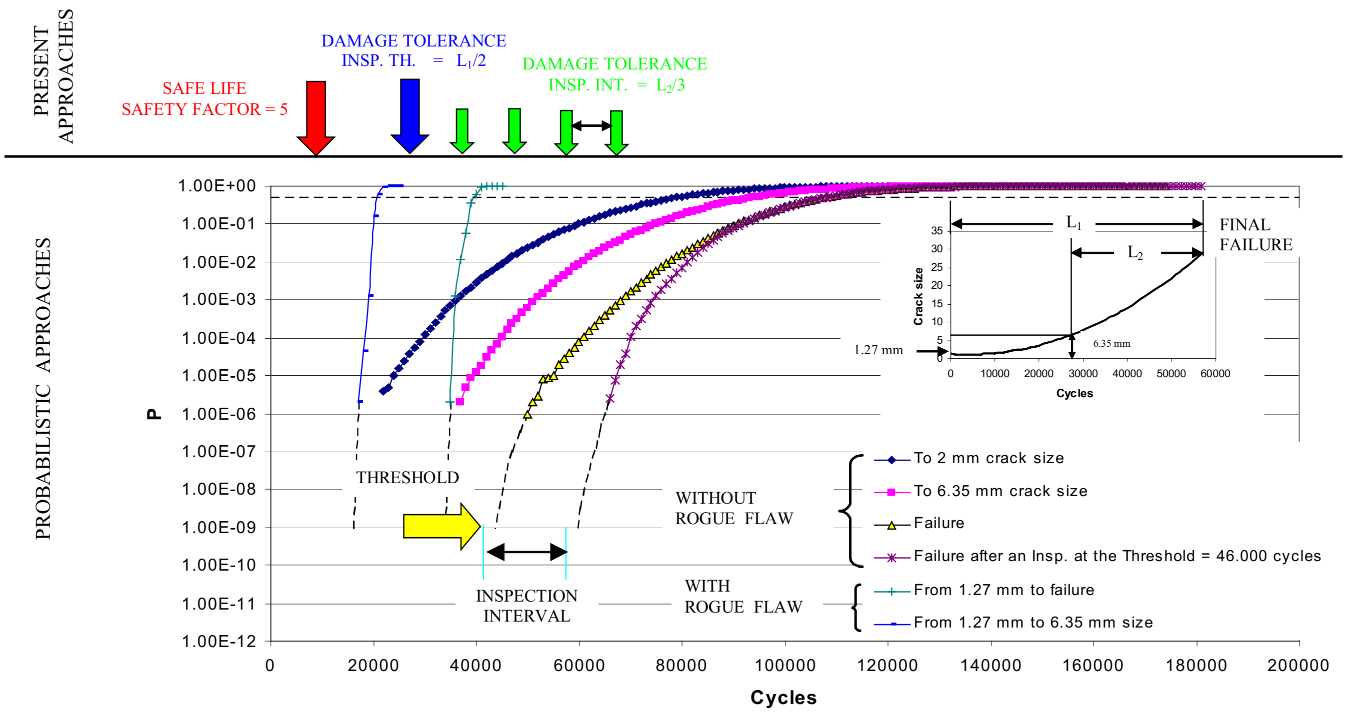

Figure 11 : Comparison between the probabilistic and deterministic methods in terms of prescribed inspection intervals (by University of Pisa).

the fatigue approach for the inspection threshold calculation. Therefore, thresholds will be obtained assuming an initial flaw and considering the crack propagation up to reach the maximum allowable crack length. Consequently it is necessary to set up a database with a set of real cracks discovered during fatigue tests with their associated "Equivalent Initial Flaw Size" and to obtain statistical distributions to be applied in the initial flaw size for design and justifications of damage tolerant structures. This database should be continuously updated in the future.

Conclusions

The high level objectives of the ADMIRE project included the gaining of knowledge about the Risk analysis within the European industry and the improvement of fatigue and damage tolerance practices. The project contributed to achieving these goals and the research performed demonstrated that the Risk analysis is necessary.

In particular, the ADMIRE major achievements were:

- Benefits for maintenance and inspection programs by simultaneously maintaining the required level of structural safety.
- A better understanding and technical background of the Initial Flaw Concept useful to help communication with airworthiness authorities (FAA, JAA) and transatlantic specialists groups such as GSHWG (General Structure Harmonization Working Group). This development will assist compliance with current and future airworthiness regulations and requirements.
- Reduction of needed testing activities (and thereby reduction of design costs) by improvements on analytical and numerical procedures for structural performance simulation.
- An effective basis for establishing the optimal design/repair/replacement/proof test maintenance for life management of aeronautical structural components.
- Establishment of a risk procedure for structures designed on damage-tolerant principles: for every stage of aircraft operation the procedure defines the probability of failure occurrence and determines the inspection threshold and inspection interval consistent with the chosen safety objective and available

detection methods.

- Identification of design keys that have economic potential by sensitivity analysis and evaluation of partial safety factors to optimize the overall safety structure.

The probabilistic investigation will accompany conventional approaches for life extension calculations in the frame of the value creation process for new aircraft.

The developed results will be used within the design and certification process in order to justify a chosen reserve factor.

Moreover, the results obtained can be used to validate advanced design tools for the simulation of the structural behaviour in the presence of manufacturing damage. These tools help the design offices to optimise the weight of the structure and then to propose more efficient structural parts which will contribute to reducing the maintenance costs whilst maintaining the same reliability and confidence levels in flight safety.

Some further results for the consortium with respect to probabilistic investigation can be summarized as follows (Fig. 11):

- Probabilistic risk design provides the analyst with a provable insight and detailed information about the safety structure of DT-design.
- Test simulation and accumulation of test data of the predicted distribution of the response variable will be possible.
- Use of updated inspection results ensures ability to maintain the reliability level throughout useful life.
- Probabilistic analysis can be used for life extension programme, by targeting low risk levels.
- In the frame of an optimisation process for the best maintenance strategy, cost-efficiency and reliability increase are included.

A very positive outcome for industry is that the manufacturers involved now have the Risk analysis based probabilistic and stochastic procedures in place as well as the method to evaluate and improve them. This is a significant step forward for industry, as these procedures have a direct impact on operational safety and cost.

Furthermore, original models have been developed, notably for crack growth analysis within the framework of probabilistic analysis. These new design tools will enable the aerospace company to compute, on the basis of a probabilistic approach, failure risk associated with the designed component. Aerospace companies can benefit by employing new methodologies for updating the risk level in case of in-service damage.

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