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NUMERICAL MODELLING FOR PREDICTING DAMAGE TOLERANCE OF COMPOSITE STRUCTURE

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Abstract

In the past years, primary composite structures have been introduced on civil aircraft by Aerospatiale (ATR 72 outer wing, A330/A340 ailerons...). For damage tolerance, the substantiation of the component was up to now mainly based on intensive test programs and empirical formulas. The costs involved by such an approach and the lack of understanding of the physical phenomena appearing in the post-impact behaviour of composite structures have lead to research activities on mechanical prediction.

Theoretical methods have been developed and yet presented in the literature, but the analysis was made at the microscopic level, leading to long calculation time and requiring extensive material data. This kind of analysis is thus not directly applicable for the aeronautical industry.

Aerospatiale approach is based on a non-linear finite element model including geometrical and physical data (dent depth, delaminated area) and a degraded modulus in the damaged area.
Good correlation is obtained between numerical results and an extensive test program performed on T300/914 and IM7/977-2 including complex loading (tension/tension, compression/tension/shear...).

1. Introduction

In the last decades, primary composite structures have been developed and applied, particularly by Aerospatiale, to civil aircraft. The ATR 72, for example was the first commuter of such a size to be equipped in its basic definition with a carbon outer wing box (figure 1). The AIRBUS A330/340 have been equipped by a lot of composite parts like ailerons, landing gear door... of Aerospatiale/Aeronautical Branch responsibility (figure 2).

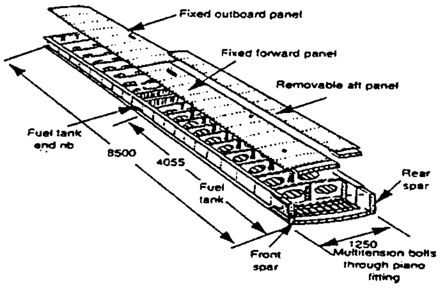

Figure 1: ATR 72 outer wing box

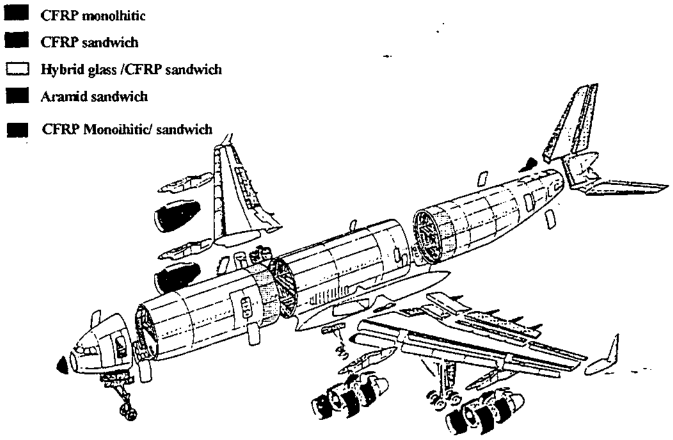

Figure 2: Airbus A330/340 composite parts

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For the certification of composite structures as far as tolerance damage is concerned, three types of damages have to be considered:

- fatigue damages,
- environmental effects (temperature, ageing, corrosion...),
- accidental damages.

This study has focused on the last point, and particularly on the behaviour of laminated monolithic composite structures damaged by a low-velocity impact (impact speed inferior to 10 meters per second) as tool fall, impact with a maintenance platform,...

The certification requirement of ACJ 20.107.A, ACJ 25.571 and ACJ 25.603 § 6.2.2 in the damage tolerance executive are:

- " The growth or no growth evaluation should be performed by analysis supported by test evidence or by tests at the coupon, element or subcomponent level".
- "The number of cycles applied to validate a no-growth concept should be statistically significant".

Aerospatiale philosophy [1] for damage tolerance is based on the no-growth concept (figure 3), it consists to demonstrate that the most important damage that cannot be detected in the maintenance program by the selected method of inspection will not propagate during the aircraft life, that the residual strength is higher than the required static load (ultimate load), end that the detectable ones will no grow within during an inspection interval.

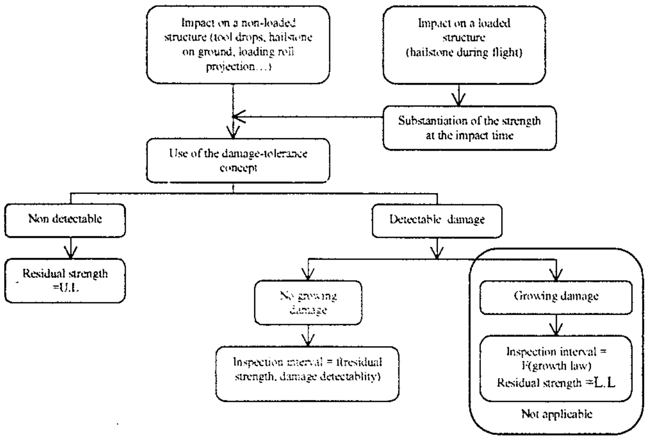


Figure 3: Aerospatiale damage tolerance philosophy.

2. State of the art

Composite structures damaged by a low-velocity impact present an important reduction of their residual mechanical characteristics, especially in compression. This leads to consider the presence of the maximum damage undetectable by the methods used in maintenance (Barely Visible Impact Damage), to justify the structure sizing at ultimate load.

The current approach is based on specimen results representative of the considered structures (material, stacking sequence...) that lead to the realisation of abacus used to perform the sizing. This approach is very arduous because each new configuration needs new series of tests to characterise the empirical graph. Furthermore, test on these specimens are only realisable for simple loading conditions and their extrapolations to complex loading are limited, implying conservative assumptions to cover these configurations.

The object of this study is to develop a calculation method to predict the behaviour of impacted structures. This would result in a reduction of the test matrix necessary to validate the sizing data, and an increased reactivity and quality of the analysis

3. Objective, purpose of the investigation

The aim of this investigation is to predict the behaviour of damaged monolithic composite structures under static and fatigue loading. Two approaches are proposed.

The first one allows the prediction of the global behaviour for static and fatigue loading. The object of this type of study is to develop a tool which must be workable for an engineering office. The results of the analysis must be quickly available. This approach is based on a 2 dimensional model using field measurable data (available in service).

The second approach has for aim to follow the damage growth. The experience has shown a damage growth for high load (around 80% of the failure load) before a brutal or explosive failure. A 3 dimensional model is presented. A step by step description of the damage is necessary.
The test programs described in paragraph 4 have been used to validate these 2 methods.

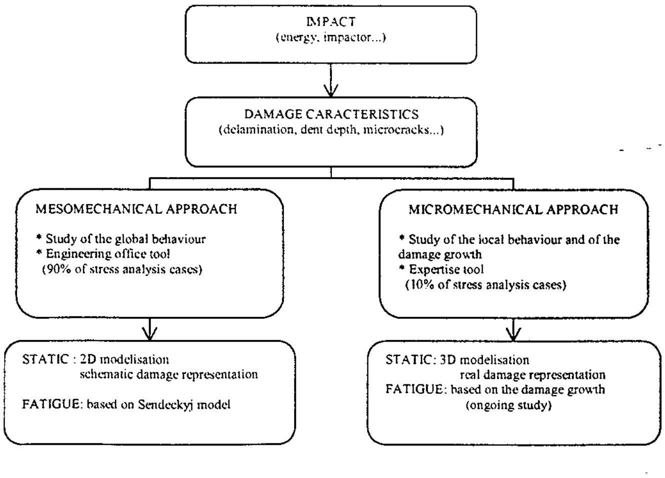


Figure 4: Proposed approaches

4. Damaged structure behaviour

4.1 Test description

A lot of tests have been realised, in particular on After Impact Compression specimens (AIC) and bi-axialy loaded specimens (figures 5 and 6). Table 1 summarises the different tests realised for this study.

Specimen type	*Material*	*Loading*
AIC	T300/914	- Pure compression
AIC	IM7/977-2	- Pure compression
Bi-axial	IM7/977-2	- Compression/compression - Tension/Tension - Tension/compression - Shear

Table 1: Summary of the different tests

The impacts on the After Impact Specimen, have been realised by static indentation [2]. A non-destructive inspection has been performed to characterise the damages by:

- the damaged area size (A-Scan mapping in amplitude).
- the size and the thickness position of all the delaminated surfaces (A-Scan mapping in deepness).
- the aspect and the deepness of impact dent (A-Scan mapping in deepness).

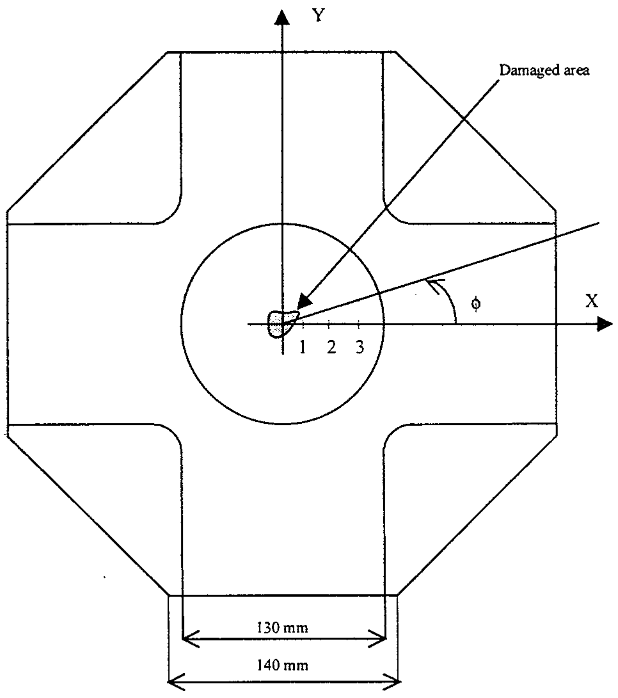


Figure 5: Bi-axial specimen description

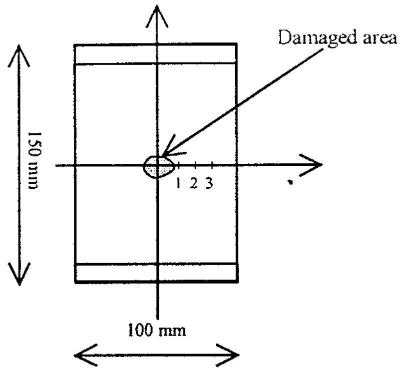


Figure 6: After Impact Compression specimen description

4.2 Interpretation of experimental results

Experimental results have shown:

- for tension loading (figure 7), the stress/strain curves are linear up to a threshold situated at approximately 80 per cent of the failure load and slightly non-linear after this value.
- for compression loading (figure 8), the stress/strain curves are linear to a threshold situated at approximately 80 per cent of the failure, and strongly non-linear for higher loads.In the area near the damage, the strain gages on impacted side indicate a strong compression whereas the values on the non-impacted face indicate a reduction of the compression level leading, for some extreme cases, to tension. In combined loading compression/compression, the results are similar following X and Y-axis.

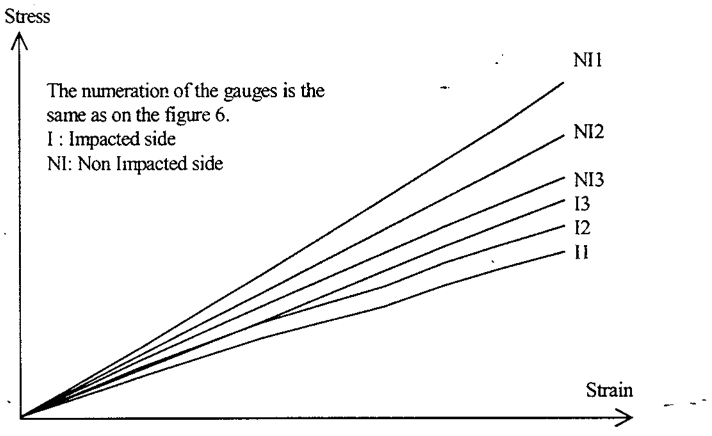
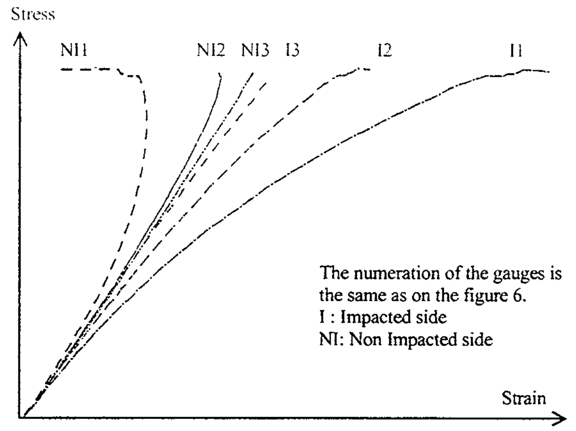


Figure 7: Tension behaviour



The numeration of the gauges is the same as on the figure 6.
I : Impacted side
NI: Non Impacted side

Figure 8: Compression behaviour

This behaviour can be explained by a distribution of plane (Nx, Ny, Nz and Tx, Ty) and out-of-plane solicitations (Mx, My and Mxy).

For compression loading (figure 9), the displacement caused by the moment induced by the impact dent depth, lead to send away the neutral line out of the middle plane, and as a consequence to increase the bending moment and the divergence between the 2 sides.
But for tension loading, the displacement caused by this moment leads to bring the neutral line and the middle plane together, and as a consequence to decrease the mechanical strain divergence.

In the AA section (figure 9):

* impacted side

$$\varepsilon_I = \varepsilon_I^{(N)} + \varepsilon_I^{(M)} = \frac{N}{E.t} + \frac{M(t/2)}{EI}$$

* non-impacted side

$$\varepsilon_{NI} = \varepsilon_{NI}^{(N)} + \varepsilon_{NI}^{(M)} = \frac{N}{E.t} - \frac{M(t/2)}{EI}$$

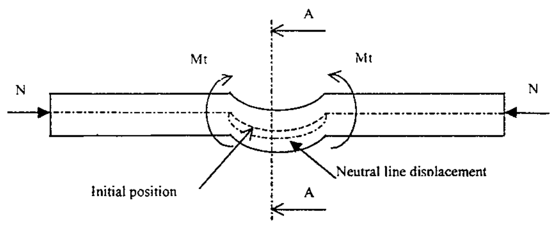


Figure 9: Bending moment induced by the impact dent depth

An ultrasonic control method has been developed to follow in real time the damage growth [3]. This process enables to display the propagation of delaminated surfaces and the associated load level.

5. Modelisation of impacted structures

The bibliographical study has shown that the damage tolerance analysis and more particularly the behaviour of composite structures damaged by an accidental damage is a critical point in composite stress analysis but the methods proposed are up to now uncompleted. Many models have been proposed in the literature. Most of the approaches have been realised at a microscopic level and thus cannot easily be used to simulate the global behaviour of composite structures.

The 2 approaches proposed in this study are (figure 4):
- A mesomechanical approach, with a 2 dimensional model, to predict the global behaviour of the specimen in a short delay (some CPU minutes).
- A macromechanical approach, with a 3 dimensional model, to follow the damage growth thanks to the evolution of the delaminated areas.

5.1 Mesomechanical approach

5.1.1 Numerical analysis

The microscopic Model needs a lot of experimental data that are difficult to measure on aircraft and lead to a very important calculation time incompatible with the industrial requirements for such a tool. This first part of the numerical study has for objective to develop an analysis tool to predict the behaviour of damaged composite structures under complex loading, the aim of this tool being to be used by engineering offices for the product support activities.

The results presented in the paragraph 4.2 have lead to different principles for the model, summarised in the table 2.

Parameters	*Parameters proposed for the 2D model*
- multi-delaminations - microcracks	Reduction of the Young's modulus in the damaged area
- indentation	Local deformation representative of the damage shape
- bending moment (tension/compression)	
- failure in the centre of the damage	- Hill criterion

Table 2: Principles of modelisation

A parametric study has been done to quantify the influence of all parameters on the result accuracy and has shown that:
- the dent depth is very influential. Indeed, the neutral line deport due to the dent induces the bending moment in the centre of the damage, and so the non-linear behaviour of the impacted structure (CF § 4.2).
- the precision of the simulation of the non-linear material behaviour of the composite (different Young's modulus in tension and compression) was secondary but

necessitated a very important calculation time (several hours).
- the failure criterion used is the Hill criterion.
- the decrease of the local rigidity in the damaged area has to be taken into account.

Figure 10 shows the bi-axial model.

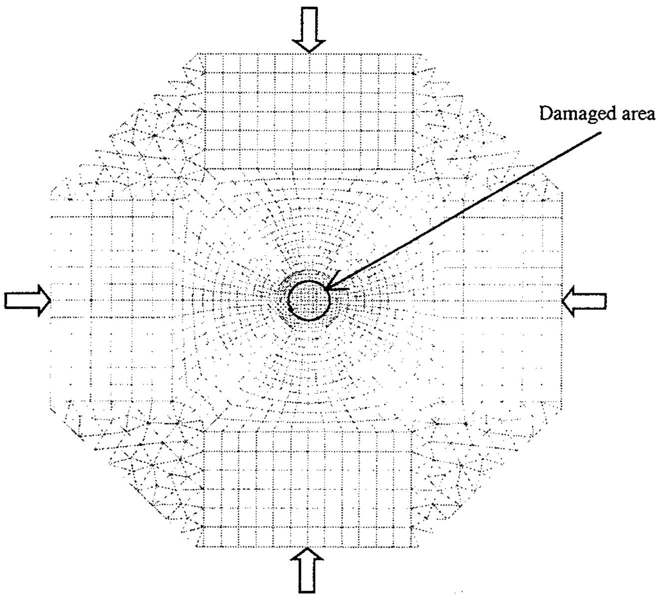


Figure 10: Description of the bi-axial model at the mesomechanical level

5.1.2 Correlation between finite element analysis and experimental results

The correlation between the finite element model (FEM) and the experimental results has been based on the test programs presented in paragraph 4. The comparison has been performed on 60 impacted specimens (After Impact Compression), loaded under complex solicitation compression/compression, compression/tension, tension/tension and shear.

Numerical results (load at failure) are slightly conservative (of around of 5%) for the tension dominant loading (figure 10) and a little over-estimated for compression dominant loading.

Figures 11 and 12 show an example of compression dominant loading.

The numeration of the gauges is the same as that in the figure 6. The I indicates that the strain gauges are on Impacted side and NI on the Non Impacted side.

The failure criterion is the Hill criterion. Figure 13 presents the results for After Impact Compression specimens impacted from 3 to 30 joules. The calculation over estimates the failure load of less than 10%.

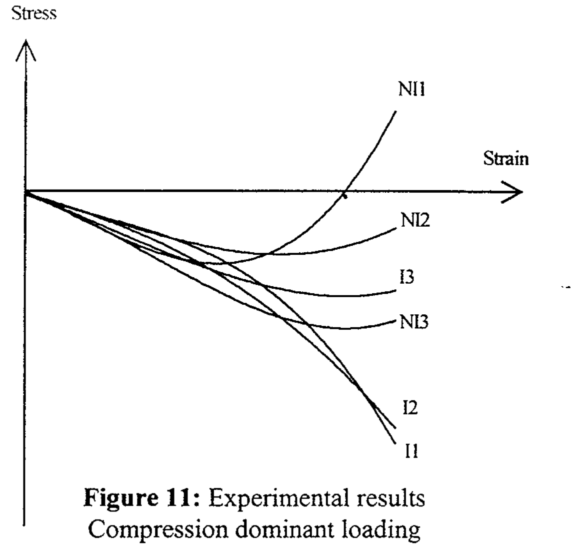


Figure 11: Experimental results Compression dominant loading

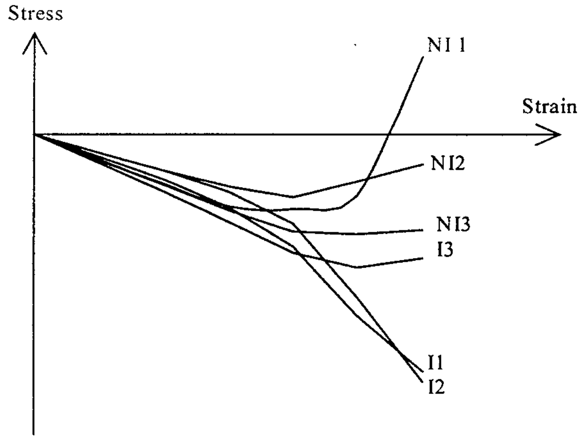


Figure 12: Numerical result Compression dominant loading

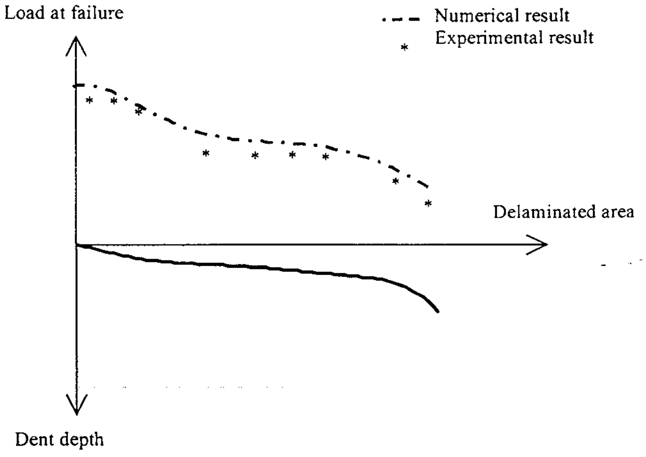


Figure 13: Correlation test/FEM for the AIC specimen - Failure criterion

5.2 Micromechanical approach

The mesomechanical approach presented in the last paragraph allows the prediction of the global behaviour of impacted structures. Experimental results have shown that for high loads (80% of the failure loading), there is a propagation of the delaminated areas and thus a growth of the damage. Then as soon as the delamination grows, there is an important instability leading to a brutal failure. The aim of the micromechanical approach is to estimate the load corresponding to the damage growth with the calculation of the strain energy release rates.

The model proposed for this computation is a tridimensional model that takes into account the shape of the damage and the dent. This type of approach was developed to:

- calculate the strain energy release rates for mode I, mode II and mode III for all the delaminations and so determine the interface that propagates.
- analyse the influence of the stacking sequence on the growth load and so on the failure level.

Unlike the mesomechanical model, this model needs precise experimental data (shape and height position of all delaminations in the thickness).

5.2.1 Numerical approach

The method used to calculate the strain energy release rate is the Virtual Crack Extension (VCE).

A reduced model containing the delamination front is extracted from the global model. A computation with the reduced model gives a first evaluation Ep1 of the potential energy of elastic strain. A small perturbation is introduced in the reduced model, and a new computation gives a second evaluation Ep2 of the potential energy of elastic strain. This assumes that the perturbation is such as the energy dissipated in the reduced model.

The strain energy release rate is given by the expression:

$$G = -\frac{EP_2 - EP_1}{\Delta A}$$

The mode partition is obtained by the local distribution calculation Pi(s) (i=1,2 and 3) of the strain release rate in the 3 components (mode I, II and III) with:

$$P_i = \frac{Fi.\Delta U_i}{\sum_{i=1}^{3} Fi.\Delta U_i}$$

With Fi: nodal force in the crack front on the i direction
Δui: opening crack displacement in the i direction

The expression of the propagation criterion is equal to:

$$c = \left(\frac{G}{G1c}\right) + \left(\frac{G}{G2c}\right) + \left(\frac{G}{G3c}\right)$$

The values p, q and r are taken equal to 1 for a good correlation with experiments.

The prediction of the propagation is done in 3 steps:

- calculation of the global strain energy release rate,
- calculation of the mode partition,
- estimation of the interface(s) that will propagate and of the associated load level.

5.2.2 Finite elements model

The plate is modelled with volumic multilayer elements. The conical profile of the damaged area in the thickness is respected (figure 14). The dent depth is introduced (§ 3.2 and 5.1.1). All the delaminations are taken into account for the analysis (figure15).
Figure 16 shows the description of the After Impact Compression 3D model.

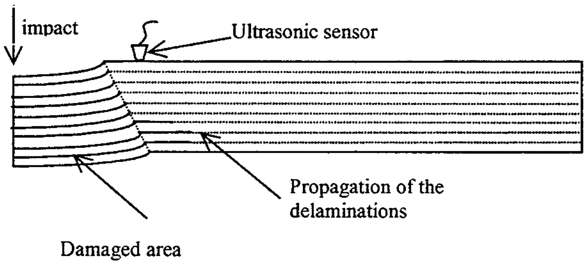


Figure 14: Damage area profile in the deepness

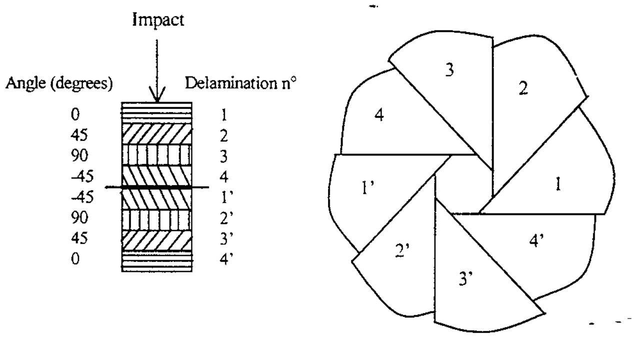


Figure 15: Delaminations profile

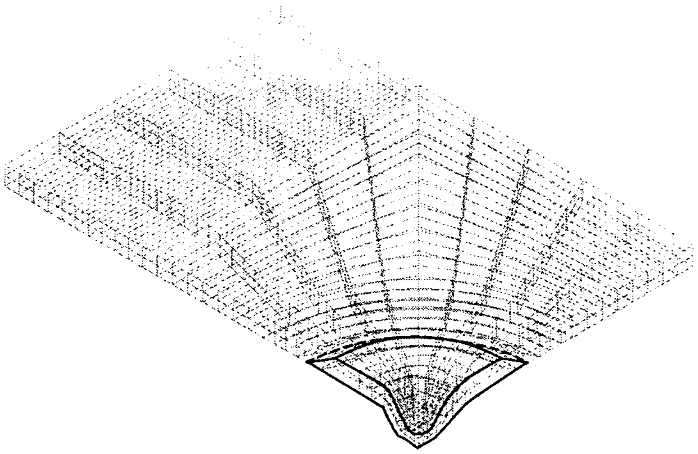


Figure 16: Description of AIC model

5.2.3. Correlation model / experimental results

The correlation between the Finite Element model and the experimental data is based on the After Impact Compression specimens.

The propagation of the delaminations has been controlled by 8 ultrasonic sensors connected to an US multiplexed machine. The sensors are bonded to the periphery of the most important delaminations. A software has been developed by Aerospatiale [3] to deliver, in real time, the 8 A-Scan.

Numerical results (figure 17) have shown the same results as the experimental results:

- the delaminations propagate perpendicularly to the compression load,
- the delaminations that propagate are situated in the 1/3 inferior of the laminate,
- the difference between numerical result (propagation load) and the experimental result is lower than 15%.

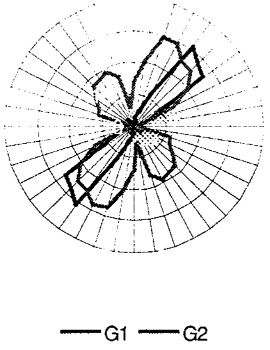


Figure 17: Evolution of the strain energy release rate along the front of the delamination.

6. Fatigue behaviour

The mathematical model proposed to analyse the fatigue behaviour of impacted composites is based on studies made for interpreting composite fatigue data [4,5]. The basis of this approach is an empirical formulation. The assumption leading to this approach is that the residual strength after cycling, the static strengths and the fatigue behaviour of impacted CFRP structures are controlled by the same dominant phenomenon which means that the strongest specimen in static has the highest residual strength as well as the longest life duration.

The deterministic equation (figure 18) is [6]:

$$\sigma_e = \sigma_a * \left[\left(\frac{\sigma_r}{\sigma_a} \right)^{\frac{1}{S}} + C * (N-1) \right]^S$$

where (figure) σe is the equivalent static strength,
σa is the maximum cyclic strength,
σr is the residual strength after N cycles,
S is the asymptotic slope on a log-log plot of the (σ-N) curve,
C is the correction factor to be applied at high cyclic stress level,
N is the number of cycles applied.

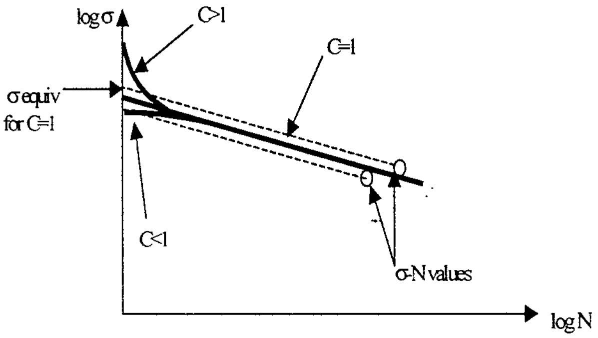


Figure 18: Theoretical model approach

Test results have led to the following σ-N curve (figure 19) for T300/914 specimens cycled at 0,5; 0,65; 0,7; 0,75 * static strength and associated to ratio R=-1 and -10.

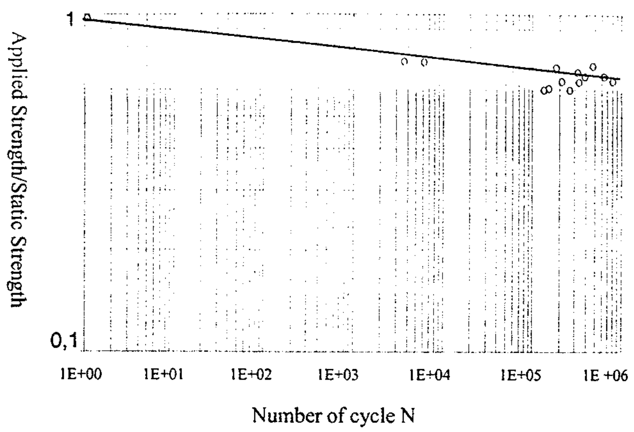


Figure 19: σ-N curve for T300/914 impacted specimen

The different parameters of the model have been optimised experimentally and, statistical analysis has been performed in order to define the maximum strain level (on a B basis for certification issues) and the associated number of cycles to which a composite structural part damaged by an impact can be subjected without reduction of the residual strength (figure 20).

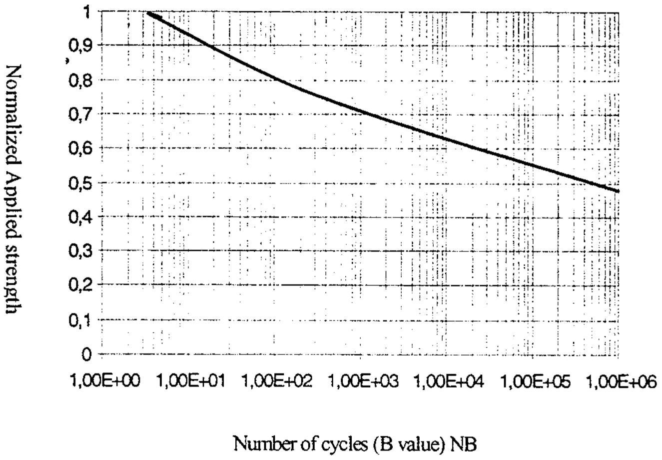


Figure 20: Life duration (B value) versus normalised compressive strength

This result is very important because it demonstrates that, as far as damage tolerance is concerned, a monolithic carbon fiber / epoxy resin structure sized in static is justified in fatigue (at least for the case of fatigue spectrum representative of civil aircraft).

A second approach is being developed. This latter is based on the damage growth with the calculation of the strain energy release rate threshold in the front of the delamination. This approach is based on the micromechanical model (§ 5.2). The aim of this part is to compare different materials (G_1, G_2 …), to justify by stress analysis experimental results …

Conclusion and perspectives

This paper summarises Aerospatiale philosophy and developments for analysing impacted monolithic composite structures.
From 2 approaches based on an extensive test program, 2 calculation methods have been developed.

The first one allows the prediction of the global behaviour of composite monolithic structures damaged by a low-velocity impact through a bidimensional model. The result is available quickly (10-15 min CPU) and so, can be used by an engineering office with a good accuracy compared to test data, even for complex loading.

The second one allows to follow the damage growth, and more particularly, the delamination growth through an expertise tool based on a tridimensional model. Another model, based on the strain energy release rate, is being developed to predict the fatigue behaviour of the damaged composites structures.

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