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Development of a Flaw Tolerant Enhanced Safe Life Concept for Composite Parts in Turbo-Engines

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The safe life concept of lifetime determination is prescribed for aero engine parts. Especially in composite parts initial flaws exist that impose a certain amount of internal damage to the structure but can nevertheless be tolerated. Continuum damage mechanics based on the equivalent energy principle is used to determine the stiffness release due to accidental overload, such as impact. The equivalent lifetime consumption of these initial flaws can be determined by a stiffness based damage accumulation theory. The results are useful for an enhanced safe life concept that accounts for the deteriorating effects of initial flaws.

1 Fatigue Phenomena in Polymeric Composites

In recent years a lot of research has been done on the topic of fatigue of polymeric composites and especially laminates. There is not as much knowledge as for metallic materials but the general behaviour is well known.

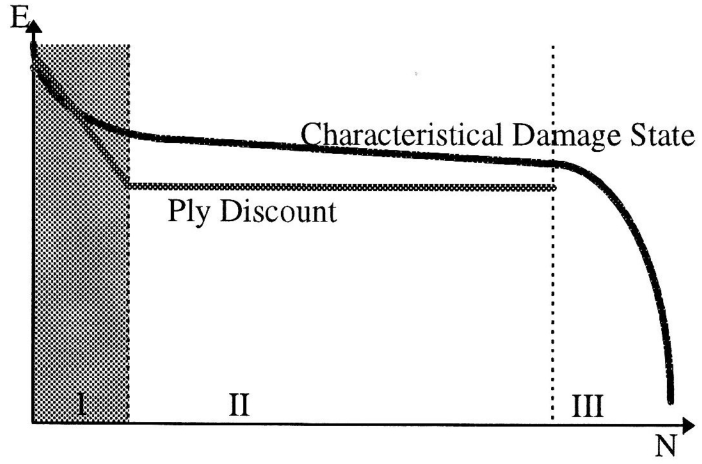

Figure 1: Decreasing Stiffness During Fatigue Life

Cyclic loads tend to lead to failure at a load amplitude that could undoubtedly be withstood if applied statically. The properties of laminates deteriorate in a characteristic manner while in service.

The whole life of a laminated part can be divided into three stages (Figure 1). During stage I and III considerable damage accumulation can be found, while in stage II little happens. Reifsnider, 1991, reports about the basic damage modes that can be found in the different stages of life.

In the beginning there is one pre-dominant damage mode. In the "off-axis"-plies of a laminate (the layers that have fibre directions that do not match with the principal stress directions) the weaker matrix shows small fibre aligned cracks. From a macroscopic viewpoint this deterioration is reflected by a significant stiffness drop.

There exists a stable crack configuration called "characteristical damage state" CDS (Reifsnider, 1991) that has a regular cracked shape with a certain crack distance mainly determined by ply thickness. At the end of stage I no more microcracks appear but other mechanisms begin to get important (mainly crack coalescence that is much slower and less worsening the structural properties).

During the first stage stiffness can be used as a parameter to describe damage state. There are even approaches to use the remaining stiffness for calculations of the whole life (Schulte, 1996). The usage of stiffness is promoted by the comparatively steep slope of stiffness vs. cycle number plot in stage I compared to stage II that enables quite accurate computation of lifetime consumption even by simple linear relations.

If stiffness C_I and cycle number N_I after stage I are given, the stiffness release due to matrix cracking caused by fatigue ΔC and the according number of cycles ΔN are related by:

$$\frac{\Delta C}{C_I} = \frac{\Delta N}{N_I} \tag{1}$$

2 Lifetime Consumption of Initial Flaws

In an enhanced safe life concept, initial flaws and their deteriorating effect on material properties are taken into account which are neglected in a conventional safe life concept.

In contradiction to a damage tolerance concept that also assumes initial defects the initial flaws are not treated individually by a growth analysis but only in a gross manner by lowering the life expectation for a initially damaged part. The European JAR-E regulations require the proof of safe-life. An enhanced safe life concept gives the opportunity to fulfill this requirement without neglecting initial defects.

Initial flaws caused by accidental overloads, like tool drop impacts are characterized by a damage mode that is very similar to fatigue damage as described above. For not too severe damage, small fibre-aligned matrix cracks can first be found that also lead to a stiffness drop (Reifsnider, 1991, Puck, 1996).

Out of this parallelism the approach is born to compare fatigue damage processes during stage I of fatigue life and small flaws like tool drops by the crack density that follows and thus by stiffness drop.

3 Impact Matrix Cracking

To simulate the stiffness drop due to impact damage (or other sources, as well) a degradation model is

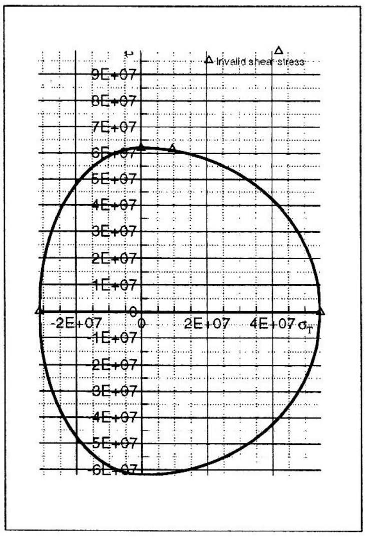

Figure 2: UD Layer Failure Curve

necessary. A simple failure criterion for unidirectional layers is used that marks degradation onset.

$$f(\sigma_T, \tau) = \left(\frac{\sigma_T - \sigma_0^{\pm}}{S^{\pm}}\right)^2 + \left(\frac{\tau - \tau_0^{\pm}}{T^{\pm}}\right)^2 = 1 \tag{2}$$

The parameters have to be adjusted independently for tensional and compressive transversal direct stress (Figure 2). Equation (2) is a conservative simplification of a criterion given by Puck, 1996to avoid more experiments. Woven fabric layers are simply treated like cross ply laminates.

If during a process the stress state reaches $f = 1$, Puck, 1996, proposed to diminish the remaining stiffness depending on the overload factor (reciprocal reserve factor). This simple procedure has been compared und verified by a more detailed Continuum Damage Mechanics theory.

Allen, 1994, proposed an anisotropic equivalent energy approach for a Continuum Damage Mechanics theory by locally averaging the Helmholtz free energy density in a RVE in undamaged state:

$$\psi_{EL} = \hat{\psi}_{EL}(\mathbf{E}_L, \mathrm{T}_L) \tag{3}$$

$\mathbf{E}_L$ is the mean actual strain tensor, T_L the mean absolute temperature. No dependency on Temperature Gradient is assumed. The RVE consists entirely of linear elastic materials and cracks. The equivalent uncracked body can be found by applying fictitious crack face tractions to close the cracks under the same strain. Therefore, the locally averaged Helmholtz energy of the equivalent uncracked body ψ_{EL} can be found from the damaged state ψ_L by calculating the external work per unit volume $\gamma_L \delta_L$ done for crack closure.

$$\psi_{EL} = \psi_L + \gamma_L \delta_L \tag{4}$$

Here the mean crack surface energy density γ_L and the locally averaged crack density δ_L are used. The scalar nature of these variables makes it impossible to model a change in material symmetry. As the symmetry is dominated by the fibres that are not affected in any way, this fault is acceptable. Assuming a constitutive equation for γ_L (theoretically it could be obtained by solving the fracture mechanics boundary value problem):

$$\gamma_L = \hat{\gamma}_L(\mathbf{E}_L, \mathrm{T}_L, \delta_L) \tag{5}$$

the internal variable δ_L will shine up in a constitutive equation for ψ_L as well, and if the constitutive equations are expanded into Taylor series by equation (4) the coefficients can be expressed by the coefficients of the other constitutive equations. In special this applies to the stiffness $\overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_{EL} = \frac{\partial^2 \hat{\psi}_{EL}}{\partial \mathbf{E} \partial \mathbf{E}}$.

$$\overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_L = \overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_{EL} - \delta_L \overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_{\gamma} \tag{6}$$

As Puck, 1996, and many others claim, the ply discount degradation limit for the stiffness is setting zero that part of stiffness induced by matrix properties. Actually, this means that the composite acts like a web. The fibres are considered to carry load only in their direction and be pinned together at their crossing points.

Taking $\overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_{EL}$ as the undamaged stiffness of the fabric layer as known from experiments and

$$\overset{\langle 4 \rangle}{\bar{\mathbf{C}}}_{0L} = \begin{bmatrix} E & 0 & 0 \\ 0 & E & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{7}$$

(2D Voigt notation) as the ply discount limit (E is Young's modulus in Fibre Direction, shear modulus and Poisson ratio$G = \nu = 0$), the partially degraded states may be found on the interpolation line between the two limiting states.

Hence, actual damaged stiffness $\overset{\langle 4\rangle}{\bar{\mathbf{C}}}_L$ as a function of an interpolation parameter, d, is

$$\overset{\langle 4\rangle}{\bar{\mathbf{C}}}_L(d) = \overset{\langle 4\rangle}{\bar{\mathbf{C}}}_{EL} + d\left(\overset{\langle 4\rangle}{\bar{\mathbf{C}}}_{0L} - \overset{\langle 4\rangle}{\bar{\mathbf{C}}}_{EL}\right) \tag{8}$$

If one compares this to equation (6) one finds that obviously

$$\delta = d \tag{9}$$

$$\overset{\langle 4\rangle}{\bar{\mathbf{C}}}_\gamma = \overset{\langle 4\rangle}{\bar{\mathbf{C}}}_{0L} - \overset{\langle 4\rangle}{\bar{\mathbf{C}}}_{EL} \tag{10}$$

and the stiffness degradation based on a RVE approach and on simple macroscopic observations are equivalent.

4 Application to the BR700-710 Structural Bypass Duct

The Structural Bypass Duct (SBPD) is one of the major structural parts in the BR700-710 aero engine. Its main purpose is to contain the pressure of about 80% of the intake airstream that is not lead through the engine core but passes by. In addition the SBPD is the main loadpath between the two mountpoints that are bolted to its forward and rear flanges. Thus it is subjected to combined cyclic loads. One of the most important cases is the thrust reverser operation that must be sustained by the sole SBPD.

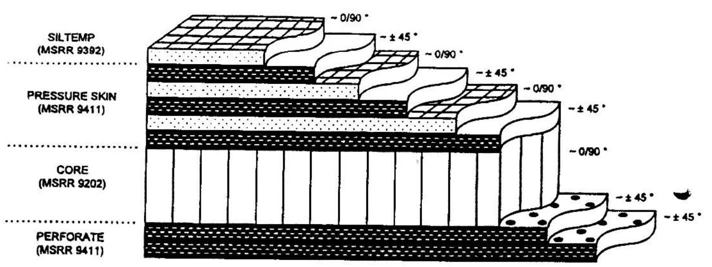

Figure 3: Basic Layup of the SBPD

The 710 SBPD is a modern lightweight carbon fibre laminate / honeycomb core sandwich construction. The use of taylored laminates for this purpose is not yet standard in the industry. Woven fabric prepreg layers are used in the inner and outer skin. During manufacturing and assembly it is possibly subjected to different accidental situations that can be accounted as initial flaws.

Lloyd and Woolfries, 1996, performed a damage tolerance test to show safe life of the structure after subjecting it to impact damage. To simulate this test, a typical impact situation has been modeled as a static indentation of a 28 mm diameter rigid hemisphere. These two tests lead to comparable results for equivalent peak forces (Sankar, 1996). A stiffness degradation model as described before, in combination with a damage/overload relation taken from Puck, 1996, was implemented with the FEM code ABAQUS and the damaged part of the model was subjected to a simulated tension test that gave the remaining stiffness of the outer skin of the laminate.

As one sees clearly in Figure 4 where a variable equivalent to δ_L is shown in the contour plot and a sketch of a suitable experiment is given for comparison the damage is concentrated at the impact target point in the center of the honeycomb cell. Another cumulation point is located at the cell wall.

The computations were performed for several indentation depths and equation (1) was used to calculate the equivalent lifetime consumption. The results are shown in Table 1 and Figure 5. Two of the results had a very similar remaining stiffness but a different impact force. The solid line in Figure 5 marks the life-stiffness relation, the symbols indicate the force-stiffness relation. As the life line is always[1]

[1] with one exeption close to the line

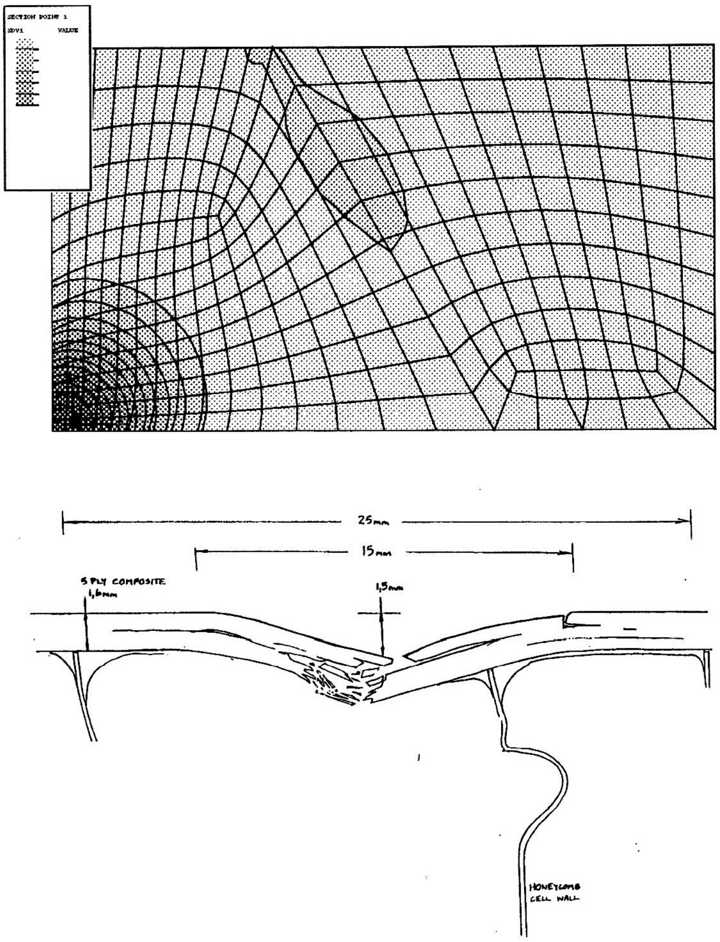

Figure 4: Impact Damage (Computed and Experimental)

below the force symbols it is conservative to connect both y-scales with vertical lines to read the lifetime consumption from impact force.

Depth	[mm]	0	1	2	3	4	5	6	7	8
Force	[N]	0	164.5	337.3	514.5	695.4	879.4	1066.3	1255.8	1447.3
Stiffness	[%]	100	99.93	99.62	99.23	98.62	98.18	97.20	97.22	96.29
$\frac{\Delta N}{N_{\max}}$	[%]	0	0.11	0.62	1.28	2.28	3.03	4.67	4.63	6.17

Table 1: Affects of Impact Damages

5 Conclusion

It was shown that matrix cracks developed during a simulated indentation test lead to a stiffness drop that is equivalent to 6.17% of lifetime consumption, if the indentation force for the quarter model is not exceeding 1447 N, resulting in 5788 N for the whole indentation process. The defect size connected with that test is the target honeycomb cell and its neighbours.

This knowledge is useful to adapt the S-N curve for this material in an enhanced safe life concept.

Independently from these considerations it was shown by fracture mechanics methods that delaminations of similar size that usually arise in impact situations are not growing under the load conditions one finds in operation (Schurig, 1999).

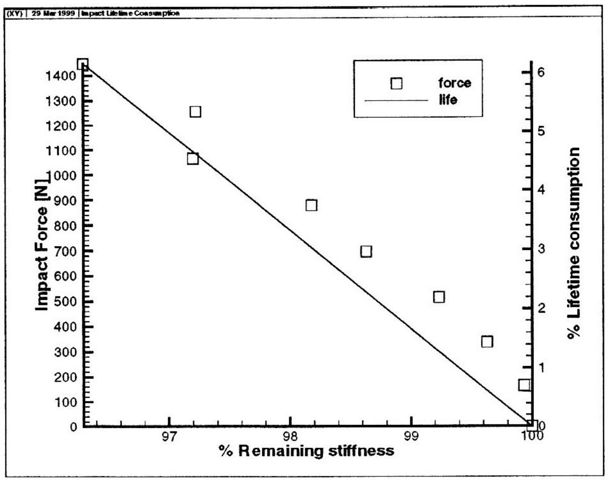

Figure 5: Life Time Consumption of Impact Matrix Damage

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