A NEW SEMI-EMPIRICAL DAMAGE TOLERANCE AND FATIGUE EVALUATION APPROACH FOR COMPOSITE ROTORCRAFT AIRFRAME STRUCTURES

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Abstract

A new semi-empirical methodology to perform a damage tolerance and fatigue evaluation for composite airframe Principal Structural Elements (PSE) is proposed, to comply to new CS/FAR requirement §29.573. “Damage tolerance and fatigue evaluation of composite rotorcraft structures”.
This methodology consists out of five different steps.
1st , identification of airframe PSE based on the consequence of their failure, e.g. by a FMECA.
2nd , individual threat assessment for each PSE, based on in-service experience, in-house and from others.
3rd, determination of detectability thresholds for individual PSE by performing impact tests on specific coupons to derive Barely Visible Impact Damages (BVID)/ Clearly Visible Impact Damage (CVID) detectability thresholds and CVID/Obvious damage detectability thresholds.
4th, no-growth demonstration of damages on impacted coupons by applying repeated loads with constant amplitude for a certain number of load cycles which cover one design service goal (DSG/life). Those test results are then used to derive allowables in terms of strain limits for sizing of PSE.
5th, structural full scale component tests (static and fatigue) of PSE with BVID/CVID and other typical in-service damages and repairs, to verify Design Ultimate Load (DUL) capability, no-growth behavior of damages, suitability of repairs and residual strength capability, which is minimum Design Limit Load (DLL).

1. ABBREVIATIONS

AH – Airbus Helicopters

BVID – Barely Visible Impact Damages

CAI – Compression After Impact

CAIF – Compression After Impact & Fatigue loading

CFRP – Carbon Fibre Reinforced Plastic

CVID – Clearly Visible Impact Damage

DET – Detailed Visual Inspection

DLL – Design Limit Load

DSG – Design Service Goal

DUL – Design Ultimate Load

FEM – Finite Element Method

FMECA – Failure Mode Effect and Criticality Analysis

GAG – Ground Air Ground cycles

H/C - Helicopter

H/W – Hot/Wet environment

J – Joule, Impact Energy

LCF – Low Cycle Fatigue

NDT – Non Destructive Testing

OEM – Original Equipment Manufacturer

PSE – Principal Structural Element

RT – Room Temperature

RTM – Resin Transfer Molding

UT C-Scan – Ultra Sonic Testing method, which provides images

2. INTRODUCTION

To know the damage tolerance- and fatigue behaviour of composite PSE is of vital interest for each OEM, to guarantee product safety and to ensure customer satisfaction.
Airbus Helicopters (AH) use extensively composite airframe PSE on their current products, like H225 intermediate structure, NH90 and Tiger complete airframe, H135/H145 tail boom structure and on future products coming soon.
Based on the good experience with composite technology and to comply to new requirement of CS/FAR §29.573, a 5 step methodology is proposed.
It has to be noted that a damage tolerance evaluation for PSE is required as normal case evaluation and a mere fatigue evaluation is allowed only, if the applicant can demonstrate that a damage tolerance evaluation is impractical within the limits of geometry, inspectability and good design practice.

The proposed methodology follows the classical building block approach acc. to Ref (1), see Fig.1

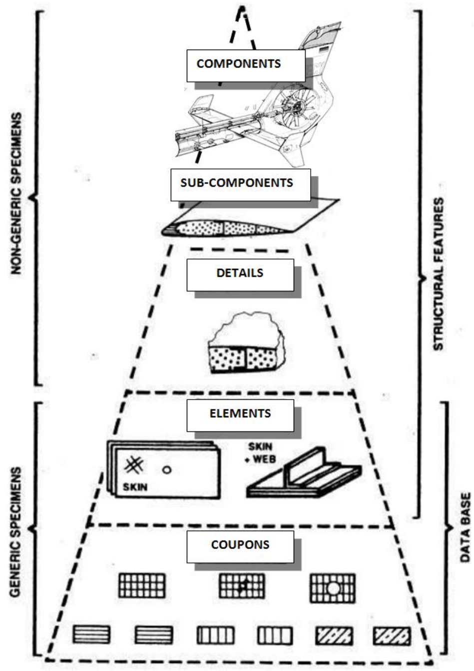

Fig. 1: Schematic diagram of building block tests, acc. to Ref. (1)

2.1. Composite Airframe PSE are specific

When airframe structures are sized for static load cases, mostly compressive loadings drive the design to cope with instabilities like buckling or flange crippling of e.g. monolithic frames or wrinkling of face sheets and/or shear crimping of sandwich shells. In terms of fatigue loading airframe PSE are to be sized for Ground-Air-Ground (GAG) cycle loading. GAG cycles cover low frequency large amplitude load cycles such as load fluctuations between various flight conditions. A number of cycles lower than 10^5 mark the low cycle fatigue (LCF) range which is typically associated with such GAG cycles.

There is also a difference in the behavior of conventional aluminium structure compared to composite ones under static- and fatigue loading. Aluminium structures are sensitive to fatigue w.r.t. cracks, when loaded in tension, see Fig.2.

Fig 2 provides a comprehensive picture of the difference in behavior of Aluminium and CFRP coupons (notched and un-notchd), loaded in fatigue.

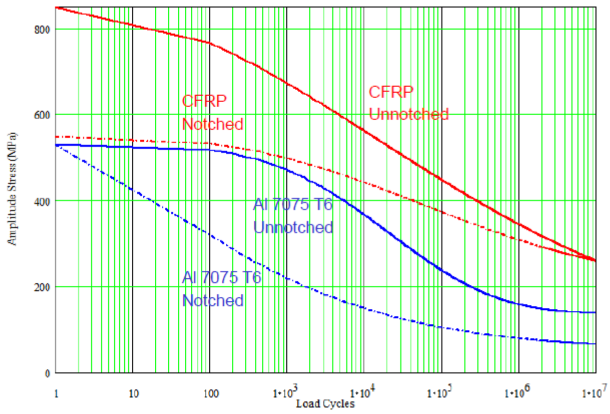

Fig.2: 4 different S/N curves for notched & un-notched coupons made out of Alu. 7075 and CFRP, (quasi-isotropic lay-up) loaded with a stress ratio of R=-1.

The endurance limit of the notched and un-notched coupons made out of CFRP is almost the same, whereas it is significantly different for the Aluminium ones. So consequently the effect of stress concentrations can be seen much better on composite parts at static loading, as composites do not have the ability to relief stress concentrations by plasticity.

Composite structures however are more sensitive to impact damages, which can cause the growth of delaminations, when loaded repeatedly in compression, so called compression after impact (CAI), see Figs, 3 & 4 resp.

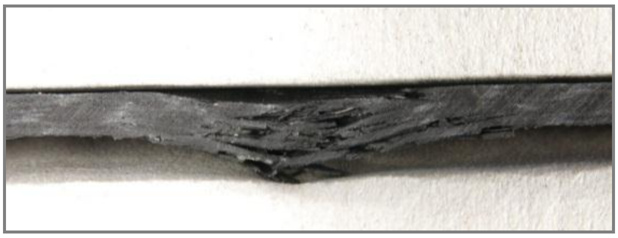

Fig.3: Typ. delamination of a monolithic part after an impact with 9J.

Fig.4: Typ. delamination of a sandwich part after an impact with 5J.

3. DEFINITION AND IDENTIFICATION OF COMPOSITE AIRFRAME PSE, (1ST STEP)

Ref. (1) provides a definition of PSE: "A structural element that contributes significantly to the carrying of flight- and ground-loads and whose failure can lead to catastrophic failure of the rotorcraft".

It also defines "catastrophic" in § 29.602 as follows: "the term catastrophic means the inability to conduct an autorotation to a safe landing….".

Usually a FMECA or an equivalent method is used to identify PSE candidates. In this methodology it is proposed to assume as failure of a PSE its loss of capability to sustain DUL, due to possible in-service damages which led to a partial destruction of the PSE. To regard as failure a complete disappearance of a PSE is not regarded as meaningful.

Typical airframe PSE are e.g. portions of main frames, if e.g. main gear box struts are attached on them, or highly loaded shells where a FMECA results in a catastrophic failure condition for the rotorcraft.

4. A PROPOSED METHOD FOR A THREAT ASSESSMENT FOR COMPOSITE AIRFRAME PSE, (2ND STEP)

Ref. (1) requires a threat assessment that specifies the locations, types and sizes of damage considering fatigue, environmental effects, intrinsic and discrete flaws, impacts or other accidental damage that may occur during manufacture or operation.

To perform such kind of threat assessment on composite airframe PSE, AH uses in-service experience of its fleet and others, e.g. results published in Ref. (2), as they confirm AH's in-house experience.

Fig.5 shows possible impact threats like e.g. impacts due to dropped tools, dropped parts, stowed baggage drops, foot & boots, ground starting equipment, edge and corner impacts due to dropped parts during manufacture and service and terrain objects impacts. The related impact energy is shown versus its probability.

Based on AH's in-service experience, an impact energy threat of 25J can be regarded as a max. realistic threat for H/C airframes. This is also confirmed by Fig.5., as ~85% of the most severe impact threats, i.e. impacts due to terrain objects (curve 11), occurred at energy levels of 25J or less.

The energy cut-off for this severe threat is 50J, however 98% of those impacts occur at energy levels of 45J or less.

Almost all other impacts occur at energy levels smaller than 25J.

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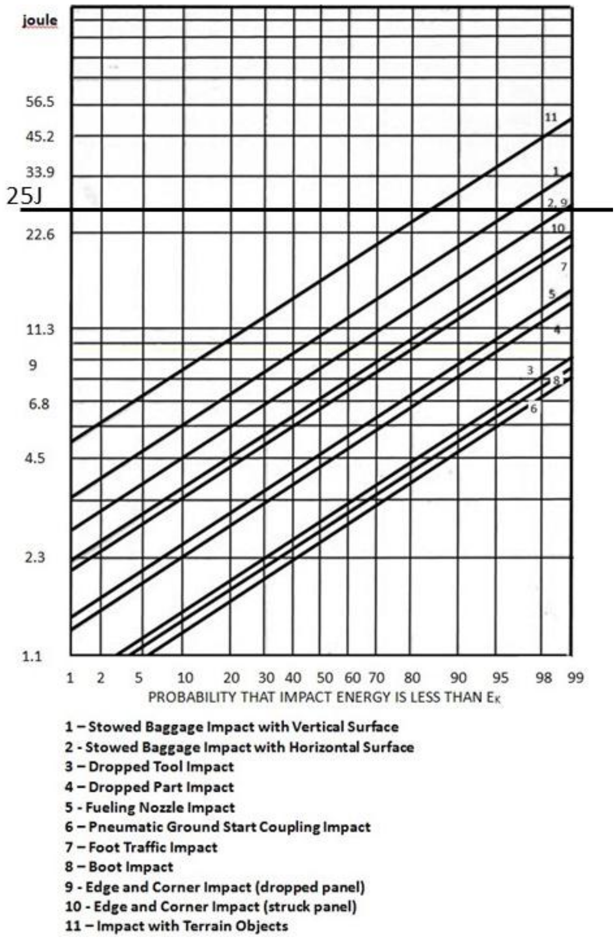

Fig.5: Possible threats on H/C airframes in terms of impact energy vs. their probability, acc. to (Ref.2)

Fig.6 & 7 show as an example identified threats on typical H/C composite airframe PSE.

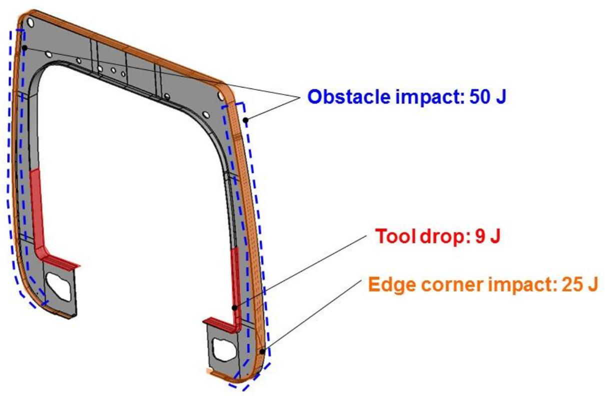

Fig.6: Identified possible threats on a typical composite main frame

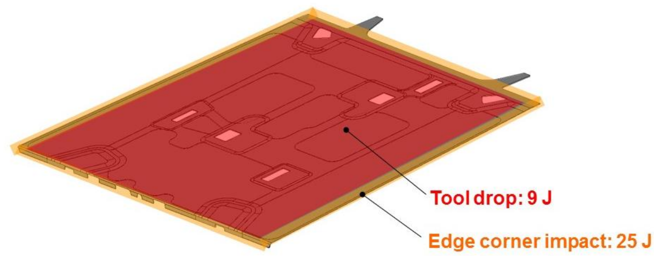

Fig.7: Identified possible threats on a typical composite sandwich panel

5. A METHOD FOR DETERMINATION OF DETECTABILITY THRESHOLDS, (3RD STEP)

Impact energy threat and its subsequent possible damage is linked to detectability thresholds of those impacts. Ref. (1) proposes Design Ultimate Load (DUL) capability for Barely Visible Impact Damages (BVID) and no-growth of them within one Design Service Goal (DSG) and in addition Design Limit Load (DLL) capability for certain detectable damages, which are addressed in the following as Clearly Visible Impact Damages (CVID) and no-growth of those CVID within one inspection interval.

To find out those detectability thresholds, Airbus-Group in-house investigations had been carried out on representative composite structures, which were impacted to different dent depths, to determine BVID and CVID detectability thresholds.
The dents of those impacts need to be found visibly through so called “detailed visual inspection” procedure.

Definition: “Detailed visual inspection” acc. to Ref.(3):

“Close proximity (i.e. within one arm length) to cleaned surface and appropriate access to gain proximity, available lighting is normally supplemented by direct source of good lighting. Inspection aids may be e.g. lenses, grazing light etc”.

To determine the visibility thresholds for BVID & CVID with a.m. means, aforementioned composite panels had been impacted in such way that dent depths ranging from 0.05mm to 1mm occurred on them.
Then blue collar workers had been tasked to find those impact dents by doing a detailed visual inspection.
It turned out that dent depths ≥ 0.3mm were found by them to 100%, see Fig.8.

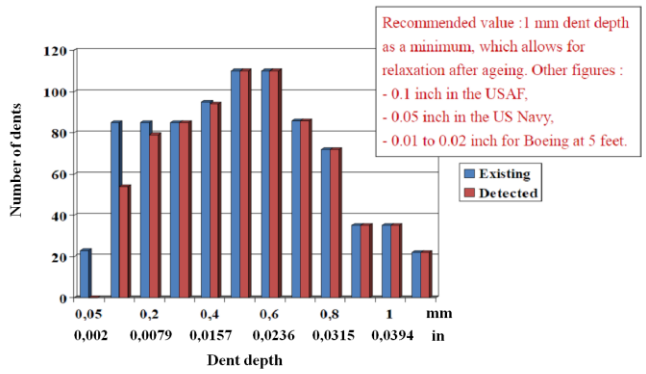

Fig.8: Detectability of impact dents w.r.t. dent depth acc. to Ref. (4).

Out of this investigation a dent depth of 0.3mm is recommended to mark the detectability threshold between BVID and CVID zone.

One has to recognize that relaxation due to hot/wet ageing of dent depths on composite structures plays a role, which needs to be regarded.
Ref. (5) addresses this relaxation phenomenon.
Fig.9 shows the reduction of dent depths of several impact damages on CFRP parts w.r.t. hot/wet ageing vs. time.

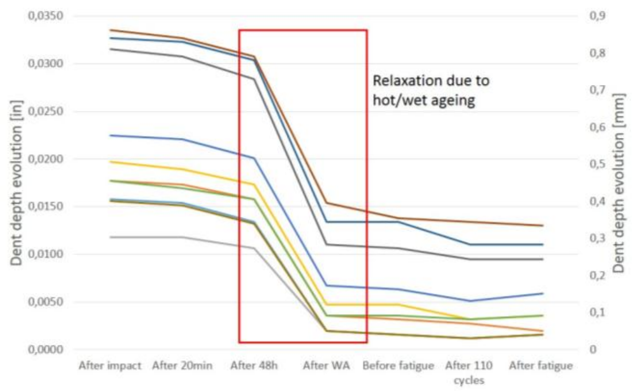

Fig.9: Dent depth relaxation vs. time due to hot/wet ageing acc. to Ref.(5).

Based on all of these investigations, a dent depth of 0.3mm after relaxation for the BVID/CVID threshold and a dent depth of 1mm after relaxation is recommended as the CVID/obvious damage threshold. Detected obvious damages need an immediate action, e.g. a repair.

Fig.10 shows a picture of an impacted sandwich coupon and a UT C-Scan of delaminated area. The impact energy was 5J.

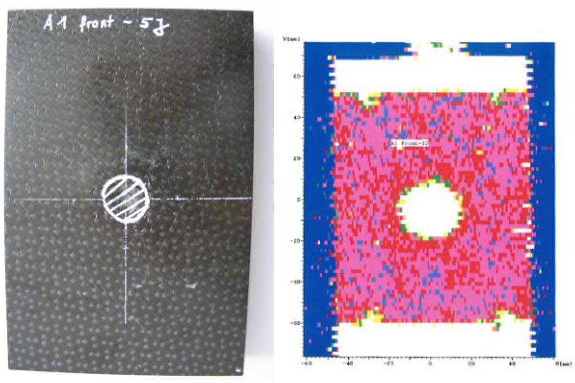

Fig.10: Sandwich coupon (CFRP facing/Nomex core) impacted with 5J. Picture and UT C-Scan.

As dent depth depends on material, geometry and manuf. technology, in-house tests have been carried out on different specific monolithic- and sandwich coupons which represent airframe PSE, to determine BVID & CVID detectability threshold levels in terms of dent depths (mm)
with several impact energies (J), see Figs. 11 & 12.

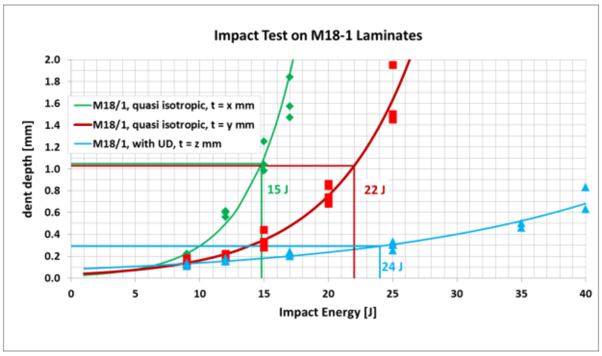

Fig.11: Measured dent depth (mm) vs. different impact energies (J) on several specific impacted monolithic coupons representing airframe frame-PSE.

Thin laminates show already at relatively low energy levels clearly visible impact damages (CVID).

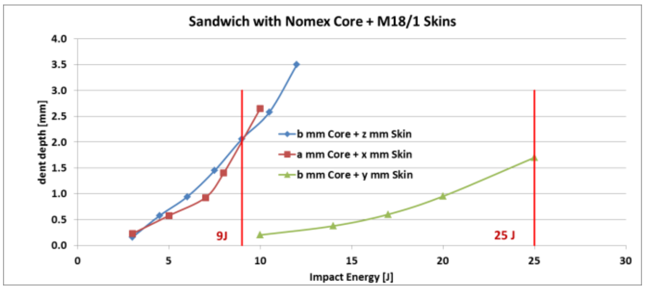

Fig.12: Measured dent depth (mm) vs. different impact energies (J) on several specific impacted sandwich coupons representing airframe shell-PSE.

It seems that dent depth on sandwich construction depends more on face sheet & core properties and is not so much dependent on core thickness.

6. NO-GROWTH DEMONSTRATION OF BVID & CVID UNDER REPEATED LOAD, (4TH STEP)

To demonstrate no-growth behaviour of BVID/CVID resp., AH uses compression after impact testing of generic- and specific representative coupons performed under relevant environmental conditions. Coupons are manufactured which represent identified airframe PSE in terms of material, geometry and technology. Then those coupons are impacted acc. to their identified threats and BVID/CVID detectability thresholds.

Fig.13 shows the test set up for performing impact tests on coupons

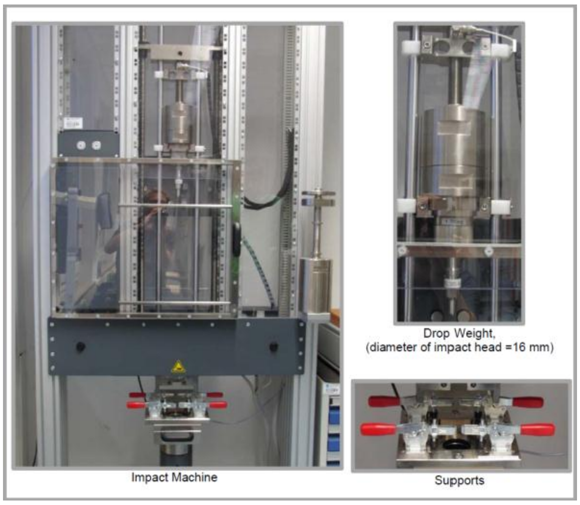

Fig.13: Test setup for impact testing of coupons

After having impacted the coupons, the corresponding delaminated area (mm²) is measured via UT C-Scans.

Then some impacted coupons are tested statically to determine their residual static strength σ_{CAI}, static H/W. The derived strain out of those static tests is used as max. allowable strain for showing DUL/DLL resp. capability for BVID/CVID resp. Then other impacted coupons are tested under constant amplitude loading which represent a certain amount of DLL for ~10^5. load cycles to demonstrate No-growth behavior.

Fig.14 shows the test set up for the σ_{CAI} static and fatigue tests.

Fig.14: Test setup for **σ**CAI static & fatigue testing

To demonstrate No-growth behavior of impact damages, those tests are periodically interrupted and the size of the delaminated area is measured with UT C-Scans see Fig.15.

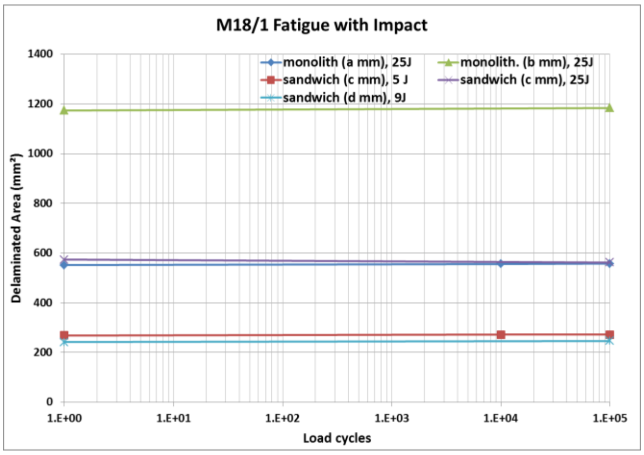

Fig. 15: Measured delaminated area vs. load cycles

Fig.15 shows a No-growth demonstration of delaminated area of several impact damages (BVID) under constant amplitude compressive loading (at R=10) on different specific coupons representing monolithic- and sandwich PSE for a composite airframe.

7. VERIFICATION OF DUL/DLL CAPABILITY, NO-GROWTH OF BVID/CVID BY COMPONENT TESTING, (5TH STEP)

To verify this new method, structural full scale component tests are performed to cover both, static strength demonstration to comply to CS/FAR 29.305/307 and damage tolerance and fatigue demonstration to comply to new CS/FAR 29.573. Ref (4) proposes test sequences depending on the novelty of the airframe structure. For new structures a complete testing sequence of the composite PSE is recommended, see Fig.16.

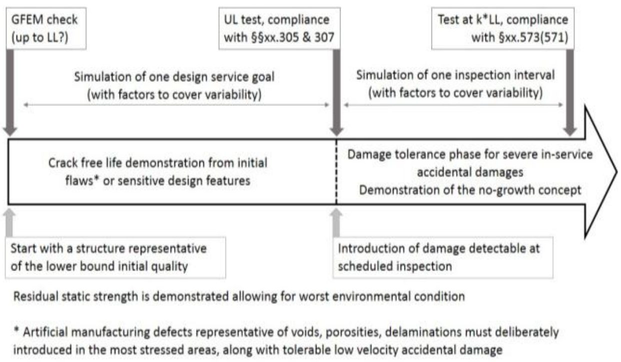

Fig.16: recommended test sequence for a new structure, full scale test.

Such full-scale test can be done on either a complete, or on a portion of an airframe with flight and ground loads applied to the test article. Service simulation loads in form of a spectrum are applied instead of constant amplitude loads for such tests.

Fig.17 shows a picture of the test set up of a composite tail boom full scale test

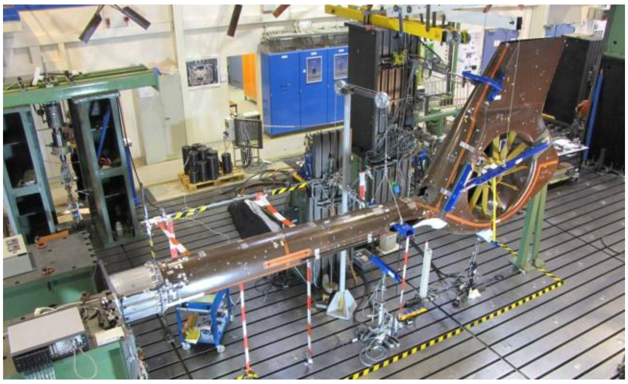

Fig.17: Test set up for a composite tail boom full scale test.

If the PSE is a so called “Similar New Structure”, i.e. a structure that utilises similar or comparable structural design concepts such as details, geometry, structural arrangements and load path concepts and materials to an existing tested design, as outlined in Ref.(7), an alleviated test sequence is proposed, see Fig.18.

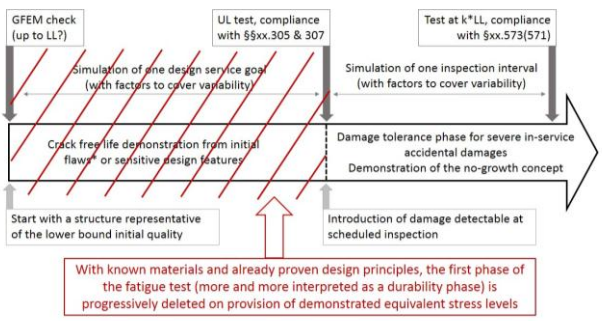

Fig.18: Alleviated test sequence for a “similar new structure” acc. to Ref.(7)

8. CONCLUSION

To perform a damage tolerance evaluation for composite airframe PSE, a detailed and in depth understanding and knowledge of the specific behavior of such parts with their different possible technologies, e.g. sandwich design, monolithic design in prepreg- or RTM technology is indispensable.

Their specific behavior w.r.t. static- and fatigue loads under relevant environmental conditions, considering the effects of possible damages during manufacture & service and long term experience from operational usage has to be known and understood.

To evaluate the damage tolerance behavior of such parts, not only sophisticated analytical and numerical tools need to be applied, but also extensive testing on coupon- and full scale component level is required and a profound experience in NDT methods is needed.

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10. REFERENCES

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