

CERTIFICATION OF AIRCRAFT COMPOSITE STRUCTURES

by
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For the certification of composite structures**

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A summary of the English notes taken during the training
given by J. Rouchon (French Training, April 2007) is
available at the end of the present file.

Summary

This course is mainly dedicated to engineers from the Industry or the Certifying Agencies, who are deeply involved in the certification of composite structures, either for substantiation preparation or acceptance. Engineers from other organisations as airlines or institutes can also be interested by this course.

From the experience now gained since the mid eighties with the introduction of composite primary parts in major programmes such as Airbus A320, A330/340, A380, ATR and Falcon series, this course will present the approach and methodology, widely in used Europe, to address the certification of such advanced material aircraft structures.

The course will start with an overview of the aircraft certification purpose and the associated procedures. Then, general regulatory requirements developed for structures will be shortly addressed before going to the composite attributes that has led to a different certification approach as compared to metallic structures.

The chapters of the regulatory requirements which are mainly impacted by those composite attributes will be then successively addressed, and commonly accepted means of compliance and methods will be shown.

Content

Chapter 1 – Certification Procedures Overview.

Chapter 2 – Structures Airworthiness Requirements and Composite Attributes.

Chapter 3 – Composite Certification Scheme.

Chapter 4 – Design Requirements.

Chapter 5 – Environmental effects.

Chapter 6 – Materials Qualification.

Contenu (suite)

Chapter 7 – Allowables and Design Values.

Chapter 8 – Static Strength Requirements.

Chapter 9 – Fatigue and Damage Tolerance Requirements.

Chapter 10 – Lightning Strike Protection.

Chapter 11 – Continued Airworthiness, Inspection and Repairs.

Chapter 12 – Quality Assurance.



Chapter 1 – Certification procedures overview

The certification purpose

The main purpose of certification, in civil aeronautics, is to guarantee the safety of people flown over or transported by any aircraft that might, due to its mass and speed characteristics, present a significant hazard in case of accident.

Certification is part of the application of the air transport regulation

Air transport regulation

- **WHY ?**
 - Safety of the population flown over (protection of the law and order).
 - Safety of the passengers unaware of the risk being taken (consumer protection).
 - Safety of the in-flight staff (labour regulation).
- **HOW ?**
 - Airworthiness codes (regulation).
 - International agreements (standardisation and uniformity needs).
- **OBJECTIVES**
 - To achieve an acceptable risk of safety :
The aeronautics related risk should be comparable to other risks.
The target is 10^{-7} fatal accidents* per flight hour for transport category aircraft.

** Leading to at least one fatality.*

The current level of safety in air transportation

- **TRANSPORT CATEGORY AIRCRAFT RELATED RISK**
 - Better than 10^{-6} fatal accident per flight hour (statistics often better in the USA than in the rest of the world).
- **ROTORCRAFT RELATED RISK**
 - Around 10^{-5} per flight hour.
- **GENERAL AVIATION (PRIVATE) RELATED RISK**
 - Around 10^{-4} per flight hour.

It is commonly admitted that the risk related to air transportation is comparable to the risk attributed to other means of commercial transportation, and is equal to :

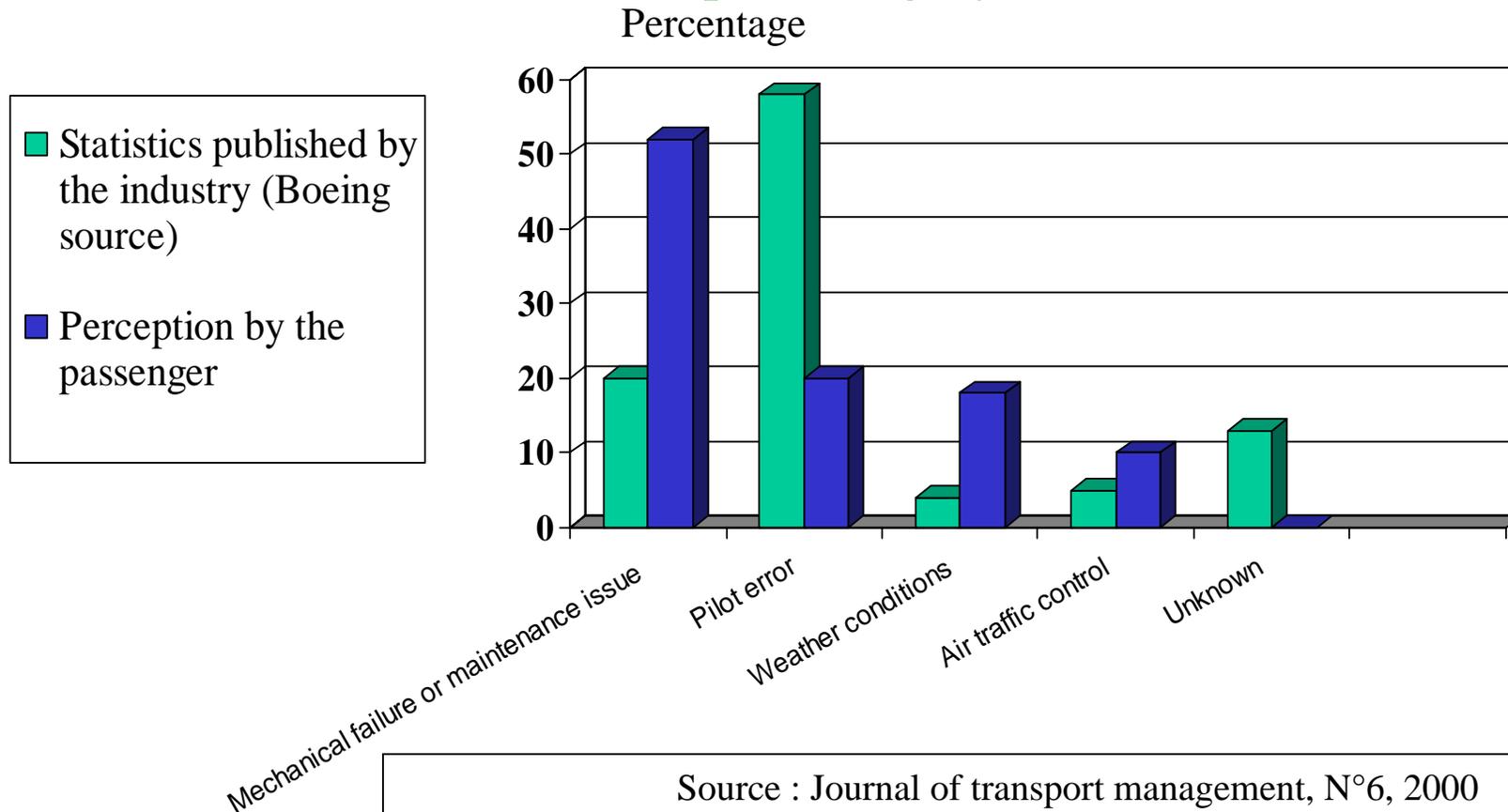
0.5% for the passengers,
5% for the in-flight staff.

The current level of safety in air transportation (Cont'd)



Around the same risk to perish in an aircraft fatal accident as to win the jackpot with such famous French game

Main cause breakdown for civil aviation accidents (for transport category aircraft)



Should you prefer an other mean of transportation.
Number of fatalities per 100 millions of seat-kilometres

Mean of transportation	Mean per year 1975_95	Ratio compared to aircraft
Aircraft	0.03	1.0
Bus	0.04	1.3
Train	0.1	3.3
Car	0.4	13.3
Ship	0.6	20.0
Motorbike	9.7	323.3

Source : Royal society for the prevention of accidents (UK, 1998)

Air transport regulation, the domain covered

- **THE QUALITY OF THE AIRCRAFT (PRODUCT INTEGRITY)**

- Initial definition in terms of airworthiness.
- maintenance.

Certification purpose

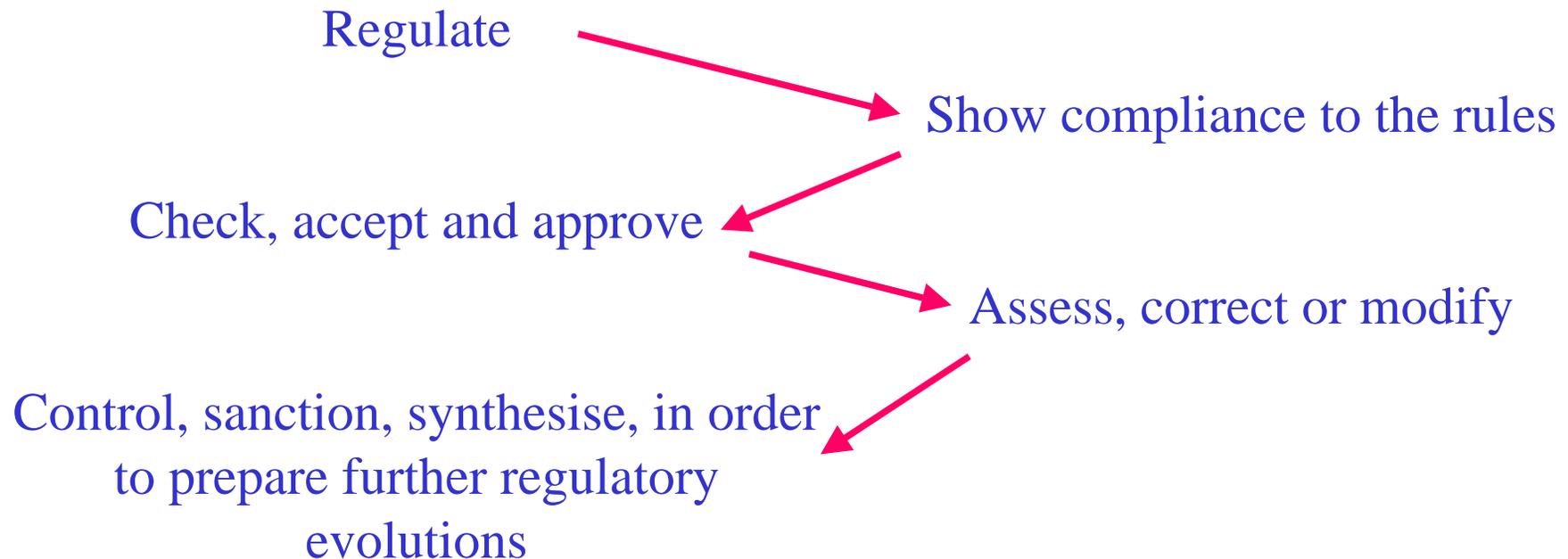
- **THE OPERATING CONDITIONS**

- Crew qualification.
- Air traffic rules.
- Airport facilities.
- Operating conditions and limitations.
- Nuisance.
-

The role of the main actors

THE AIRWORTHINESS AUTHORITIES

THE MANUFACTURERS (APPLICANTS)



Air transport regulation, existing organisations

**‘ TOP STRUCTURE ’ : THE INTERNATIONAL CIVIL AVIATION ORGANISATION (ICAO)
WHO IMPOSES MINIMUM REQUIREMENTS**

(Convention of Chicago dated 7 December 1944)

The ‘ quality of the flying material ’ is specifically covered by the annex 8



Various interpretations



UNITED STATES

EUROPE

FEDERAL AVIATION REGULATIONS (FAR)

Prepared and published by the
Federal Aviation Administration (FAA)

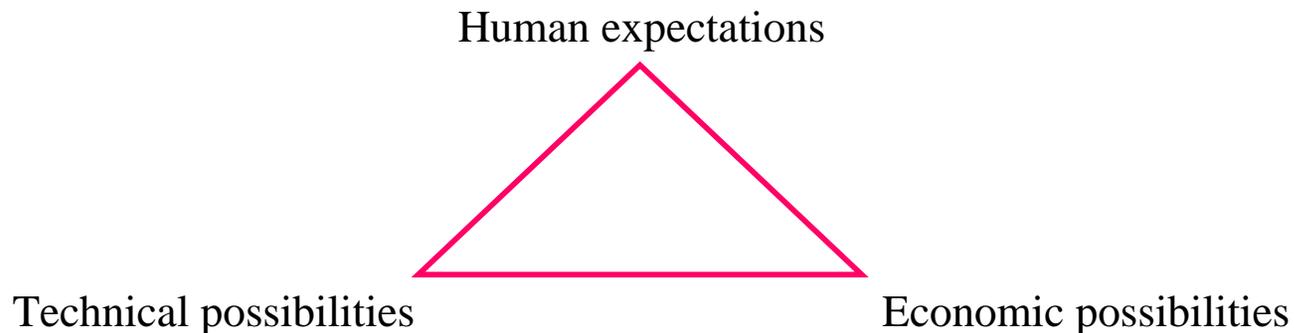
CERTIFICATION SPECIFICATIONS (CS)

Prepared and published by the European Aviation
Safety Agency*

** The European Aviation Safety Agency was created on 15 July 2002 by the law 1592/2002 of the Parliament and the European Council. The Agency (EASA) is effective since 28 September 2003 and is being installed in Cologne (Germany) since November 2004. EASA is the normal follow-up of the Joint Aviation Authorities (JAA), created in 1980, which involved 33 member countries in 2002.*

The quality of the regulation

- **AIR TRANSPORT REGULATION MUST BE :**
 - Precise enough in order to prevent mis-interpretation.
 - Flexible enough not to impede technical advances.
 - Durable.
- **THIS IS THE RESULT OF A COMPROMISE BETWEEN :**
 - Human expectations : zero accident.
 - Technical possibilities : what is actually feasible.
 - Economic constraints : What are we ready to pay.



Main airworthiness standards
(Federal Aviation Administration code)

- FAR 21 : Certification Procedures for Products and Parts.
- FAR 23 : Airworthiness Standards : Normal, Utility, Acrobatic and Commuter Category Airplanes (*9 passengers, or less, MTOW 12,500 lbs, or less. These figures are expanded to 19 passengers and 19,000 lbs respectively, for commuters*).
- FAR 25 : Airworthiness Standards : Transport Category Airplanes.
- FAR 27 : Airworthiness Standards : Normal Category Rotorcraft (*9 passengers, or less, MTOW 7,000 lbs, or less*).
- FAR 29 : Airworthiness Standards : Transport Category Rotorcraft.
- FAR 33 : Airworthiness Standards : Aircraft Engines.
- FAR 35 : Airworthiness Standards : Propellers.

Main airworthiness standards (European Aviation Safety Agency code)

- CS 21 : Certification Procedures for Aircraft, and related Products and Parts.
- CS 22 : Sailplanes and Powered Sailplanes.
- CS 23 : Normal, Utility, Aerobatic, and Commuter Category Aeroplanes (*9 passengers, or less, MTOW 5,670 kg, or less. These figures are expanded to 19 passengers and 8,618 kg respectively, for the commuters*).
- CS 25 : Large Aeroplanes.
- CS 27 : Small Rotorcraft (*9 passengers, or less, MTOW 3,175 kg, or less*).
- CS 29 : Large Rotorcraft.
- CS E : Engines (corresponds to FAR 33).
- CS P : Propellers (corresponds to FAR 35).
- CS VLA : Very Light Aeroplanes (*MTOW 750 kg, or less, stalling speed in landing configuration 45 kts, or less*). This code is recognised by the FAA (C.F. AC 21.17-3)

The content of an airworthiness standard (the example of CS 25 and CS 29)

SUBPART A - GENERAL

SUBPART B - FLIGHT

SUBPART C - STRUCTURE (SAID STRENGTH REQUIREMENTS IN CS 29)

SUBPART D - DESIGN AND CONSTRUCTION

SUBPART E - POWERPLANT

SUBPART F - EQUIPMENT

SUBPART G - OPERATING LIMITS AND INFORMATION

SUBPART J - GAS TURBINE AUXILIARY POWER UNIT INSTALLATION (in CS 25 ONLY)

Subparts C, D and F, highlighted in red, are impacted by the introduction of composite materials.

The certification process

THE CERTIFICATION PROCESS CONSISTS IN ALL THE OPERATIONS ALLOWING TO ENSURE THAT A PRODUCT MEETS, AS A WHOLE AND CONSIDERING ALL ITS INDIVIDUAL PARTS, A SET OF PRESCRIBED TECHNICAL CONDITIONS CALLED : THE ‘ CERTIFICATION BASIS ’.

THIS PROCESS INVOLVES THE FOLLOWING STEPS :

- The mailing of an **Application Letter** for a Type Certificate to the relevant airworthiness authorities (incorporating a three-view drawing with preliminary basic data and performances of the product, attached to this letter).
- Definition, by the Airworthiness Authorities, of the **CERTIFICATION BASIS**.
- Demonstration, by the manufacturer, of the compliance to this certification basis.
- Acceptance, followed by the issue of the **TYPE CERTIFICATE**.

The certification basis content

IT INCLUDES (c.f. CS § 21-17) :

- **THE APPLICABLE REQUIREMENTS**

Designated at their latest amendment, effective at the date of reception of the application letter.

- **SPECIAL CONDITIONS**

Deemed necessary by the airworthiness authorities and covering situations where (c.f. CS § 21-16) :

- there are novel or unusual design features, relative to the design practices on which the applicable standard is based,
- the intended use of the product is unconventional,
- experience from other similar products in service has shown that unsafe conditions may develop.

- **SOME ADMENDMENT PROJECTS TO THE APPLICABLE STANDARD.**

They consist in NPA (Notice of Proposed Amendments), already published when the certification basis is established, and the manufacturer wishes they are already considered.

Supplemental documents to the certification basis

THESE DOCUMENTS, WITH RESPECT TO, CONFORMITY **CANNOT BE REQUIRED INVOLVE:**

- **THE ADVISORY CIRCULARS WHICH ARE AVAILABLE IN THE OFFICIAL DOCUMENTATION ASSOCIATED TO THE AIRWORTHINESS STANDARDS**

These document may explain one specific point of the rules, or propose means, but not the only means, that are acceptable to show compliance with the rules (as an example : the AC20 107A or AMC N°1 to CS 25 603 for composites).

- **OTHER INTERPRETATIVE MATERIALS OR ACCEPTABLE MEANS OF COMPLIANCE**

Specific to the application under concern and not covered by the previous documentation. (as the document covering GLARE introduction on the A380).

- **ANY OTHER DOCUMENT RECOGNISED BY THE AIRWORTHINESS AUTHORITIES**

Example : the MIL HDBK 17 for composites.

Example : The A380 certification

- **CERTIFICATION BASIS :**

- The airworthiness standard applicable on 20 April 2001 (date of the application letter for type certification), that is JAR 25 at change 15.
- 36 special conditions of which :
 - 28 are associated to novelties or unusual technologies,
 - 3 are associated to an unconventional usage of the product,
 - 5 are associated to feedback where unsafe situations have, or could have, developed.

(some of these special conditions are associated to on-going updates of the rules, the manufacturer proposes to allow for).

- **ASSOCIATED DOCUMENTS :**

- The whole available set of relevant Advisory Circulars, plus :
- 89 specific ‘ Interpretative Materials ’ including the IM D-29 covering the GLARE.

The manufacturer has now 5 years to show compliance to this certification basis (c.f. §JAR 21-17).

This duration would be the same for a JAR 29 rotorcraft, but would be reduced down to 3 years for any other product.

The various certificates

- **THE TYPE CERTIFICATE**

- the Type Certificate is issued at the end of the certification process, when compliance with the certification basis has been shown. The type certificate is intended to cover all manufactured products pertaining to a pre-defined type, and can be amended to cover further derivatives, if any.
- The type certificate is effective until it is surrendered, suspended or revoked.

- **THE CERTIFICATE OF AIRWORTHINESS**

- It pertains to each individual manufactured product, defined in terms of modifications with respect to the type (this is the owner who applies for a Certificate of Airworthiness).
- It is mandatory for registration of each individual product (aircraft or rotorcraft).
- It is effective over a prescribed period of time, provided maintenance is properly performed under the conditions accepted by the airworthiness authorities (c.f. CS § 21-181).

The Type certificate (in former JAA procedures)

JOINT
AVIATION
AUTHORITIES

A330-303 CERTIFICATION

PCM FINAL STATEMENT OF COMPLIANCE

The compliance demonstration of Airbus Industrie for the A330-303 model as defined in the Type Design Definition document 00G00A203/C00, has been subjected to an investigation by the A330/A340 JAA Team, based on the major change procedure.

The investigation has satisfied the Joint Team that:

- The Type Design is adequately documented;
- All data required for the issuance of a Type Certificate or equivalent documents specific to each of the participating Airworthiness Authorities are available;
- The documents necessary for Type Certificate are acceptable;
- The compliance documents are kept available to the JAA Team, and to the NAA.

Based on the investigation, the JAA Team has been satisfied that the Type Design as specified above complies with the applicable airworthiness and environmental requirements, as notified in CPE G-101 dated March 1996.

Place : PARIS

Dated: November 20, 2001

Signed:
Rachel Daeschler,
A330/A340 Project Certification Manager

90, Rue Henry Farman - 75720 PARIS CEDEX 15 - FRANCE - TEL. STANDARD (33) (1) 88.00.43.21

The statement of compliance
(JAA procedure)



Open on the Type Certificate
issued by each JAA member country



DIRECTION GENERALE DE L'AVIATION CIVILE

Membre des Joint Aviation Authorities

CERTIFICAT DE NAVIGABILITE DE TYPE
Type Certificate
Numéro 184

Ce certificat établi conformément au Code de l'Aviation Civile est délivré à :
This certificate established in conformity with the French Code de l'Aviation Civile and issued to:
AIRBUS INDUSTRIE
1 rond-point Maréchal Juin
31707 Bordeaux-Mérignac

atteste que le type désigné ci-dessous satisfait aux exigences des règlements de navigabilité applicables, ainsi qu'aux autres conditions, restrictions et limitations définies dans la fiche de navigabilité établie en même temps que ce certificat et le numéro 184
certifies that the type designated below complies with the applicable French airworthiness requirements when operated within the limitations and conditions specified in the associated data sheet associated to this certificate with the number 184

type	date d'approbation
A 330-303	21 octobre 1993
A 330-300	2 juin 1994
A 330-300	2 juin 1994
A 330-300	2 décembre 1994
A 330-300	2 décembre 1994
A 330-300	
A 330-300	
A 330-300	12 avril 1999
A 330-300	13 septembre 1999
A 330-300	20 novembre 2001

Joël ANDRE
Ingénieur en Chef de l'Armement
Chef de la Division Aéronefs

*Chapter 2 – Structures airworthiness requirements
and composite attributes*

Three major categories of requirements

- **STATIC STRENGTH**
 - Capability to resist an exceptional event (gust, manoeuvre, ground loads).
- **ENDURANCE**
 - To retain, in the long run, this capability.
- **OTHERS**
 - Emergency landing, ditching, rapid decompression, flutter, etc.
 - Accidental hazards : fire, lightning strikes, bird impact.

‘ Commandement ’

**INTRODUCING A NEW TECHNOLOGY
MUST NOT LEAD TO ANY REDUCTION
OF THE CURRENTLY EXISTING LEVEL
OF SAFETY**



**COMPOSITES MAY SHOW A QUITE
DIFFERENT BEHAVIOUR WHEN
COMPARED TO METALLIC
MATERIALS**



**THERE IS A NEED FOR DEDICATED INVESTIGATIONS AND
METHODS TO DEMONSTRATE THAT A COMPOSITE
STRUCTURE WILL SHOW A SAFETY LEVEL AT LEAST
EQUIVALENT TO A METALLIC ONE**



**ISSUE OF DEDICATED NEW
PARAGRAPHS (e.g. CS 23.573) OR
MODIFICATION OF EXISTING
ONES**

**PROPOSAL OF INTERPRETATIVE
MATERIALS**

Composite attributes, with respect to metallic, that needed to revisit certification methods

- **DEGRADATION CAPABILITY**
 - Modification of the intrinsic material properties under the effects of the environment (temperature and humidity) in which the aircraft will be operated (however, the phenomenon is assumed to be reversible).
- **LAMINATED CONSTRUCTION**
 - Low through-the-thickness mechanical properties which, associated with a low ductility, makes the material particularly sensitive to accidental impact damage.
 - In this situation, the structure suffers a sudden damaging.
- **LOW SENSITIVITY TO FATIGUE**
 - Small size manufacturing defects and damage (delaminations, translaminar cracks) rarely grow under realistic service loads.
 - Then, there are large possibilities to use the no-growth concept for structural substantiations.

Composite attributes, with respect to metallic, that needed to revisit certification methods (Cont'd)

- **THE MATERIAL DOES NOT EXIST BEFORE THE PART IS MADE**
 - Large dependency between eventual mechanical properties and processing route.
 - Possible introduction of built-in manufacturing defects (voids, porosities..) at the end of the process.
 - Emphasis on quality assurance, specifically in the processing route control.
- **LACK OF MATERIAL STANDARDIZATION**
 - No authoritative identification system allowing to recognise the equivalence between two or several materials, then, potential problems in situation of second sourcing.
- **NO ELECTRICAL CONDUCTIVITY**
 - Potential problems with lightning strike behaviour and electromagnetic aggressions in general.

Evolution of the authoritative documents addressing composite structure certification (in Transport Aircraft Category)

- **THE AC 20-107 DATED 7 OCTOBER 1978 (FAA document)**
 - Proposed means of compliance to address environmental effects.
 - Emphasised quality assurance needs.
 - Raised the issue of the composite behaviour with respect to lightning strikes and fire.
- **THE TECHNICAL NOTE STPA N° 81/04, REVISION N° 2**
 - Interpretation, by French Airworthiness Authorities, of the AC 20-107 deemed insufficiently precise in some respects. This note was part of the Airbus A310/300 carbon fin certification basis.
 - A difference between ‘DEFECTS’ and ‘DEGRADATION’ is established.
 - This note is at the origin of the requirements to demonstrate Ultimate Loads after fatigue.

Evolution of the authoritative documents addressing composite structure certification (in Transport Aircraft Category), cont'd 1

- **THE PROJECT OF AC 20-107 REVISION, 1983**
 - Put the AC in line with amendment 45 (Dec 78) : a damage tolerance demonstration is required, unless it is not practical.
 - Introduces the issue of accidental impact damage that may occur in fabrication or in service.
 - Proposes to use a no-growth concept for fatigue damage tolerance demonstrations.
- **THE AC 20-107A* dated 25 APRIL 1984**
 - A relationship between the inspection interval at which a damage can be detected and the residual strength associated with the assumed damage is needed.

The AC 20-107A is the first Advisory Circular prepared by a FAA - JAA joint group

Evolution of the authoritative documents addressing composite structure certification (in Transport Aircraft Category), cont'd 2

- **THE ACJ 25-603 dated 16 JUNE 1986**
 - JAA edition of the FAA (AC 20-107A) advisory circular, then authoritative document in Europe.
 - The paragraphs addressing ‘lightning strikes’ and ‘flammability’ are deleted since they belong to other panels in the JAA organisation.
 - There is a subtle difference in the area of static strength demonstration where, depending on the experience on similar structures, FAA may accept demonstrations only up to Limit Loads. In the JAA advisory circular, ‘limit loads’ has been replaced by an ‘agreed load level’.

Within the new EASA code (Certification Specifications), the ACJ 25.603 is now referenced under AMC N°1 to CS 25.603

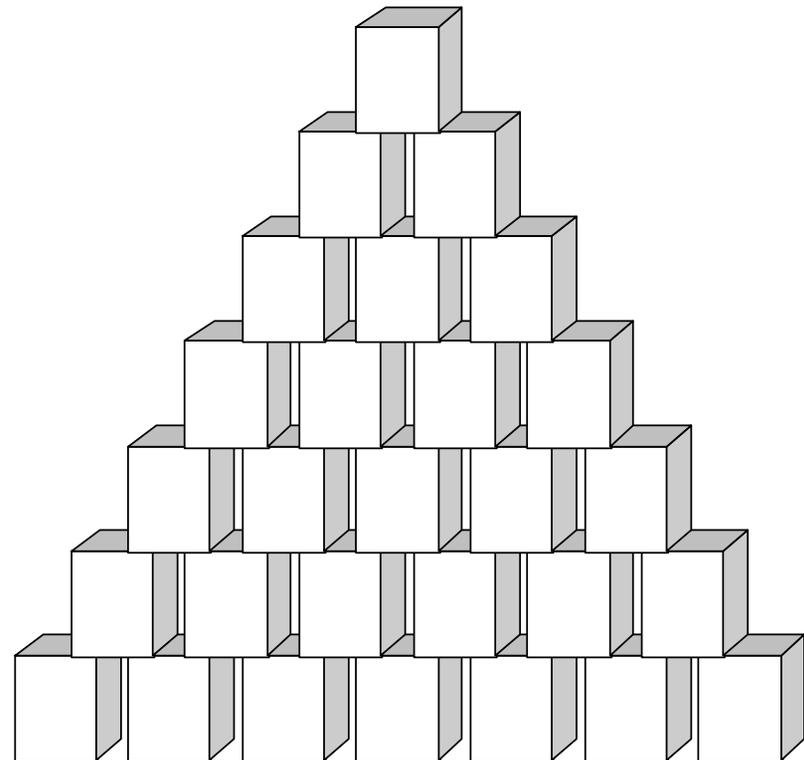
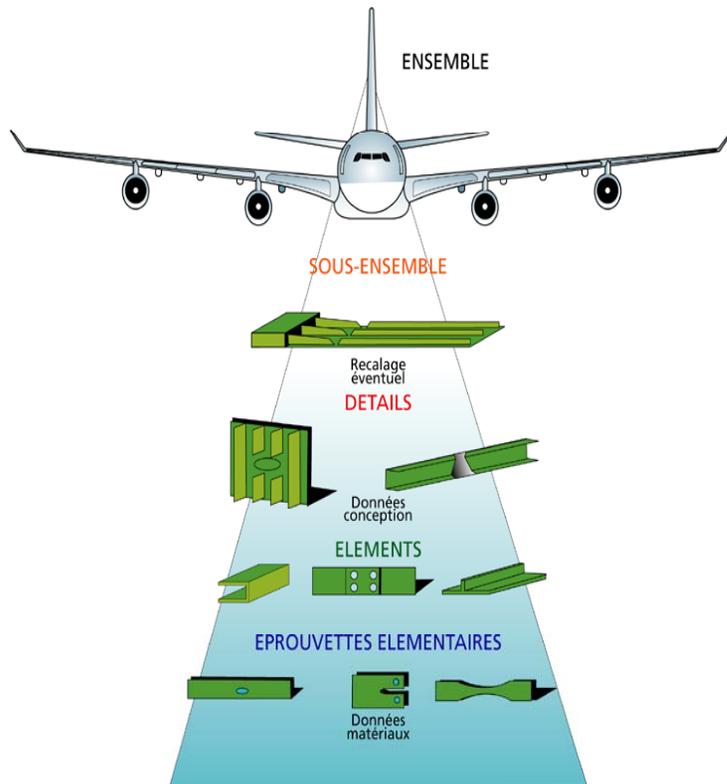
AMC N°1 to CS 25.603 (or AC 20-107 A) main paragraphs

- **MATERIAL AND FABRICATION DEVELOPMENT**
- **PROOF OF STRUCTURE - STATIC**
- **PROOF OF STRUCTURE - FATIGUE / DAMAGE TOLERANCE**
- **PROOF OF STRUCTURE - FLUTTER**
- **ADDITIONAL CONSIDERATIONS**
 - Impact Dynamics
 - Fire resistance
 - Lightning strike protection
 - Quality control
 - Production specification
 - Inspection and maintenance
 - Substantiation of repairs

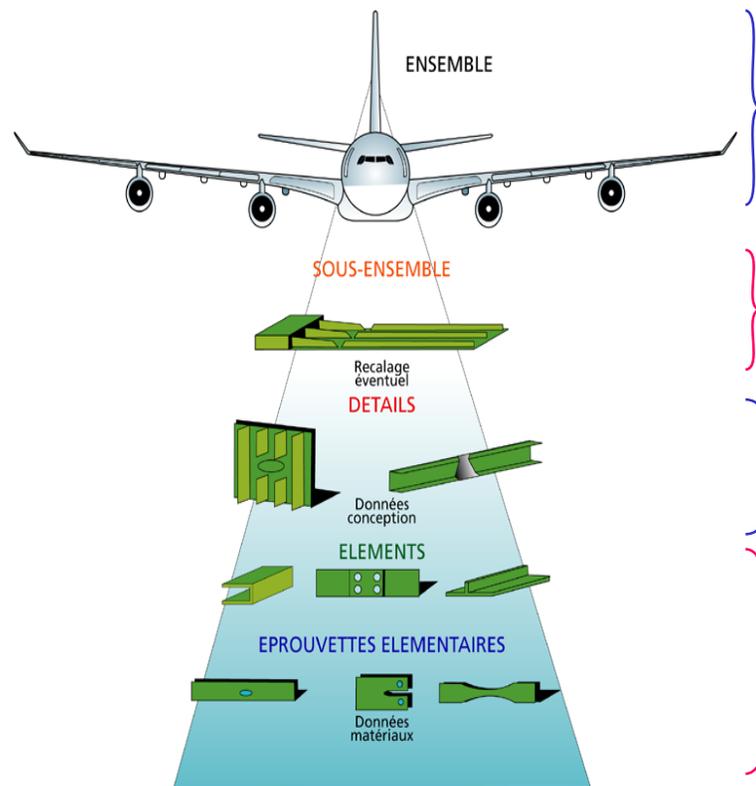
How means of compliance are coded

Compliance task	Means of compliance	Associated Compliance Documents
Engineering evaluation	<p>MC0 Compliance statement Reference to type design documents Election of methods Definitions</p> <p>MC1 : Design review MC2 : Calculation/analysis MC3 : Safety assessment</p>	<p>Type design documents Recorded statements</p> <p>Description, drawing Sustainiation reports Safety analysis</p>
Tests	<p>MC4 : Laboratory tests MC5 : Ground test on aircraft MC6 : Flight tests MC8 : Simulation</p>	<p>Test program Test report Tets interpretation</p>
Inspection	<p>MC7 : Inspection by authority specialist</p>	<p>Report of inspection visit</p>
Equipment qualification	<p>MC9 : Equipment qualification</p>	

The pyramid of tests or building block approach



The pyramid of tests, purpose of the various levels



- Final checking by integration of all the parameters
- Compliance with regulatory requirements

- Risk mitigation
- Sizing preliminary checking
- Assessment for future developments

- Generation of allowables for non generic design features, or details showing low accessibility to calculation

- Generation of allowables for materials or generic design features

The pyramid of tests, Why more tests with composite materials ?

- Low accessibility to calculation, then need to generate design values through complex test articles.
- Sensitivity to environment, then need to duplicate some tests in order to derive the ageing related knock down factors.
- Material anisotropy, then need to increase the test matrix at the coupon level to investigate various stacking sequences.
- Higher mechanical property variability than for metals, then need to increase the sample size in order to lower the knock down factors imposed in the derivation of the allowables (e.g. B values).

The situation with secondary structures

This issue is only addressed in the FAR 23 under the Advisory Circular AC 23-3 (5 September 1985), where it is said :

definition : Secondary structures are those which are not load carrying members, and their failure would not reduce the structural integrity of the airframe or prevent the airplane from continuing safe life and landing.

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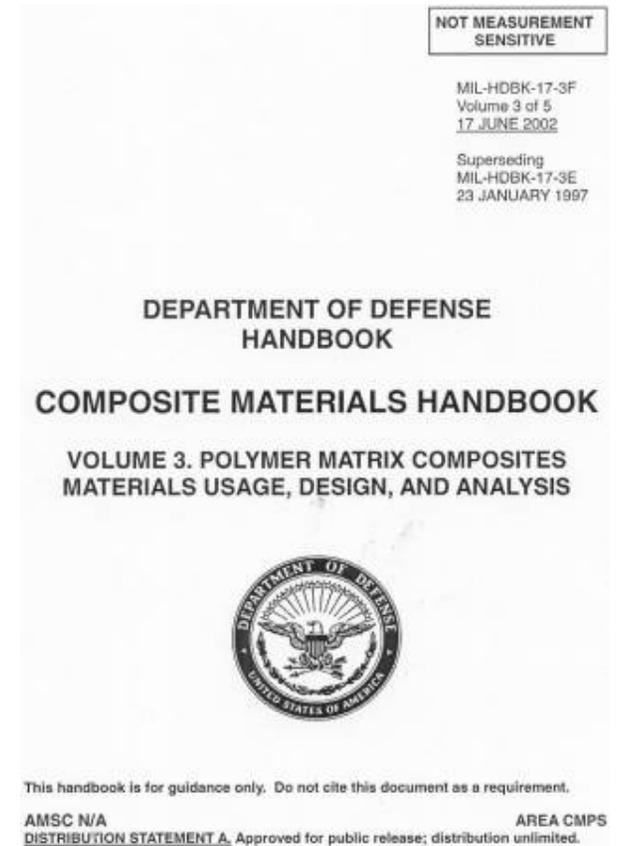
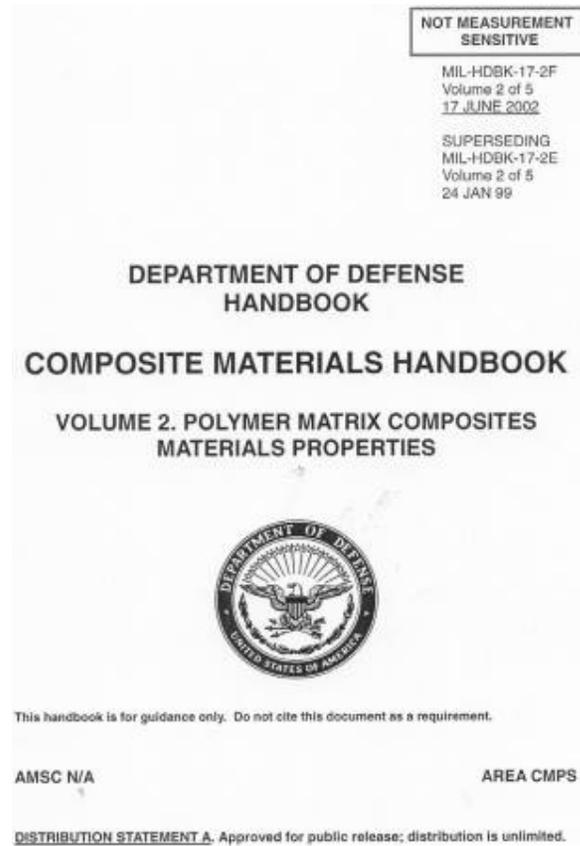
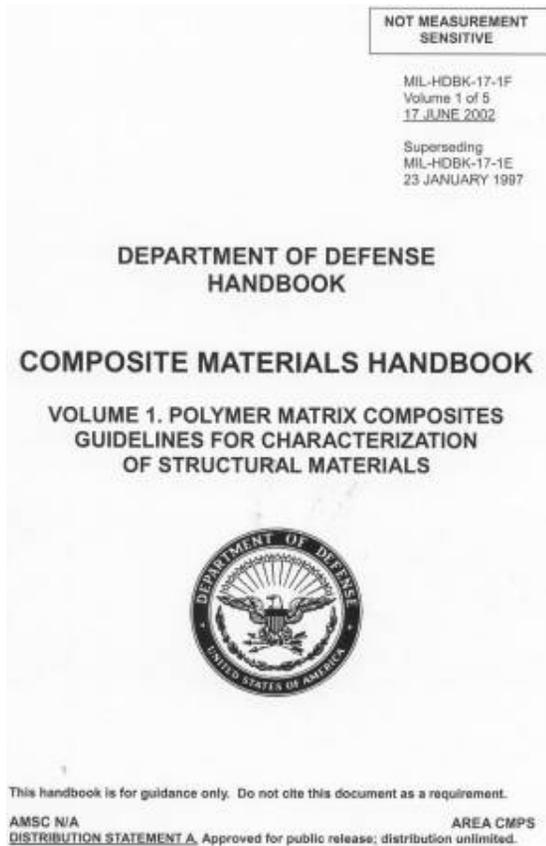
acceptable means of compliance :

- Structural analysis or static test, or a combination, may be used as the sole means of showing compliance with both limit and ultimate load conditions covering the critical points on the limit flight envelope, provided that the static loads have been obtained by flight test, or flight or wind tunnel test data derived from similar designs, or by conservative analysis. The methods of achieving the above may involve a certain amount of engineering judgment. Some pertinent considerations are as follows :

Roughly speaking and, as far as the FAR 23 is concerned, no means of compliance are associated with fatigue and damage tolerance requirements.

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The MIL HDBK 17



Latest available issue can be purchased on line at www.astm.org



Chapter 3 – Composite certification scheme

Topics to be addressed when presenting a certification plan to the Airworthiness Authorities

1 - STRUCTURE DESCRIPTION

1-1 Presentation of the design principles and their justifications.

1-2 Proposed materials with their associated qualification specifications.

2 - STRUCTURAL SUBSTANTIATIONS

2-1 Certification basis (Regulation Basis and its amendment + relevant Advisory Circulars).

2-2 Loads.

2-3 Environmental conditions with most adverse combinations load / environment :

- temperature (with possible local effects),
- humid ageing,
- service fluids,
- various aggressions (vibrations etc.).

2-4 Structure sizing.

- finite element code (validation),
- failure criteria (in static and fatigue/damage tolerance),
- generation of design values and allowables,
- other considerations (flutter, lightning strike, corrosion, bird impact, etc.),
- supporting test programme.

Topics to be addressed when presenting a certification plan to the
Airworthiness Authorities (Cont'd)

3 - FABRICATION METHODS

3-1 General principles.

3-2 Tooling.

3-3 Process monitoring.

4 - QUALITY ASSURANCE

4-1 In-coming material control.

4-2 Process control (with tolerance justifications).

4-3 Final acceptance.

4-4 Storage and handling.

5 - CONTINUED AIRWORTHINESS

5-1 Inspection programme and its substantiation.

5-2 Repair solutions and substantiation.

Documentation to be released

This documentation will include at least :

The Certification plan (with the associated test plans)

The Composite Summary Plan and Report*

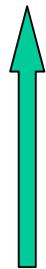
The Airframe Certification Documents

* The Composite Summary Report is the Composite Summary Plan updated with test results

Documentation to be released (Cont'd)

The Certification plan (also called 'Grand Livre') :
 'Means of Compliance' table

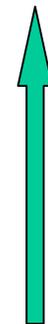
CS 25 Chapter	Paragraph involved	F/C ATA	Proof of Compliance	ATA	MoC Code	Reference of the documents
25.305b	Strength and deformation Ultimate Loads requirements	51	Analysis and test	55	2, 4	ACD 4 ref xxx and ACD 8 ref xxx



All paragraphs of the regulatory requirements and special conditions to be successively addressed



Final ATA Chapter



Contributing ATA Chapter



MoC 2 : Calculation, Analysis
 MoC 4 : Laboratory Tests

Documentation to be released (Cont'd 1)

**The Composite Summary Plan :
Content Overview**

1 - Introduction

2 - Applicable regulations

3 - General description of the structure

4 - Materials and processes

5 - Manufacturing processes

6 - Applied design requirements

6.1 - Structural requirements

6.2 - Environmental conditions

6.3 - Loading conditions

7 - Design values

8 - Proof of structure

8.1 - Compliance philosophy

8.2 - Static proof of structure

8.3 - fatigue and damage
tolerance proof of structure

9 - test plan

10 - Additional Considerations

10.1 - Lightning

10.2 - Corrosion prevention

10.3 - Quality control

10.4 - Substantiation of repairs

Documentation to be released (Cont'd 2)

ACD - AIRFRAME CERTIFICATION DOCUMENTS

The Airframe Certification Documents (ACD's) provide the compliance demonstration for the metallic and composite structures with the applicable requirements through the following chapters :

- Methods for compliance demonstration (ACD volume 3)
- Description of the structure, including the corrosion protection, the material specifications and design allowables and fabrication methods (ACD volume 2)
- Static justification summary (ACD volume 4)
- Fatigue and damage tolerance justification summary (ACD volume 6)
- Comparison Calculations tests (ACD volume 8)
- Impact resistance evaluation summary (ACD volume 12)
- Rotor burst structural design assessment summary (ACD volume 13)

Chapter 4 – Design requirements

*Regulatory requirements addressing design principles
(ref. JAR 25 Subpart D)*

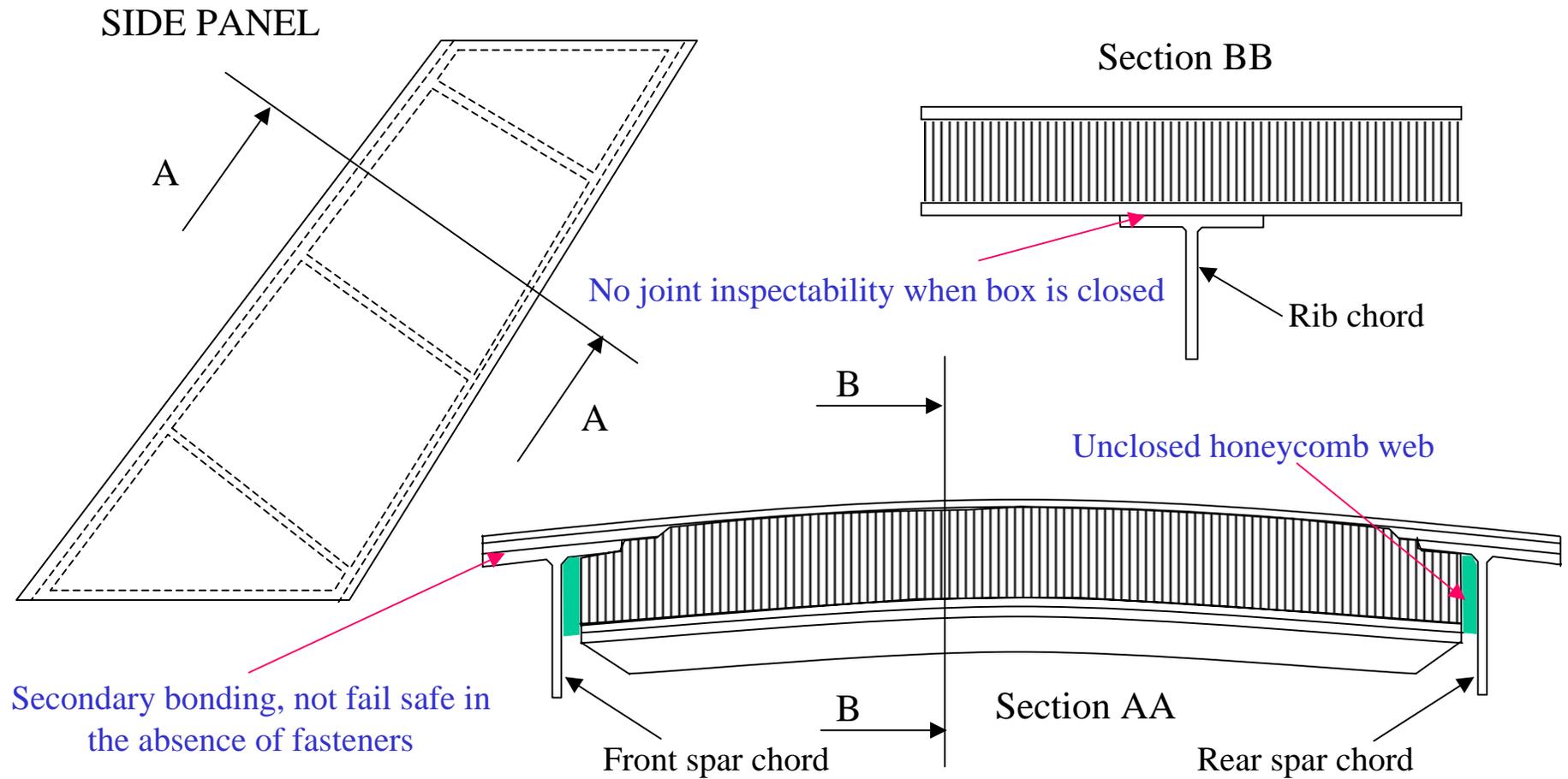
CS 25 601 Design

The aeroplane may not have design features or details that experience has shown to be hazardous or unreliable. The suitability of each questionable design detail must be established by tests.

Some good principles to be followed

- **Avoid fully bonded construction, difficult to certify with respect to damage tolerance requirements. A Limit Load demonstration will be always required assuming a total disbonding between two mechanical junctions or fasteners.**
- **Guarantee full accessibility to NDT for all bonded junctions.**
- **Prevent possible galvanic corrosion risks in metal / composite joints.**
- **Allow for manufacturing process requirements, provide easy achievement of the pressure evenness everywhere on the laminate surface and the bonding lines.**
- **Be careful with thin-walled sandwich construction, that may be water permeable in the long run.**
- **Do not introduce innovative concepts, directly in an application for a certification, without preliminary exploratory development.**

Example of design where troubles may arise



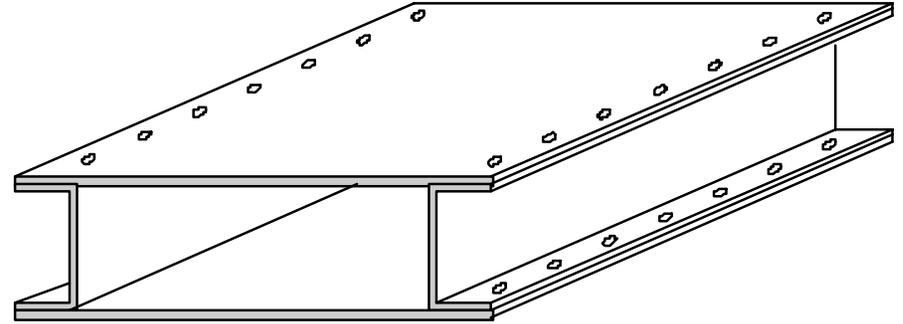
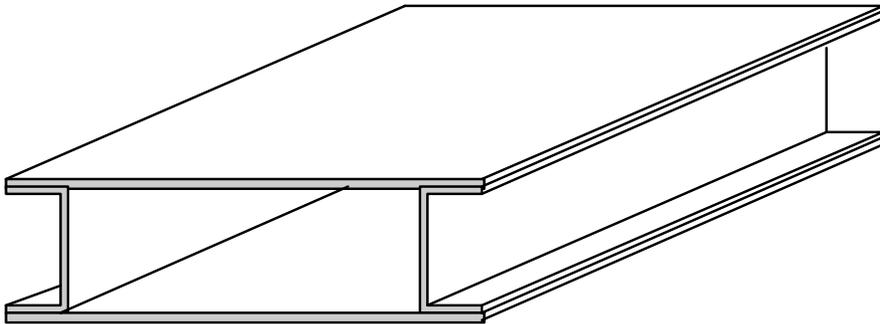
Bonded or bolted design ?

Structural bonding issues :

Joint actual performance cannot be assessed by non destructive inspection
(a clear disbonding only is detectable).

However, strict quality assurance procedures, together with manufacturing process coupon travellers
may guarantee a satisfactory initial quality level.

Nevertheless, in-service degradation remains **neither predictable nor detectable.**

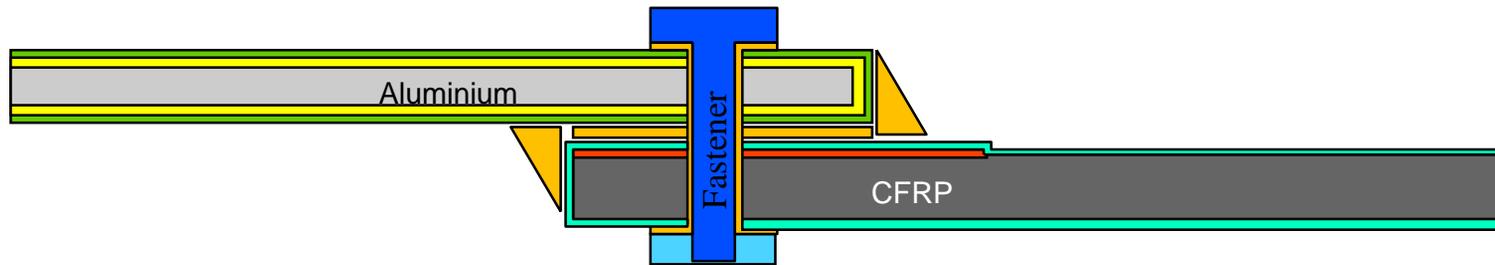


Primary structures with single load path :

If co-curing, same material ' one shot ', tolerated but not recommended.

If bonding, including secondary bonding, fasteners required to guarantee a limit load capability if a disbonded occurs within two adjacent rows of fasteners.

Precautions against galvanic corrosion



-  Anti-corrosion surface treatment
-  Primer on aluminium alloy
-  Primer on composite
-  Glass fiber woven fabric (single ply)
-  Filler

Water ingress susceptibility issue for sandwich construction

Precautions at the design level :

- As far as possible, avoid one shot processes (co-curing), and prefer a two-phase process with pre-cured skins.
- Improve tightness of the pre-cured skin by co-curing an adhesive film on the surface.
- Prefer UD tapes against woven fabric at least for the skin not located on the hard tool.
- Use, as far as necessary, water ingress barrier, Tedlar ou Idplon 1000 film (The latter can be located between the skin and the honeycomb).
- Perform, to qualify the process, tightness tests by simple immersion in hot water.

Chapter 5 – Environmental effects

Regulatory requirements and acceptable means of compliance

CS 25-603 MATERIALS

The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must :

- (a) ...
- (b) ...
- (c) Take into account the effects of environmental conditions, such as temperature and humidity expected in service.

AMC N°1 to § 25-603, § 4 MATERIAL AND FABRICATION DEVELOPMENT

To provide an adequate design data base, environmental effects on the design properties of the material system should be established.

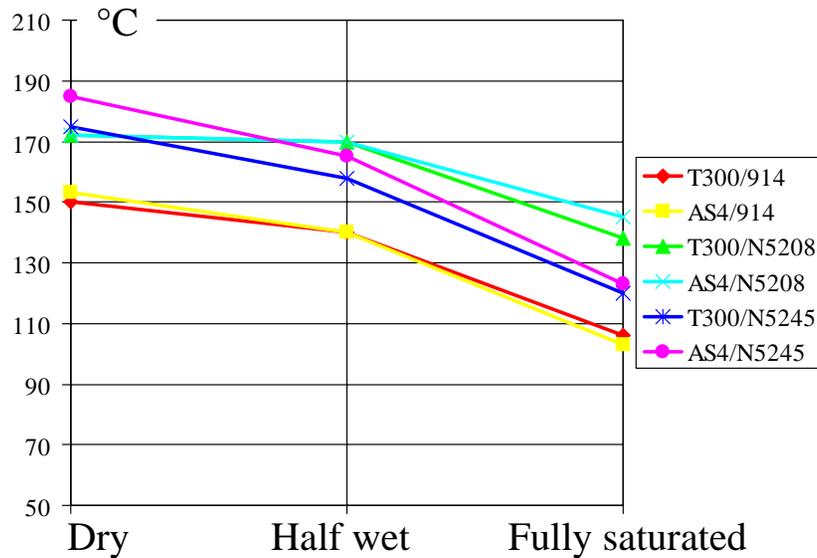
a - Environmental design criteria should be developed that identify the most critical environmental exposures, including humidity and temperature, to which the material in the application under evaluation may be exposed. This is not required where existing data demonstrate that no significant environmental effects, including the effects of temperature and moisture, exist for the material system and construction details, within the bounds of environmental exposure being considered. Experimental evidence should be provided to demonstrate that the material design values or allowables are attained with a high degree of confidence in the appropriate critical environmental exposures to be expected in service. The effect of the service environment on static strength, fatigue and stiffness properties should be determined for the material system through tests; e.g., accelerated environmental tests, or from applicable service data. The effects of environmental cycling (i.e., moisture and temperature) should be evaluated. Existing data may be used where it can be shown directly applicable to the material system.

Environmental effects on composite construction

- **ON THE SOLID LAMINATE ITSELF :**
 - Moisture pick-up, with reduction of the matrix governed strength properties (compression, bearing, interlaminar strength). This strength reduction is enhanced by elevated temperatures.
 - Reduction of the matrix glass transition temperature.
 - Very little effect on stiffness properties.
- **ON SANDWICH (BONDED) CONSTRUCTION :**
 - Moisture ingress in the bond-line (adhesive), with shear and peeling strength reduction that may lead to large disbondings.
 - Moisture ingress in the honeycomb core with subsequent effects of steam pressure or water volume expansion due to icing.
- **ON INTEGRATED METAL PARTS (e.g. FASTENERS) :**
 - Galvanic corrosion, mainly with aluminium in contact with carbon-epoxy, very critical in salt atmosphere.

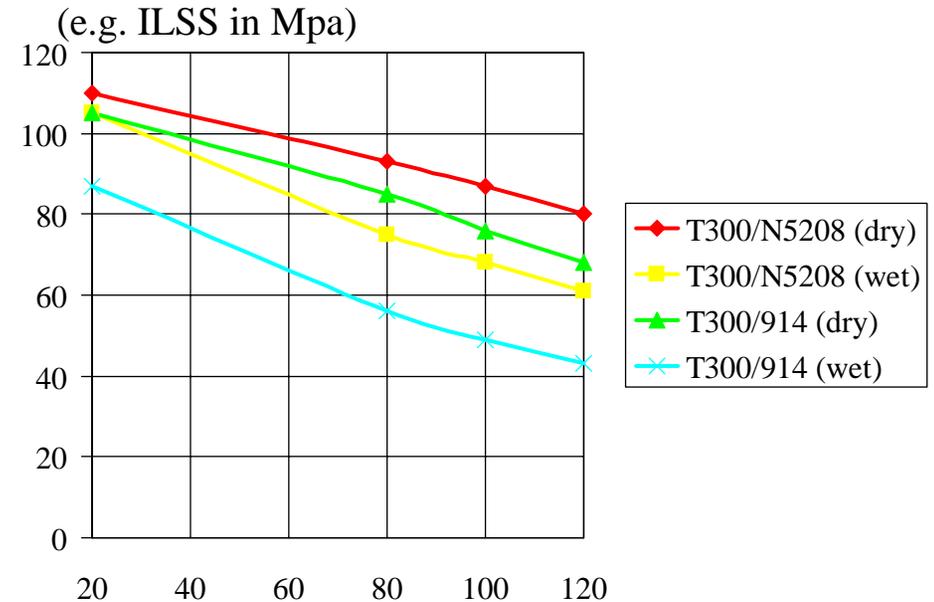
Examples of moisture and temperature effects on thermoset laminates

Glass transition temperature decreases



Composite moisture content

Matrix governed properties decrease



Test temperature (°C)

Examples of moisture and temperature effects on thermoset laminates (Cont'd)

- Humidity effect on a laminate is assumed to be reversible (and asymptotic)
- Combining most adverse conditions in terms of humidity and temperature may lead to laminate property static strength reductions in the range of :
 - -5% to -15% for a subsonic aircraft (assumed maximum temperature : 75 to 80°C)
 - -15 to -25% for a supersonic aircraft (assumed maximum temperature > 100°C)
- Only matrix governed properties are under concern (compression, shear, bearing).

For a 180°C curing system

Recent generation material data

	Equilibrium at 70°C, 85% RH	T _g	
		Dry	Wet
977/2 - HTA	0.85%	165°C	150°C
977/2 - HTS	0.85%	173°C	147°C
6376 - HTA	0.95%	190°C	160°C

Modelling composite laminate water ingress

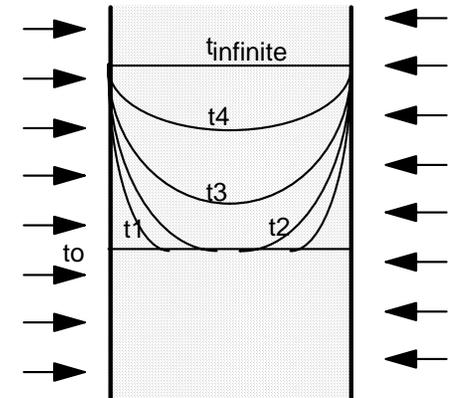
It is a satisfactory assumption to assume that water diffusion in the composite complies with the same laws as heat conduction (Fick's second law)

c = material moisture concentration, expressed in terms of mass per volume unit

x = measurement on the axis perpendicular to the laminate

t = time

D = mass diffusivity expressed in surface unit per time unit

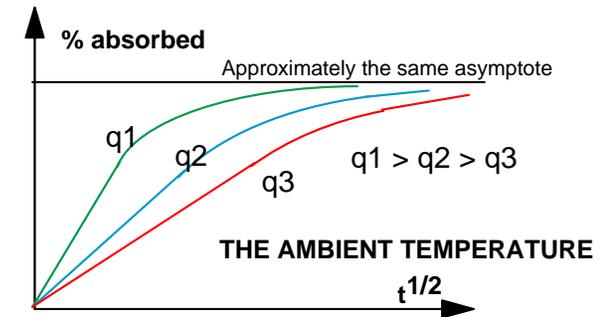
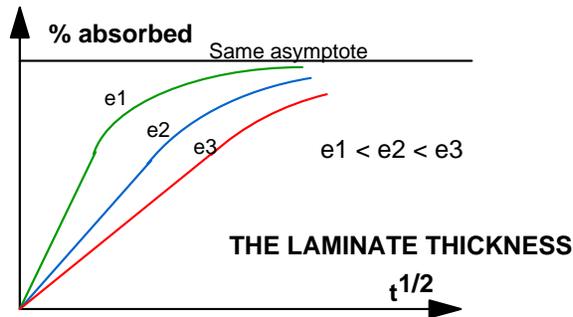
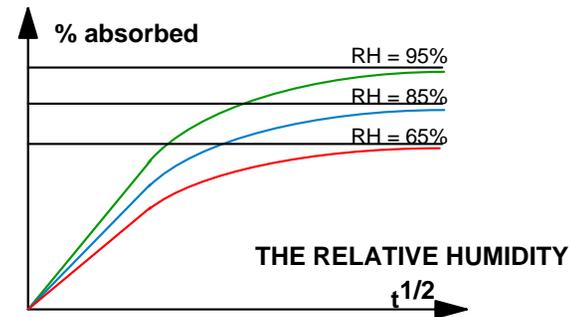
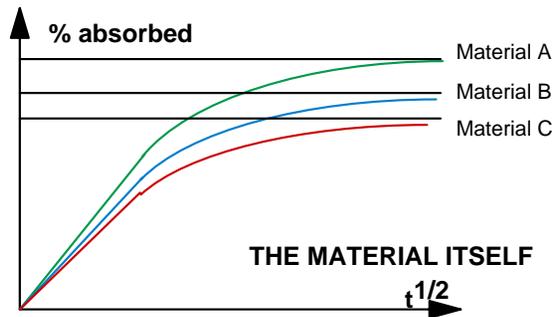


$$\frac{\delta c}{\delta t} = D \frac{\delta^2 c}{\delta x^2}$$

$$D = D_0 \cdot e^{-\frac{E}{RT}}$$

← Activation energy
 ← Temperature (°K)
 ← Gaz constant = 8.314)

The humidity absorbed by a composite complying with a 'Fickian' behaviour, depends on :

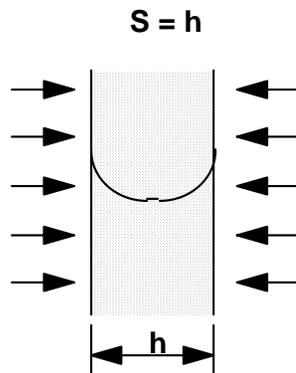


In steady conditions, the equilibrium moisture content depends mainly on the material itself and the relative humidity. This content is slightly dependent on the temperature.

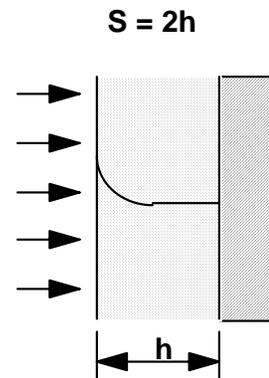
Calculation of the time needed to reach a given amount of moisture content

$$t = \frac{S^2}{D} \left[\frac{-1}{7.3} \text{Log} \left(1 - \frac{M - M_i}{M_m - M_i} \right) \right] \frac{1}{0.75}$$

Material exposed on two faces



Material exposed on one face



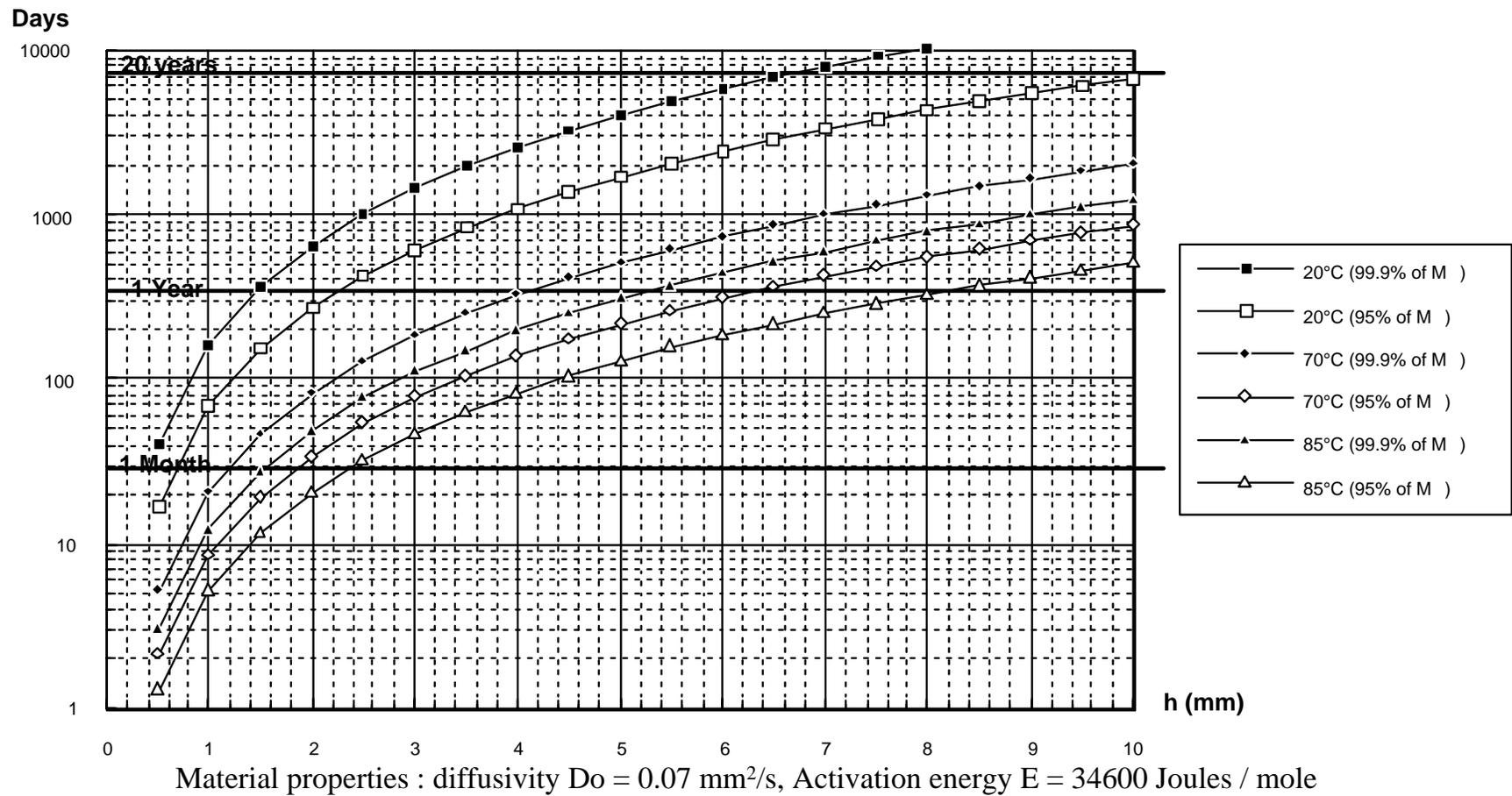
$$D = D_0 \cdot e^{-\frac{E}{RT}}$$

M_i = material initial moisture content

M_m = material equilibrium moisture content

M = material moisture content target

Example : Calculation of the time needed to reach either 95% or 99.9% of the equilibrium level – Material T300/914



Estimation of the maximum temperature to be accounted for

- **FOR SUBSONIC AIRCRAFT, EXCEPT LOCAL EFFECTS (e.g. turbine exhaust), THE MAXIMUM EXPECTED TEMPERATURE IS REACHED ON GROUND CONDITIONS AND DEPEND ON :**

- The solar radiation
- The sun position
- The solar reflection provided by what surrounds the structure
- Paint colour properties (absorptivity and emissivity)
- The ambient temperature
- The cooling effects during taxiing, taking off and climbing.



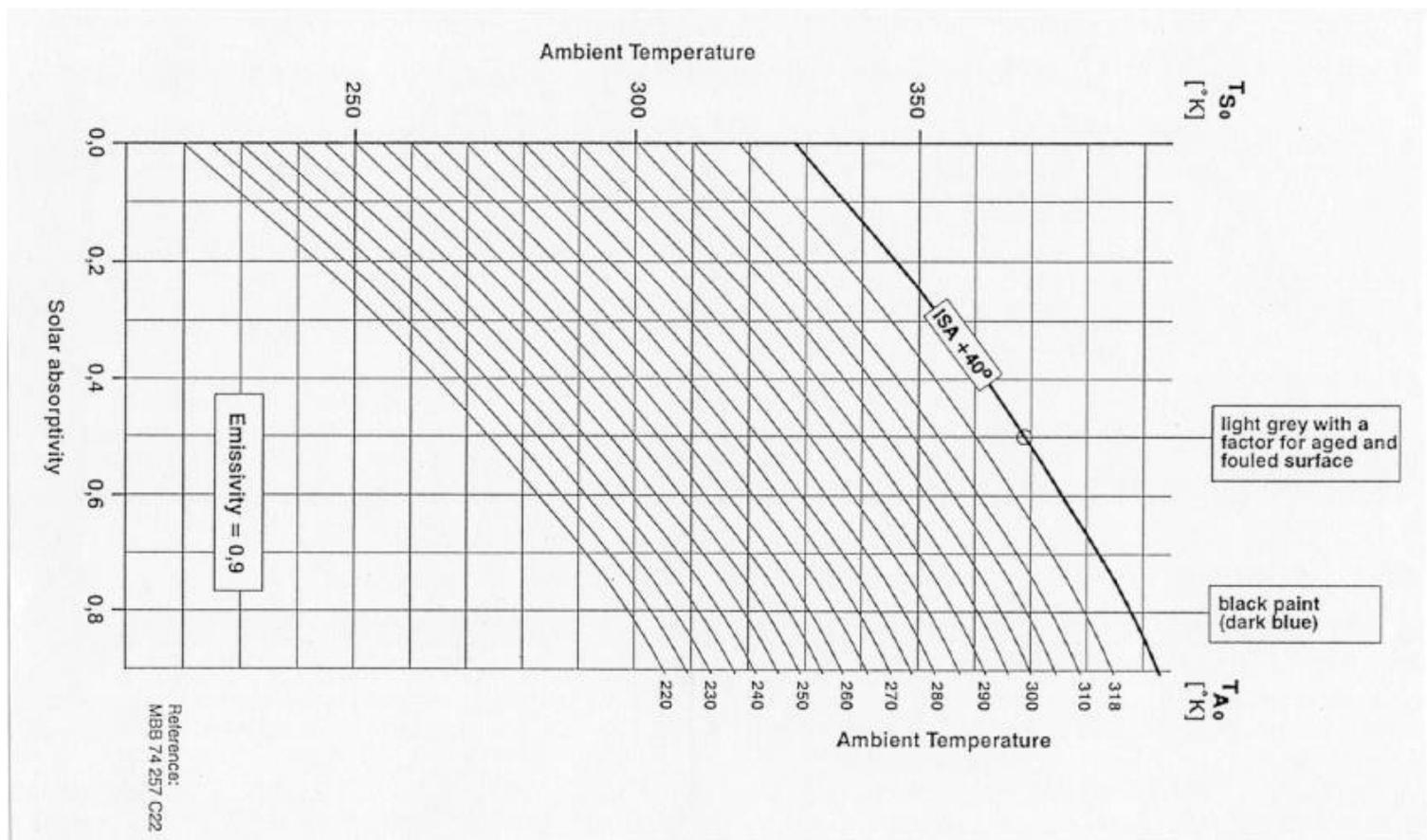
- **MAXIMUM ASSUMED VALUES**

- Airbus programmes : $ISA + 40^{\circ}C \rightarrow 55^{\circ}C$ ($131^{\circ}F$)
- FAA recommendation : $51^{\circ}C$ ($124^{\circ}F$)

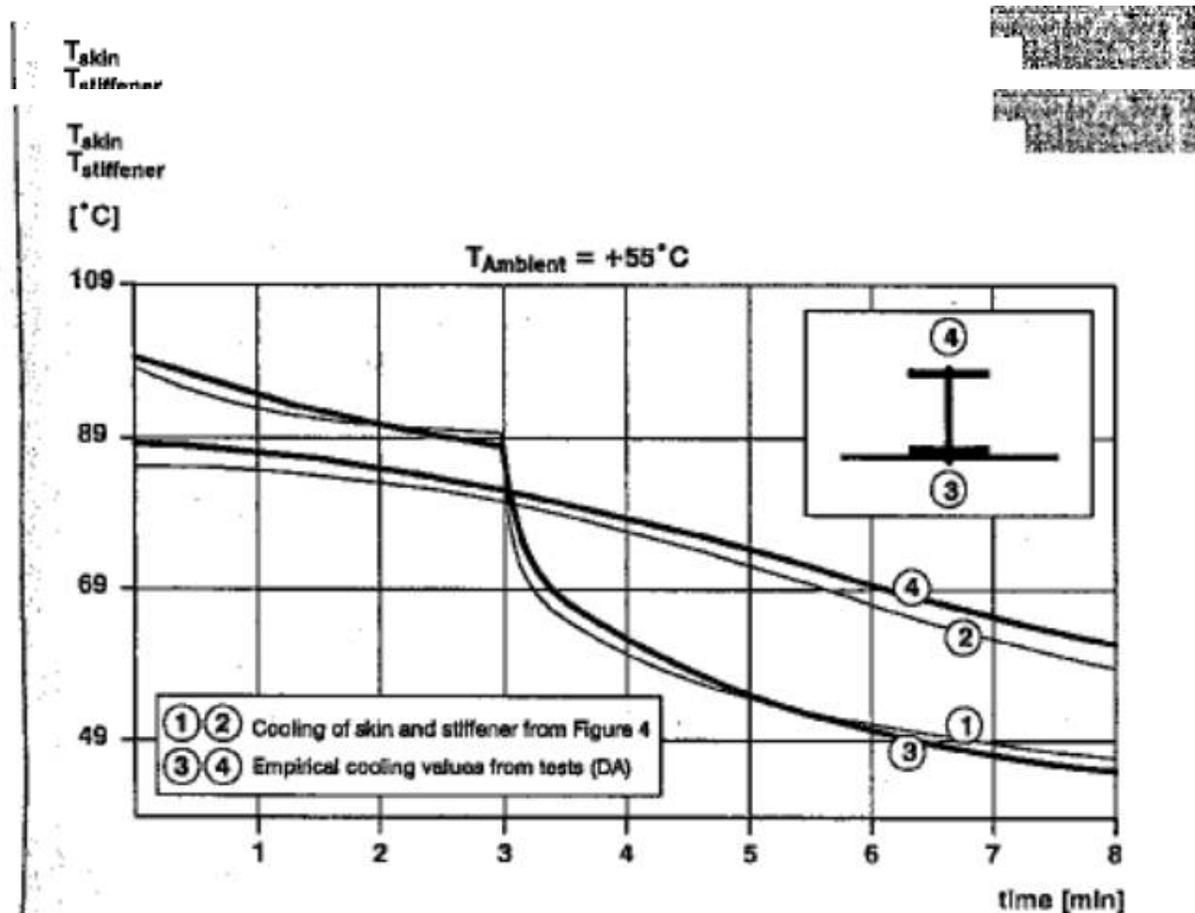


Rationale : this temperature will not be exceeded 99.9% of the time at hot dry climates (e.g. Desert Valley, Sahara)

An example of the calculation of the maximum temperature reached by an horizontal surface, in still air, sun at 90°C (Airbus source)



An example of the cooling effects (calculated) during taking off and climbing (Airbus source)



Recommended procedure for introducing the maximum expected moisture content in a test article

1 - Establish, for the selected composite material :

- Its equilibrium moisture content in a RH = 85% steady environmental condition. This content will be referenced as the 'Material Target Moisture Content' (MTMC). This content must be calculated with respect to a fully dry situation, that means established from pre-dried coupons. Knowing that this moisture content is more or less affected by the conditioning temperature, select a conventional conditioning temperature of 70°C (usual value in European certifications).

- the maximum laminate thickness expected to reach the equilibrium level within the aircraft lifetime (value dependent on the diffusivity and the average ambient temperature). A 8 mm thickness, exposed on both faces, has been accepted for AIRBUS certifications.

2 - Manufacture, in the same shot as the test article, coupons (travellers) representative of the same composite material and stacking sequence as this test article. Typical traveller size : 100 x 100 mm, two travellers per composite material and representative thickness.

Recommended procedure for introducing the maximum expected moisture content in a test article (Cont'd)

- 3 - When starting the accelerated ageing, introduce half of the travellers (one on two identical ones) in the same conditioning chamber and start immediately to dry the remaining half part in order to establish the initial moisture content at the beginning of the conditioning.

- 4 - Monitor, through successive weightings, the traveller moisture pick-up and stop conditioning when the MTMC is reached by the maximum thickness traveller (but no more than the thickness expected to reach equilibrium before the end of lifetime). This value must be calculated in '3'.

Recommended procedure for introducing the maximum expected moisture content – How to reduce the conditioning time ?

- **1 – TO INCREASE THE RELATIVE HUMIDITY (from 85 to 95% RH or more) :**
 - Quite usual. It is then recommended to end the conditioning by a steady phase at RH 85% in order to homogenize the through-the-thickness moisture content.
- **2 – TO INCREASE THE CONDITIONING TEMPERATURE :**
 - Recommended maximum values :
 - In Europe : 70°C
 - In the USA (ref. MIL HDBK 17) : 82°C.

CAUTION : A too elevated temperature may modify the chemistry of the material which will be no longer representative of the component in service, and/or introduce post-curing effects, hidden by the mechanical properties degradation.

Extract from MIL HDBK 17 § 6.3.3.1 : Since the moisture diffusion rate is too strongly dependent on temperature, there is a temptation to accelerate the process by increasing the conditioning temperature. However, long exposures to high temperatures combined with moisture may alter the chemistry of the material. 350°F (177°C) cure epoxy-based materials are typically not conditioned above 180°F (82°C) in order to avoid this problem; materials that cure at lower temperatures may need to be conditioned below 180°F (82°C).

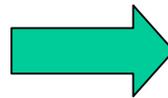
Chapter 6 – Materials qualification

Regulatory requirements (ref. CS 25 Subpart D)

CS 25 603 Materials

The suitability and durability of materials used for part, the failure of which could adversely affect safety, must :

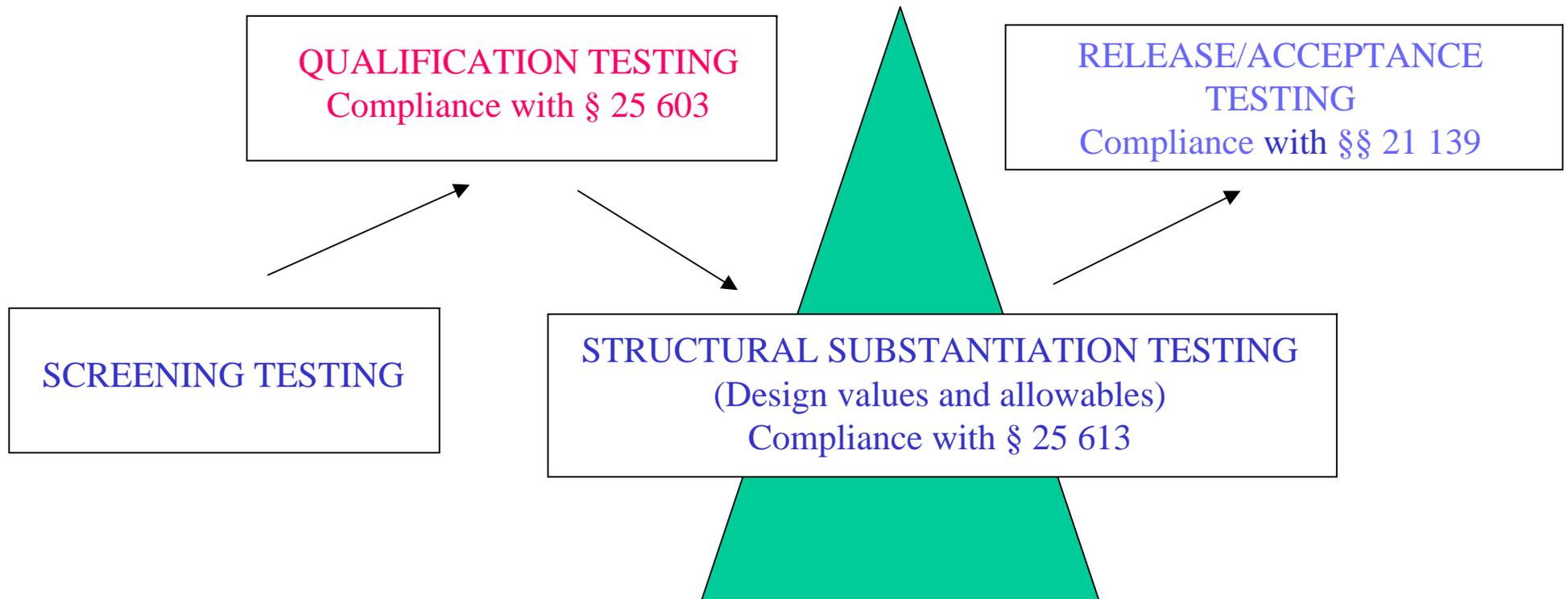
- (a) Be established on the basis of experience or tests;
- (b) Conform to specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and
- (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.



MATERIALS SELECTED FOR A GIVEN APPLICATION, CANDIDATE TO A CERTIFICATION, SHOULD BE QUALIFIED ACCORDING TO A SPECIFICATION

THE APPLICANT SHOULD HAVE DEVELOPED AN IN-HOUSE MATERIAL QUALIFICATION SYSTEM WITH ITS ASSOCIATED SPECIFICATIONS

The place of qualification testing among the various test schemes carried out on a material



Screening Testing

PURPOSE : TO DEMONSTRATE THE SUITABILITY OF A MATERIAL FOR ITS QUALIFICATION :

- IN GENERAL, SUCH A TEST PROGRAMME ADDRESSES NEW PROMISING MATERIAL SYSTEMS - OR SO FAR UNKNOWN BY THE AIRCRAFT MANUFACTURER - AND SEEKING ELIGIBILITY FOR A GIVEN APPLICATION.
- THIS INITIAL EVALUATION FOCUSES ON STRUCTURAL PERFORMANCES ALONE, GOING DIRECTLY TO THE MEASUREMENT OF CRITICAL ENGINEERING PROPERTIES e.g. DAMAGE TOLERANCE, NOTCH SENSITIVITY IN TENSION, COMPRESSION BEARING, WORST ENVIRONMENT CONDITIONS EFFECTS etc.
- ONLY ONE MATERIAL BATCH CAN BE USED FOR SUCH EVALUATION.

Material qualification testing

PURPOSE : TO PROVE THE ABILITY OF A GIVEN MATERIAL TO MEET THE REQUIREMENTS OF A SPECIFICATION

THIS SPECIFICATION SHOULD ENSURE THAT :

- THE MATERIAL PRESENTATION AND PHYSICAL PROPERTIES COMPLY WITH MANUFACTURER'S PROJECTS AND WORKSHOP CAPABILITIES.
- THE MATERIAL OWNS SUFFICIENT MECHANICAL PROPERTIES WITH RESPECT TO THE APPLICATIONS WHICH ARE ENVISIONED.
- THE MATERIAL DOES NOT CONTAIN ANY HAZARDOUS CONSTITUENT, DOES NOT SHOW ANY SENSITIVITY TO SERVICE FLUIDS OR UNEXPECTED ROGUE BEHAVIOURS.
- MATERIAL PRODUCTION PROCESS KEY PARAMETERS ARE IDENTIFIED AND TOLERANCED, A SUPPLIER'S QUALITY ASSURANCE SYSTEM HAS BEEN DEVELOPED TO ENSURE MATERIAL CONSISTENCY, WHICH HAS BEEN SHOWN THROUGH THE EVALUATION OF SEVERAL DIFFERENT BATCHES.

THE SPECIFICATION SHOULD PROVIDE MINIMUM PERFORMANCES ALONG WITH THE ASSOCIATED TEST METHODS

The limits of material qualification testing

- QUALIFYING A MATERIAL IS THE MANUFACTURER'S OWN LIABILITY AND CAN ONLY BIND HIM.
- WHILE A MATERIAL MAY BE QUALIFIED TO A GIVEN SPECIFICATION, IT STILL MUST BE APPROVED FOR USE IN EACH SPECIFIC APPLICATION. IN OTHER WORDS, QUALIFICATION IS A PEREQUISITE BUT NOT A SUFFICIENT CONDITION TO APPROVE A MATERIAL IN VIEW OF ANY APPLICATION.
- TO GENERATE DESIGN VALUES OR ALLOWABLES SHOULD BE OUT OF THE PURPOSE OF A QUALIFICATION PROGRAMME, ALTHOUGH MEASURED PROPERTIES ARE DIRECTLY ASSOCIATED TO THESE DATA.
- QUALIFICATION DATA SHOULD ALLOW ESTABLISHING THE INDIVIDUAL PRODUCT PROCUREMENT SPECIFICATION THAT WILL ENSURE THAT, EVERY BATCH SUPPLIED TO PRODUCE A TYPE CERTIFIED COMPONENT WILL BE, IN ALL RESPECTS, EQUIVALENT TO THE QUALIFIED MATERIAL REFERENCE.

An example of a qualification specification

The AIMS 5.0100 for a UD carbon with a 180°C curing resin system (issue 3, January 2000) – Main tests

- Prepreg physical properties (areal weight, resin content, volatile content, tack etc.)
- Laminate physical properties (coefficient of thermal expansion, moisture uptake and Tg)
- Mechanical properties :
 - UD laminate testing : basic matrix properties (tension and compression longitudinal and transverse, in-plane shear) + G1c, G2c and ILSS.
 - Cross ply laminate testing (with three stacking sequences) :
 - Open hole tension and compression, filled hole tension and compression,
 - Compression after impact,
 - Bearing strength.
- Exposure in aggressive fluids (Skydrol, fuel and MEK) and resistance to paint strippers.

Batch number : from 1 to 5 depending on the measured property.

Sample size : 6 specimens, excepted CAI, G1c and G2c.

Total number of specimens dedicated to mechanical tests : more than 1200 for qualification testing (around 200 in screening tests).

Structural substantiation testing

PURPOSE : TO GENERATE ALLOWABLES AND DESIGN VALUES

- ALLOWABLE AND DESIGN VALUES ARE NEEDED FOR ESTABLISHING STRUCTURAL SUBSTANTIATIONS REQUIRED BY CERTIFICATION. THEY ARE EXPRESSED IN TERMS OF STRESSES, STRAINS, LOADS, LIFETIMES, ... AND USED TO CALCULATE THE MARGINS IN EVERY STRUCTURAL SIGNIFICANT POINT OF THE STRUCTURE.
- THESE VALUES ARE GENERATED FROM TEST DATA AND MUST PROVIDE A HIGH DEGREE OF CONFIDENCE (TYPICALLY 'A' OR 'B' VALUES) . THEY MUST NECESSARILY REFLECT :
 - - MATERIAL VARIABILITY
 - - MATERIAL RESPONSE TO THE ANTICIPATED MANUFACTURING PROCESS.
- ALLOWABLES OR DESIGN VALUES CAN BE GENERATED AT VARIOUS STRUCTURAL COMPLEXITY LEVELS OF THE PYRAMID OF TESTS, DEPENDING ON THE UNCERTAINTY OF THE CALCULATION MODEL.

Material release / acceptance testing

PURPOSE : TO VERIFY THAT A LOT OF MATERIAL IS CONSISTENT WITH THE QUALIFIED REFERENCE

- THE PERFECT CONTROL, AT THE SUPPLIER'S, OF ALL PROCESS GOVERNING PARAMETERS IS A PEREQUISITE FOR OBTAINING CONSISTENCY WITH THE QUALIFIED REFERENCE AND CANNOT BE REPLACED BY RELEASE / ACCEPTANCE TESTING.
- WHILE A QUALIFICATION SPECIFICATION ENCOMPASSES SEVERAL MATERIAL REFERENCES, A PROCUREMENT SPECIFICATION SHOULD ADDRESS ONLY ONE REFERENCE AND REQUIRE PERFORMANCES REFLECTING THE USUAL ONES OF THIS REFERENCE.
- IN OTHER WORDS, WHILE A QUALIFICATION SPECIFICATION REQUIRES MINIMUM PERFORMANCES, A PROCUREMENT SPECIFICATION SHOUD DEFINE AN INTERVAL IN WHICH THESE PRERFORMANCES ARE EXPECTED TO FALL. NO DOUBT, THE RIGHT WAY TO DEMONSTRATE THIS CONSISTENCY IS THROUGH STATISTICAL COMPARISON.

The material change (second sourcing) issue

THE CURRENT SITUATION WITH COMPOSITE MATERIALS

- THERE IS NO STANDARDIZATION SYSTEM, WITH WHICH VARIOUS PRODUCTS COMING FROM DIFFERENT SUPPLIERS COULD COMPLY. EACH COMPOSITE MATERIAL IS THEN IDENTIFIED UNDER ITS OWN TRADEMARK.

ASSOCIATED CONSEQUENCES

- THERE IS NO EXPLICIT EQUIVALENCE BETWEEN TWO MATERIALS HAVING DIFFERENT TRADEMARKS.
- ANY MATERIAL APPROVED FOR A CERTIFICATED STRUCTURAL APPLICATION WILL HAVE A UNIQUE REFERENCE CALLING FOR ONE PRODUCT ONLY (FIBRE, RESIN AND ASSOCIATED PROCESS) AND COMING FROM ONE SUPPLIER. ANY MODIFICATION OF ONE OF THESE PARAMETERS LEADS TO A MATERIAL CHANGE, WHICH NEEDS A NEW APPROVAL PROCEDURE.

Chapter 7 – Allowables and design values

Regulatory requirements (ref. CS 25 Subpart D)

CS 25 613 Material strength properties and design values

(a) Material strength properties must be based on enough tests of material meeting approved specifications to establish design values on a statistical basis.

(b) Design values must be chosen to minimize the probability of structural failures due to material variability. Except as provided in paragraph (e) of this section, compliance with this paragraph must be shown by selecting design values which assure material strength with the following probability :

(1) Where applied loads are eventually distributed through a single member within an assembly, the failure of which would result in loss of structural integrity of the component, 99 percent probability with 95 percent confidence.

← CALLED 'A' VALUES

(2) For redundant structures, in which the failure of individual elements would result in applied loads being safely distributed to other carrying members, 90 percent probability with 95 percent confidence.

← CALLED 'B' VALUES

(c) The effects of temperature on allowable stresses used for design in an essential component or structure must be considered where thermal effects are significant under normal operating conditions.

(d) The strength, detail design, and fabrication of the structure must minimize the probability of disastrous fatigue failure, particularly at points of stress concentration.

(e) Greater design values may be used if a "premium selection" of the material is made in which a specimen of each individual item is tested before use to determine that the actual strength properties of the particular item will equal or exceed those used in design.

Complement provided by AMC N°1 to 25.603

4 - Material and fabrication development.

4.1 - To provide an adequate design data base, environmental effects on the design properties of the material system should be established.

4.2 - Environmental design criteria should be developed that identify the most critical environmental exposures, including humidity and temperature, to which the material in the application under evaluation may be exposed. This is not required where existing data demonstrate that no significant environmental effects, including the effects of temperature and moisture, exist for the material system and construction details, within the bounds of environmental exposure being considered. Experimental evidence should be provided to demonstrate that the material design values or allowables are attained with a high degree of confidence in the appropriate critical environmental exposures to be expected in service. The effect of the service environment on static strength, fatigue and stiffness properties should be determined for the material system through tests; e.g., accelerated environmental tests, or from applicable service data. The effects of environmental cycling (i.e., moisture and temperature) should be evaluated. Existing data may be used where it can be shown directly applicable to the material system.

4.3 - The material system design values or allowables should be established on the laminate level by either test of the laminate or by test of the lamina in conjunction with a test validated analytical model.

4.4 - For a specific structural configuration of an individual component (point design), design values may be established which include the effects of appropriate design features (holes, joints, etc.)

4.5 - Impact damage is generally accommodated by limiting the design strain level.

Basic definitions related to material property issue (extract from AMC N°1 to CS 25.603)

DESIGN VALUES :

Material, structural element, and structural detail properties that have been determined from test data and chosen to assure a high degree of confidence in the integrity of the completed structure (reference JAR 25.613 (b)).

ALLOWABLES

Material values that are determined from test data at the laminate or lamina level on a probability basis e.g. A or B base values [reference 25.613 (a)]

LAMINATE LEVEL DESIGN VALUES OR ALLOWABLES

Established from multi-ply laminate test data and/or from test data at the lamina level and then established at the laminate level by test validated analytical methods.

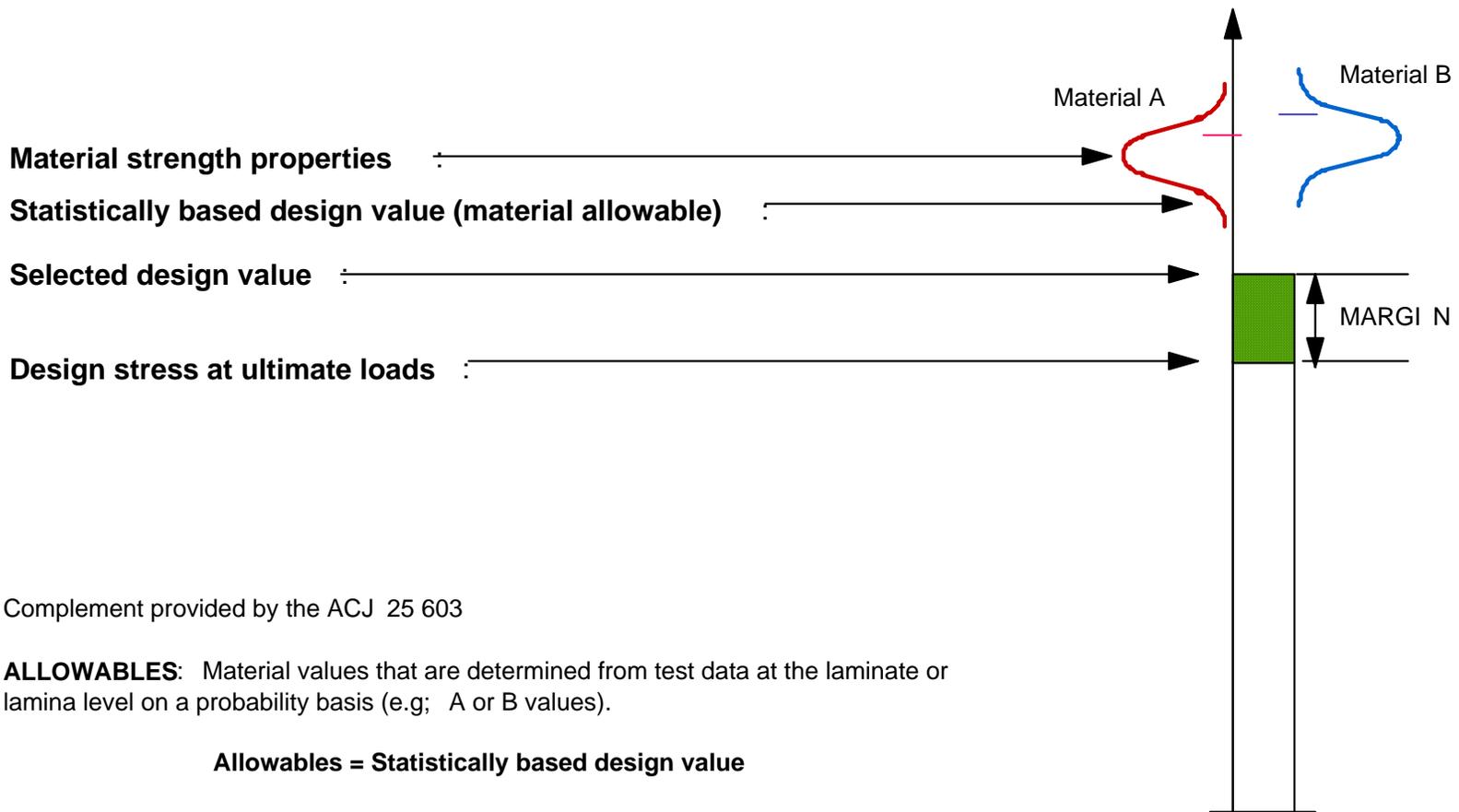
LAMINA LEVEL MATERIAL PROPERTIES

Established from test data for a single ply or a multi-ply single-direction oriented lamina lay-up.

POINT DESIGN

An element or detail of a specific design which is not considered generically applicable on other structure for the purpose of substantiation, e.g., lugs and major joints. Such a design element or detail can be qualified by test or by combination of test and analysis.

Illustration of the vocabulary



Complement provided by the ACJ 25 603

ALLOWABLES: Material values that are determined from test data at the laminate or lamina level on a probability basis (e.g; A or B values).

Allowables = Statistically based design value

Few other explanations (and recommendations) about the vocabulary

DESIGN VALUES :

Set of values used to size the component, laid down in the certification documents and used to calculate the margins.

- They must be chosen to minimize the probability of structural failures due to material variability (refer to JAR 25 613).
- They are representative of all the materials that are authorized in the application.

As far as structure strength is concerned, design values represent minimum properties for which a high degree of confidence exists. Typically, they will be expressed in terms of stresses or more often strains to failure. Failure loads will be found for details showing low accessibility to calculation. Unlike strength calculations, aeroelasticity will assume average (and not minimum) stiffness properties.

COMPOSITE MATERIAL ALLOWABLES (cf AMC N°1 to CS 25 603) :

Set of values established from the statistical analysis of test results. A material allowable is then intrinsically linked to one sample of specimen of an individual material.

Material allowables are used to establish design values in such a way that the latter can encompass all the materials and design principles that are envisioned in the application.

Providing some margin between design values and allowables will facilitate the introduction of alternate materials for an already certificated structure. This being traded against some weight penalty.

Sub-classification of design properties or allowables

1 - MATERIAL ALLOWABLES

These values are the input parameters of standard failure criteria, which means criteria that may be used at different points of the structure.

Examples :

- the strength matrix of a UD laminate associated with the Hill criterion,
- a bearing strength.

2 - DESIGN ALLOWABLES

These values directly provide a failure criterion for a point design showing no accessibility to calculation through a standard analytic formulation (case described § 4.4 of the AMC N°1 to CS 25 603).

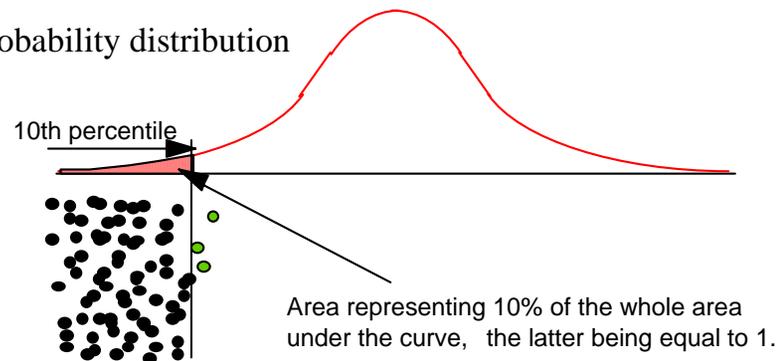
Examples :

- crushing load of a stiffener,
- tearing load of a rib,
- compression strength of a stiffened panel with an impact damage.

'A' Value, 'B' value, definition and meaning

- Let us assume, to illustrate the presentation, the 'B' value of a material static strength.
- This property is a random variable, belonging to a probability distribution (e.g. Normal, Weibull...).
- Only testing a very large amount (infinite number) of specimens would allow to exactly know this probability distribution, in particular its actual mean and standard deviation.
- This probability distribution being exactly known, the 'B' value aims at conservatively represent its 10th percentile (1st percentile for an 'A' value), percentile that would be exceeded by 90% (or 99%) of the results, should we perform an infinite number of tests.
- By definition, the 'B' value is the 95% lower confidence bound of this 10th percentile estimate. As an illustration, if we were to repeatedly obtain random samples of n specimens and calculate many of these allowables, 95% of the time the calculated value would fall below the (unknown) 10th percentile.

Actual, but not exactly known probability distribution



Computational procedure for generating allowables

Assuming a normally distributed population and no batch-to-batch variation

(Original procedure, cf MIL-HDBK-5c, Metallic materials)

$$A \text{ value} = \bar{X} - k_A \cdot S$$

$$B \text{ value} = \bar{X} - k_B \cdot S$$

Sample Size (n)	2	3	4	5	6	7	8	9	10
kA	37.094	10.553	7.042	5.741	5.062	4.642	4.354	4.143	3.981
kB	20.581	6.155	4.162	3.407	3.006	2.755	2.582	2.454	2.355

\bar{X} = sample mean based on n observations, S = sample standard deviation

Assuming the variability is known (for small sample sizes, case of structural components)

Göckol formula

$$ValeurB = \frac{1 - (Kb \cdot CF)}{1 + \left(conf \cdot \frac{CF}{\sqrt{n}} \right)} \cdot \bar{X}$$

CF = assumed coefficient of variation depending on the failure mode

Kb = 1.2816

Conf = 1.6449

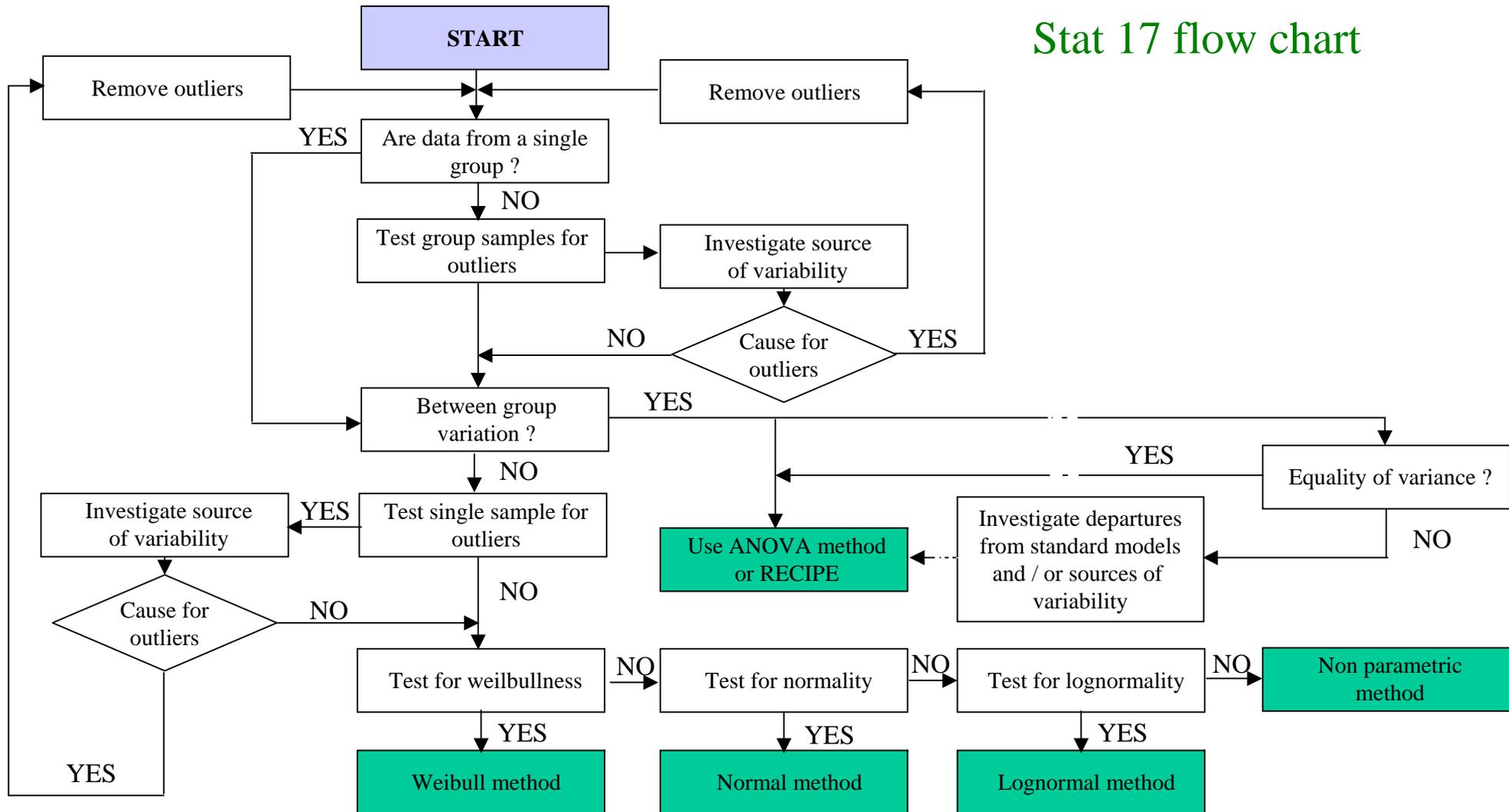
Computational procedure for generating allowables (Cont'd)

Without population normality assumption (recommended practice for composites), refer to the following tools developed in the scope of MIL-HDBK activities :

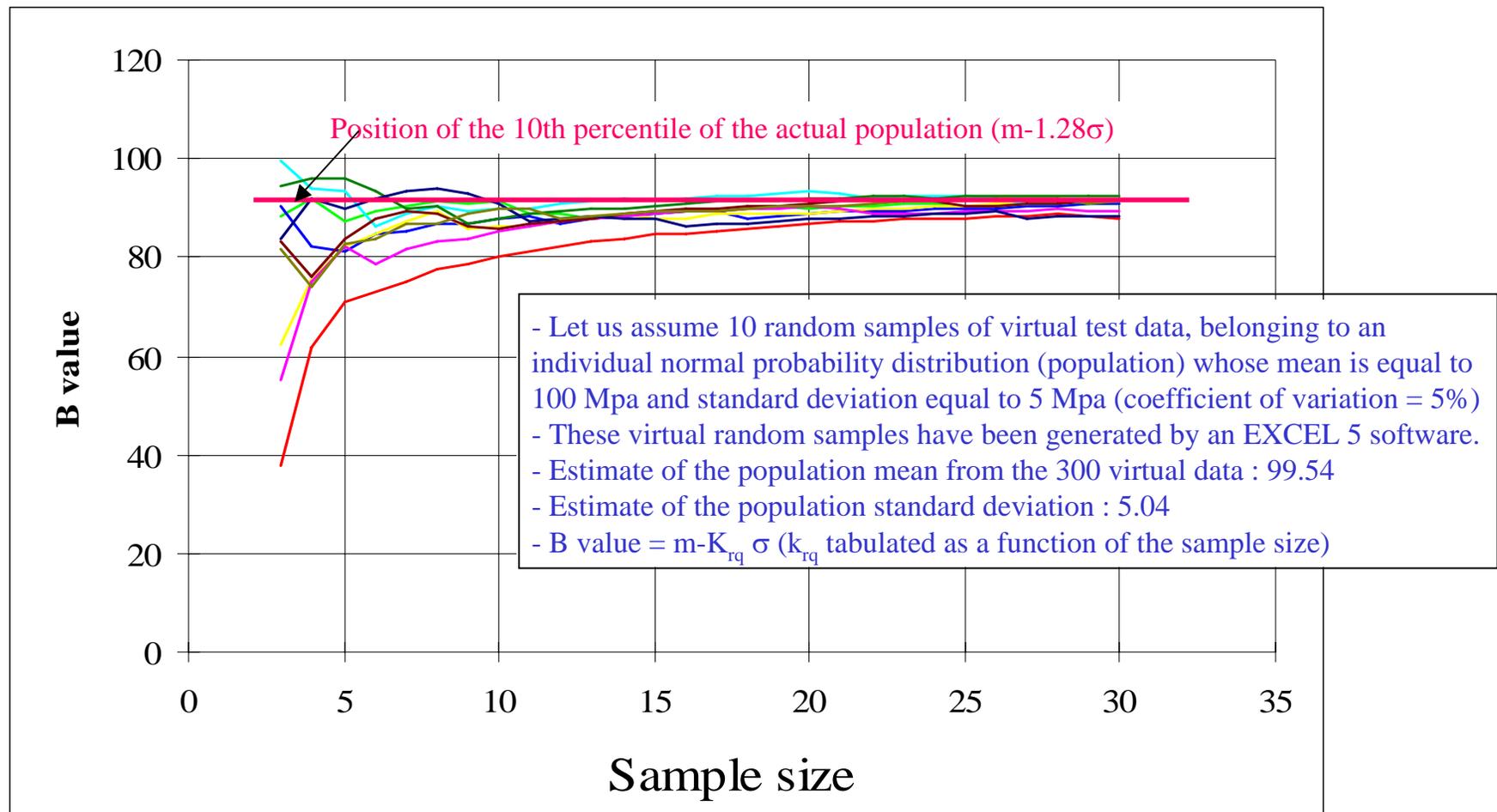
-STAT 17 (Distributed by Materials Science Corporation, Fort Washington, PA 19034, Tel 215 542 8400

RECIPE a new software developed by the 'National Institute of Standards and Technology', in the scope of MIL-HDBK activities, is a regression analysis model assuming normal distribution, but batch to batch variability.

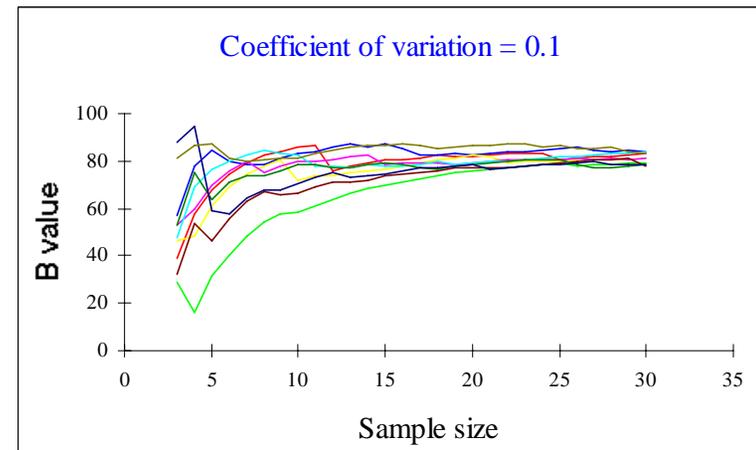
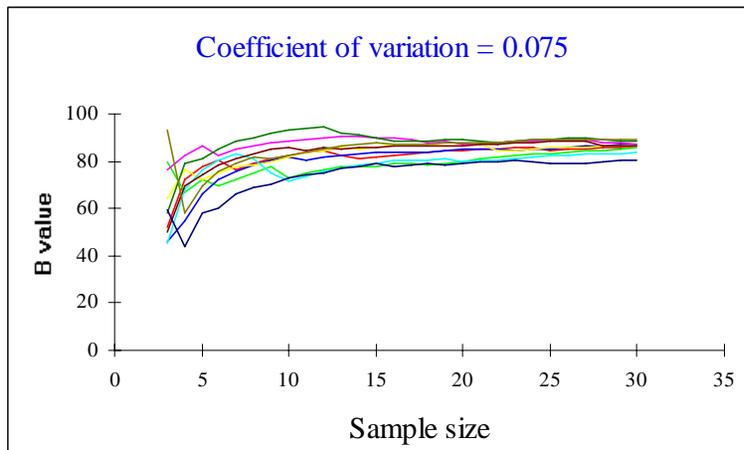
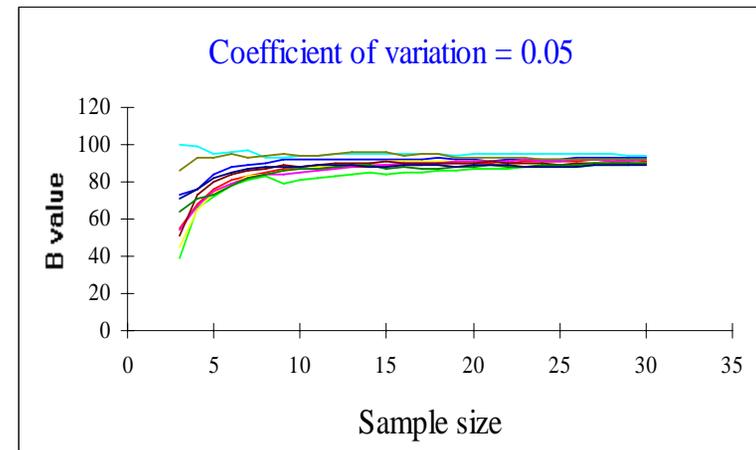
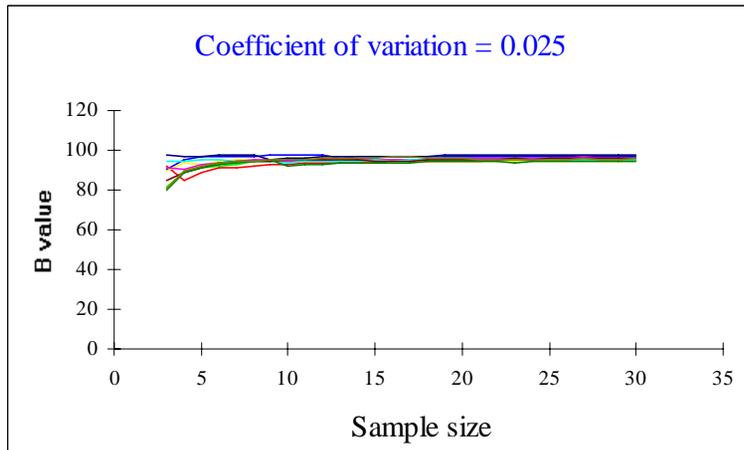
Stat 17 flow chart



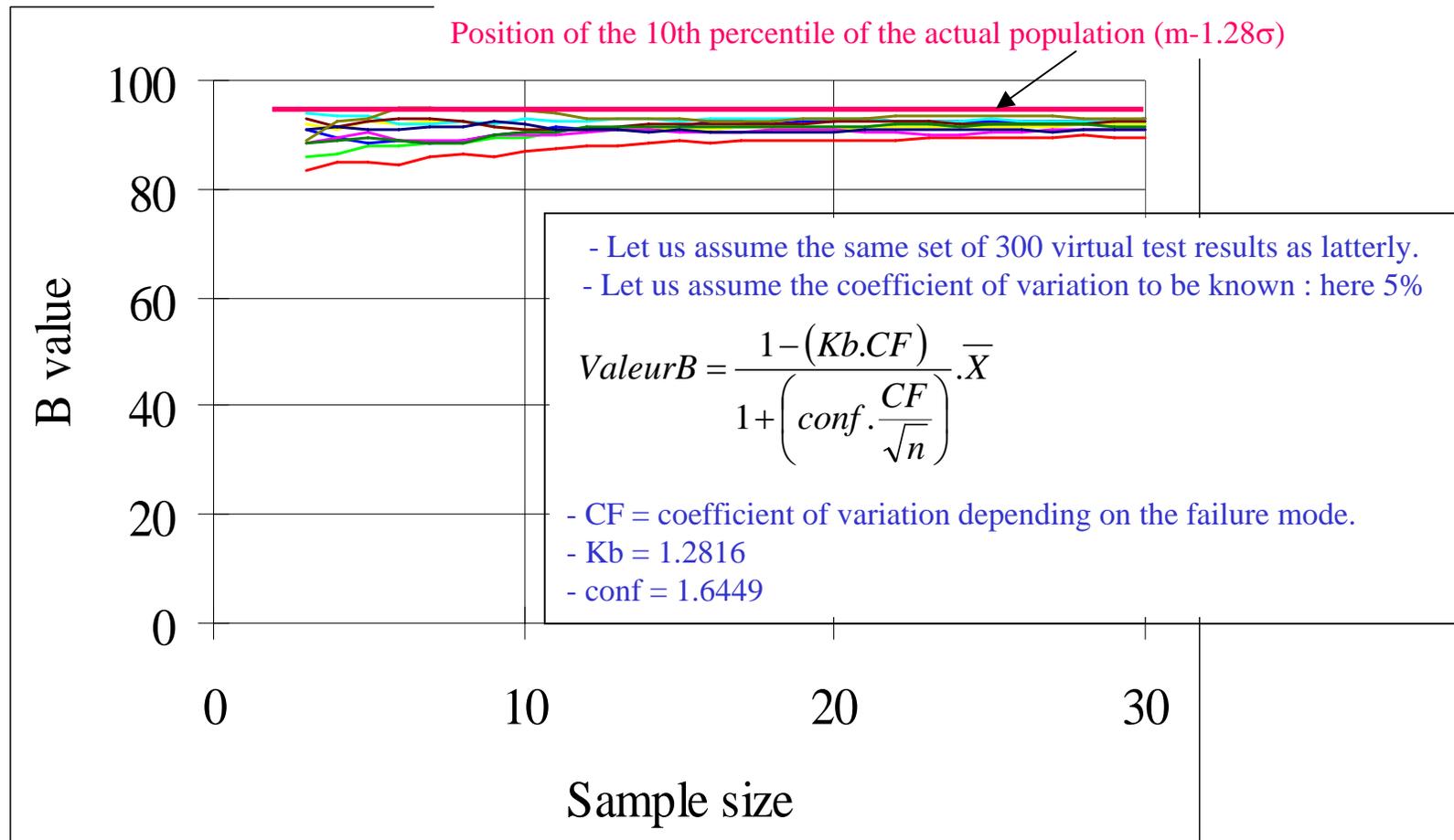
'B' values, the sample size issue



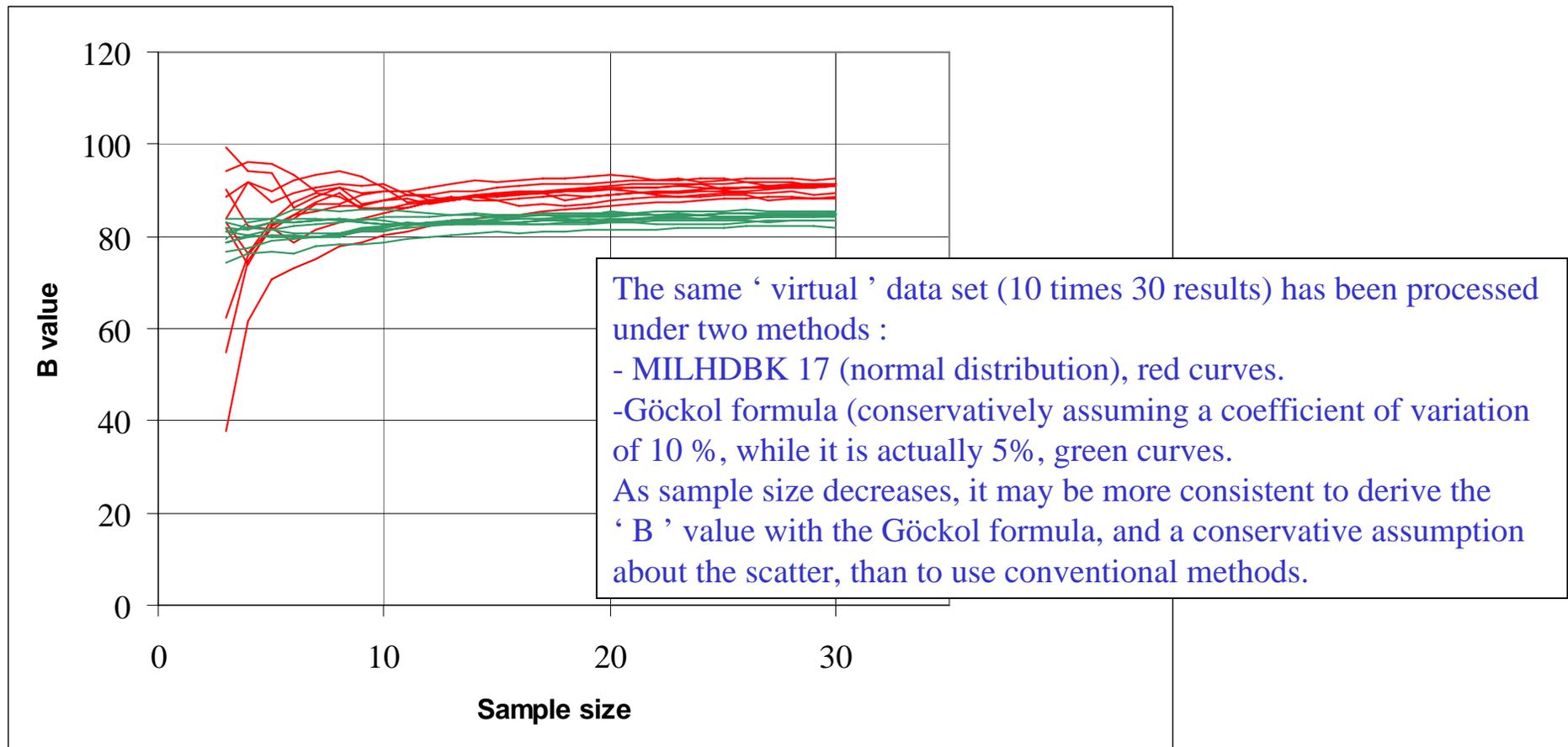
'B' values, the sample size issue(Cont'd)



'B' values, the sample size issue(Cont'd)



'B' values, the sample size issue(Cont'd)



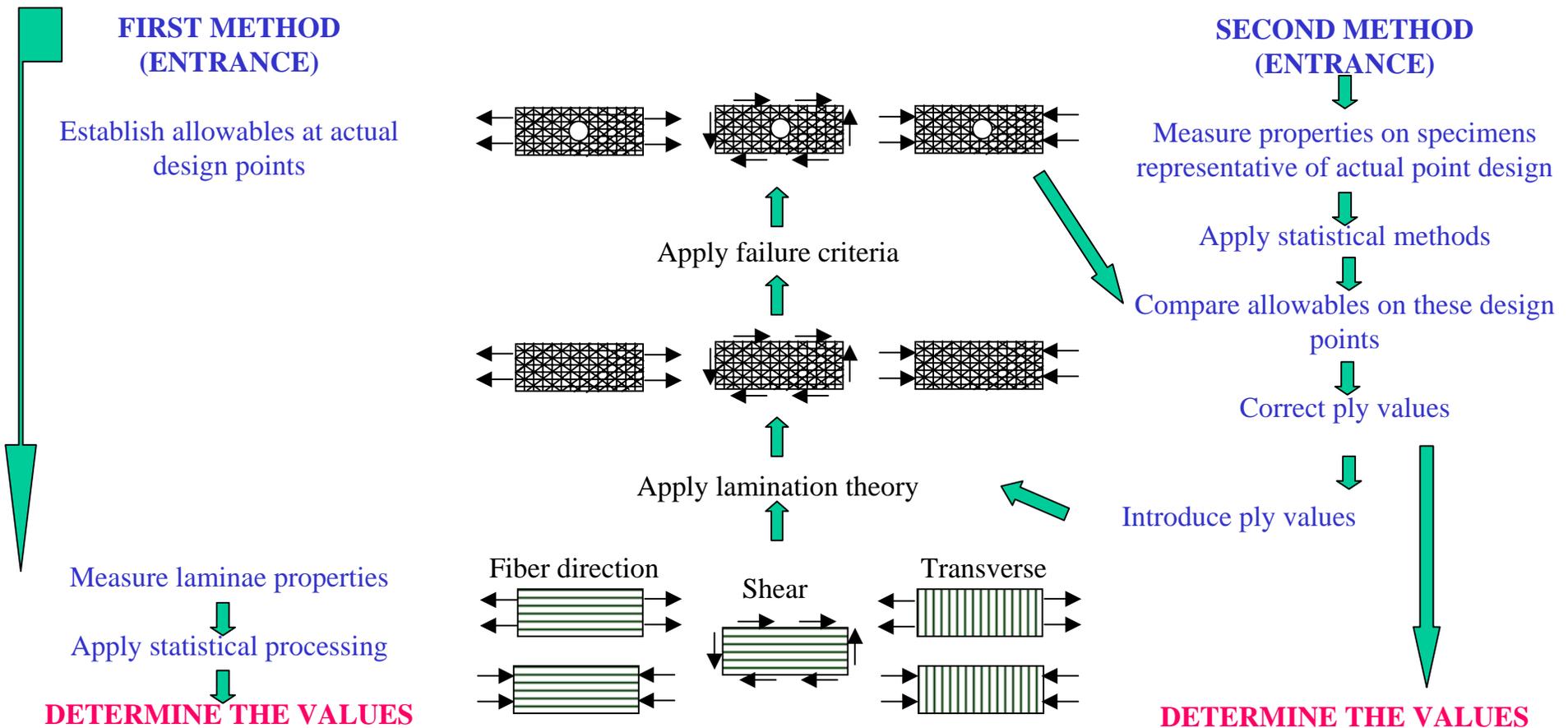
‘Reduction factor to be applied, to one, or to the mean value of few test results, in order to derive a ‘B’ value, the coefficient of variation being assumed

Relationship to be used

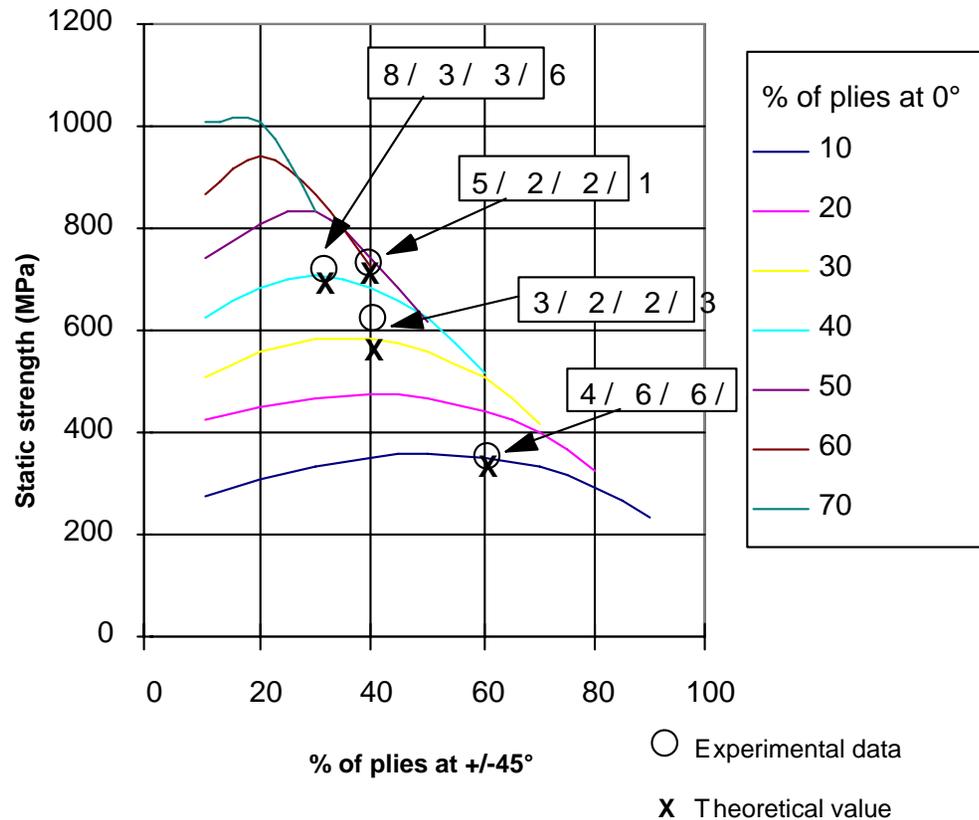
$$\text{ValeurB} = \frac{1 - (Kb.CF)}{1 + \left(\text{conf} \cdot \frac{CF}{\sqrt{n}} \right)} \cdot \bar{X}$$

		Coefficient of variation associated to the failure mode			
		5%	8%	10%	15%
umber of test results	1	14%	20%	25%	35%
	2	12%	17%	22%	31%
	3	11%	16%	20%	29%
	4	10%	15%	19%	28%
	5	10%	14%	19%	27%

Two methods to derive single ply allowables



Carpet plot principle to derive allowables



Let us assume a virtual material ABCD

Stiffness matrix :

$$E_l = 130,000 \text{ Mpa}$$

$$E_t = 8,000 \text{ Mpa}$$

$$\nu_{lt} = 0.3$$

$$G_{lt} = 5,000 \text{ Mpa}$$

Strength matrix :

$$R_l \text{ (tensile)} = 1,670 \text{ Mpa}$$

$$R_l \text{ (comp.)} = 1,080 \text{ Mpa}$$

$$R_t \text{ (tensile)} = \text{not used}$$

$$R_t \text{ (comp.)} = \text{not used}$$

$$R_{lt} = 70 \text{ Mpa}$$

Selected failure criteria :
(simplified form)

$$\sqrt{\left(\frac{\sigma_l}{R_l}\right)^2 + \left(\frac{\tau_{lt}}{R_{lt}}\right)^2} = 1$$

Chapter 8 – Static strength requirements

Regulatory requirements addressing ‘Static Strength’

REGULATORY REQUIREMENTS (FAR or CS 25)

§ 25.303 : specifies the safety factor value (1.5), between Limit Loads (LL) and Ultimate Loads (UL).

§ 25.305 : specifies requirements addressing the structure behaviour under these loads :

- No detrimental permanent deformation at Limit Loads.
- No failure within three seconds at Ultimate Loads.

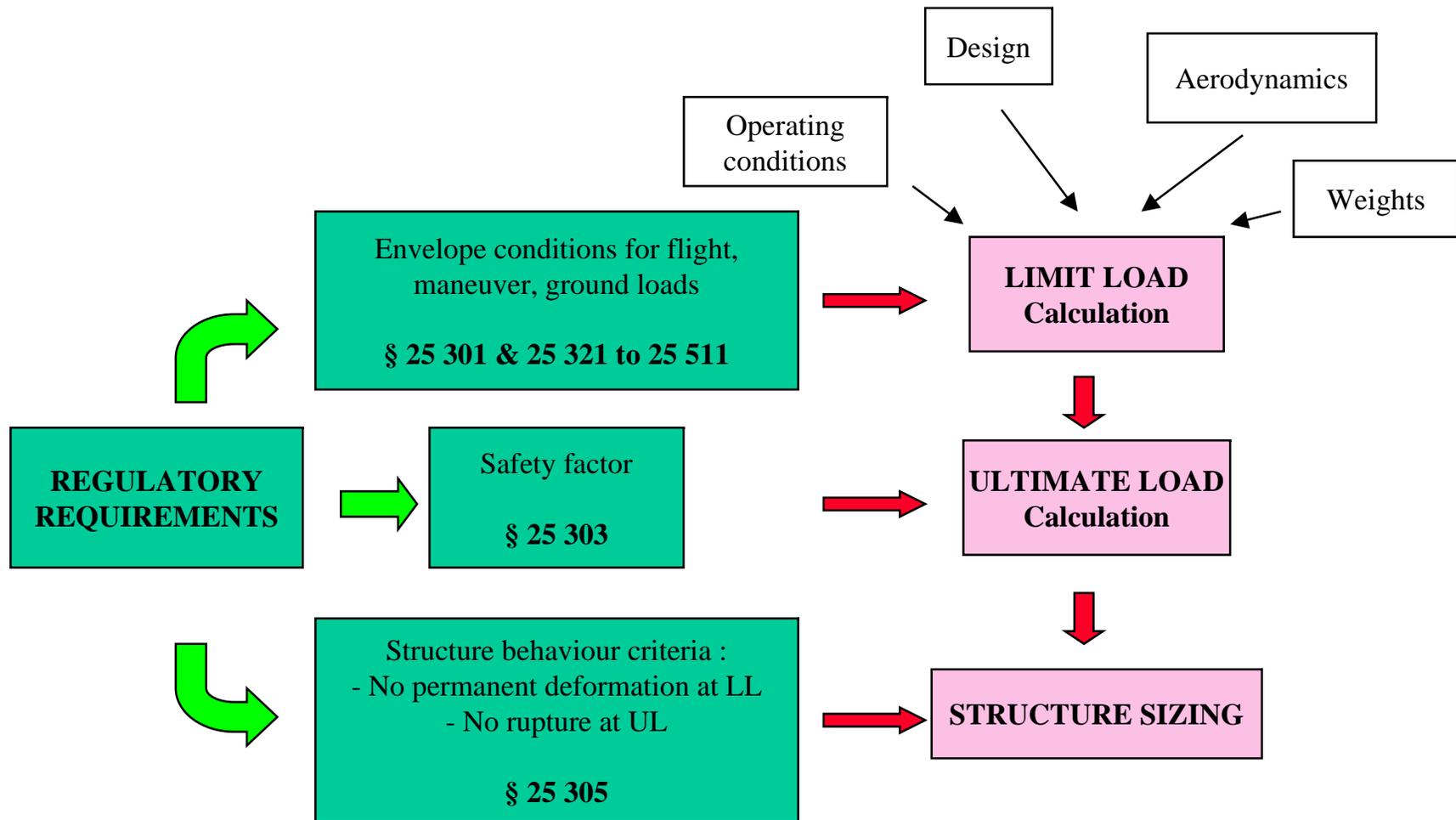
§ 25.307 : requires compliance to be shown for each critical loading condition. Structural analysis may be used only if the structure conforms to those for which experience has shown this method to be reliable. In other cases, substantiating load tests must be made. Where substantiating load tests are made these must cover loads up to the ultimate loads, unless it is agreed with the agency that in the circumstances of the case, equivalent substantiation can be obtained from tests to agreed lower levels. (See AMC 25.307.)

ACCEPTABLE MEANS OF COMPLIANCE (ADVISORY CIRCULAR AC 20.107A or AMC N°1 to CS 25.603)

§ 5 of AMC N°1 to CS 25.603 :

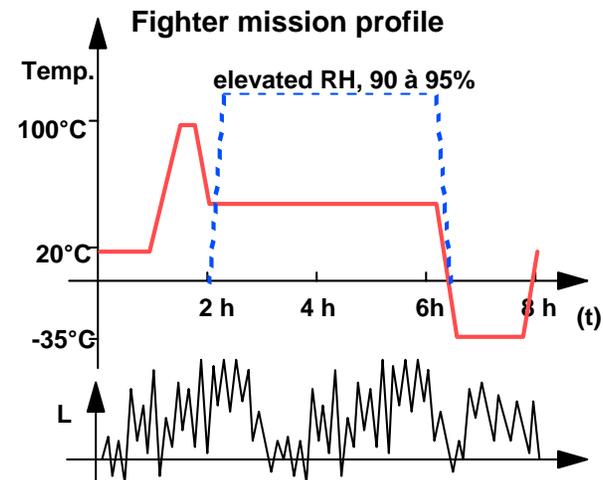
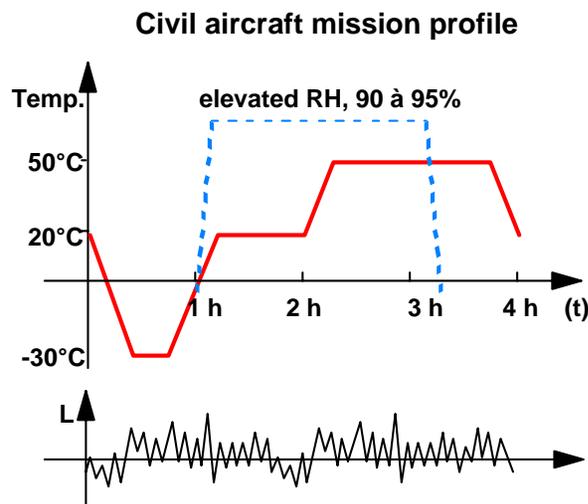
- The effects of repeated loading and environmental exposure which may result in material property degradation should be addressed in the static strength evaluation...
- When the material and processing variability of the composite structure is greater than the variability of current metallic structures, the difference should be considered in the static strength substantiation by :
 - deriving proper allowables or design values for use in the analysis...,
 - accounting for it in the static test when static proof of the structure is accomplished by component test.
- It should be shown that impact damage that can be realistically expected from manufacturing and service, but no more than the established threshold of detectability for the selected inspection procedure, will not reduce the structural strength below Ultimate Load capability.

Regulatory requirements addressing ‘Static Strength’ (Cont’d)



Allowing for solid laminate property degradation due to the combined effects of fatigue and environment

Results of experiences carried out in the 70's on coupons, detail representative specimens and small structures



Assuming that the fatigue resistance can be expressed through the residual static strength remaining at the end of the application of a representative combination of fatigue loads and environment :

- no significant effect of fatigue, combined with thermo-hygrometric mission profiles, has been found,
- the residual static strength level depends on the moisture level absorbed by the composite only.

CAUTION : Thermal cycling is to be accounted for through induced stresses at metal composite junctions.

Allowing for humid ageing in static strength substantiations

ASSUMPTION OF A DIRECT RELATIONSHIP BETWEEN THE MATERIAL MOISTURE CONTENT AND THE LOSS OF STATIC STRENGTH PROPERTIES



The mechanical property degradation due to humid ageing depends on the material moisture content only, regardless the thermo-hyrometral history (mission profiles) having led to that content



THE MAXIMUM COMPOSITE MOISTURE CONTENT AT THE END OF LIFETIME IS TO BE ESTABLISHED



THEN

SIMULATION OF THIS MOISTURE CONTENT ON THE STRUCTURE THROUGH AN ACCELERATED AGEING

OR

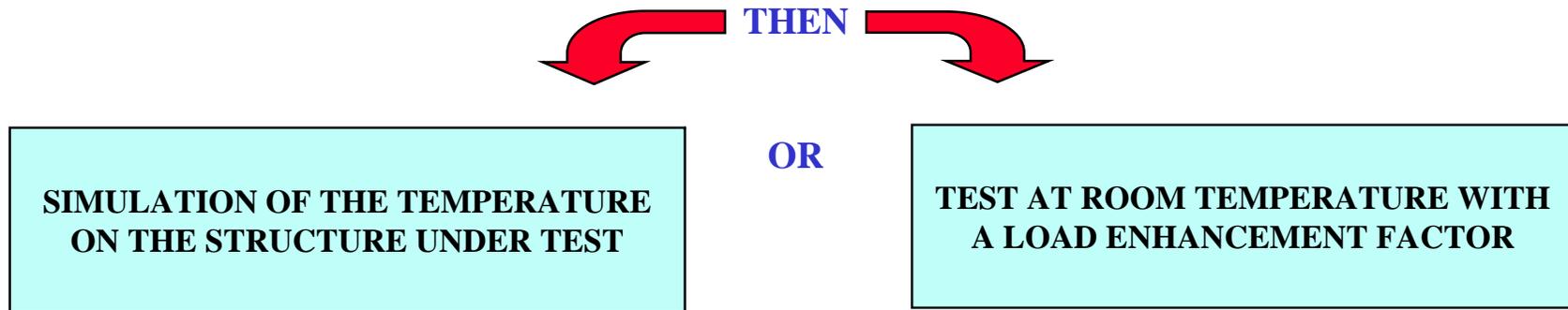
TEST OF A BRAND NEW STRUCTURE WITH A LOAD ENHANCEMENT FACTOR

NOTICE : It is a common use to accept, in qualifying a military application, results of tests only carried out at ultimate loads, without any environment simulation (either temperature or humidity), provided structural analysis is able to demonstrate that margins existing at UL may cover the degradation due to the environment.

- Such an approach needs to be supported by several sub-component tests.
- It is an exception to accept this approach in civil aircraft certifications.

Allowing for temperature in static strength substantiations

THE MAXIMUM TEMPERATURE ASSOCIATED TO EACH CRITICAL LOAD CONDITION IS TO BE ESTABLISHED



NOTICE : It is a common practice to combine, under one coefficient only, temperature and moisture effects

Allowing for degradation due to fatigue in static strength substantiations

IN THE WIDESPREAD SITUATION OF ONLY ONE TEST ARTICLE FOR STATIC AND FATIGUE DAMAGE TOLERANCE SUBSTANTIATIONS, STATIC STRENGTH SUBSTANTIATIONS, UP TO ULTIMATE LOADS, ARE PERFORMED AFTER FATIGUE

Refer to chapter 9 – Fatigue/damage tolerance

Material scatter effect on the safety level demonstrated by (deterministic) static strength requirements

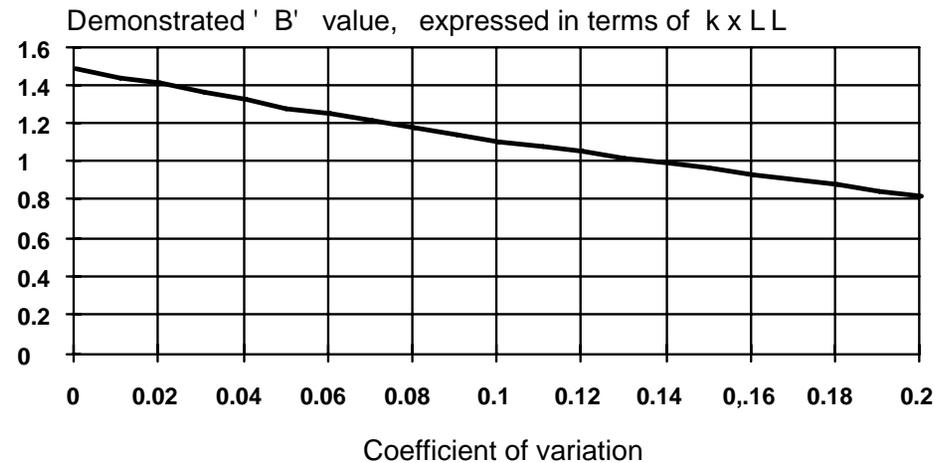
CASE 1 : THE STATIC STRENGTH DEMONSTRATION RELIES ON THE SOLE RESULT OF A STRUCTURE TEST CARRIED OUT UP TO ULTIMATE LOAD (the situation with small aircraft).

The result of the full-scale static test, expressed in terms of $k \times LL$, is one measurement of a random variable, representative of the static strength of all the structures that will be delivered.

Let us assume two kinds of structures (metallic and composites for instance), which differ by the scatter of their respective static strength. Even though both structures have shown the same strength capability, through a static test ($1.5 UL$), they will not have the same safety level.

ILLUSTRATION : 'B' value demonstrated for the population in service, as a function of the coefficient of variation

$$'B' \text{ value} = \frac{1 - (1.2816 \cdot CV)}{1 + (1.6449 \cdot \frac{CV}{\sqrt{n}})} \cdot X$$



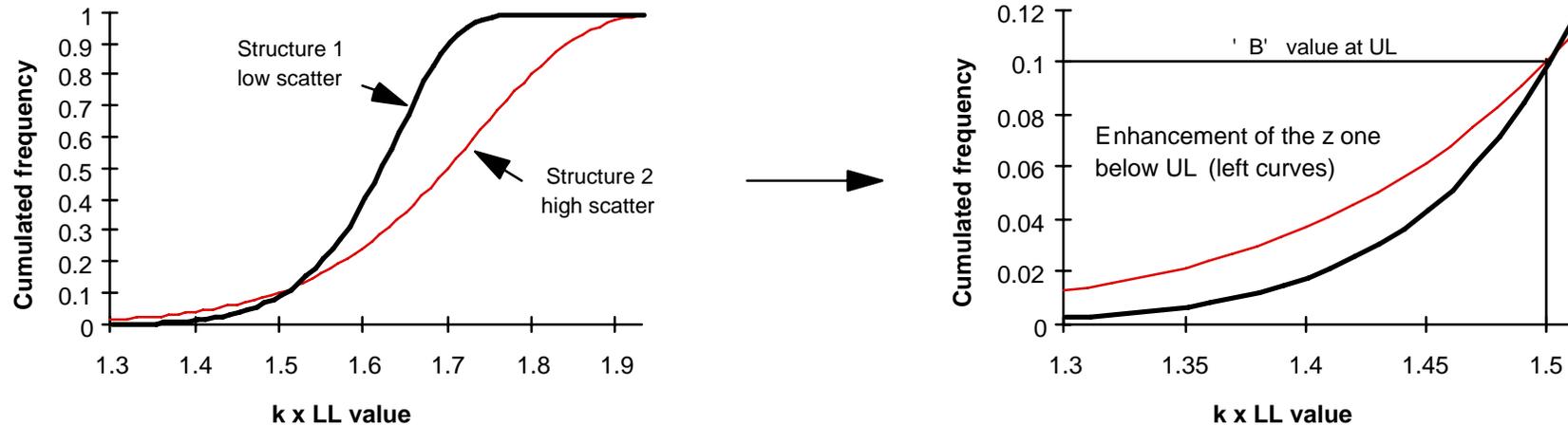
Material scatter effect on the safety level demonstrated by (deterministic) static strength requirements (Cont'd)

CASE 2 : THE STATIC STRENGTH DEMONSTRATION RELIES ON ANALYSIS SUPPORTED BY TEST EVIDENCE (Building block approach).

For each critical point of the structure, the whole test programme has supported the calculation of the margins existing at Ultimate Loads. All of these margins should be positive.

These margins are calculated with respect to, at least, 'B' values, derived from populations showing different variabilities.

e.g. : Let us assume two different structures, each of them showing a zero margin at UL, in regard to respective 'B' values, derived from two significantly different populations (in terms of variability).



Allowing for material scatter in static strength substantiations
Conclusion

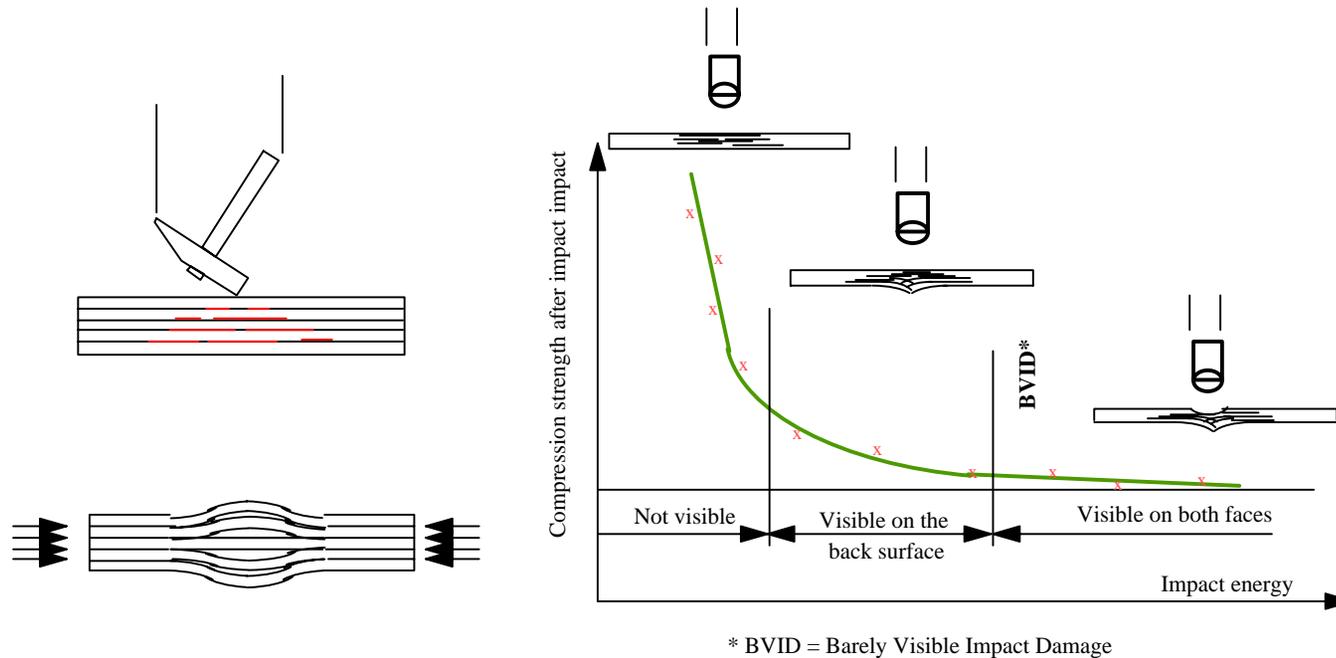
STRICTLY SPEAKING, WHATEVER THE METHOD WHICH IS USED, AS FAR AS COMPOSITE PROPERTIES ARE ASSUMED TO BE MORE SCATTERED THAN METALLIC ONES, USING A SAME SAFETY FACTOR $UL/LL = 1.5$ SHOULD LEAD TO A LOWER SAFETY LEVEL. NEVERTHELESS :

- Referring to realistic failure modes, scatter differences between composites and metallics are lower than previously anticipated.
- Allowing for most adverse environmental conditions provide additional margins, available most of the aircraft lifetime.
- Unlike metallic structures, substantiations are provided through specimens representative of the minimum quality accepted in the production line (maximum tolerable manufacturing defects, impact damages,...).

THEN, THE COEFFICIENT 1.5 HAS BEEN DEFINITELY MAINTAINED FOR COMPOSITE STRUCTURES

Composite sensitivity to low velocity impact damage, the issue

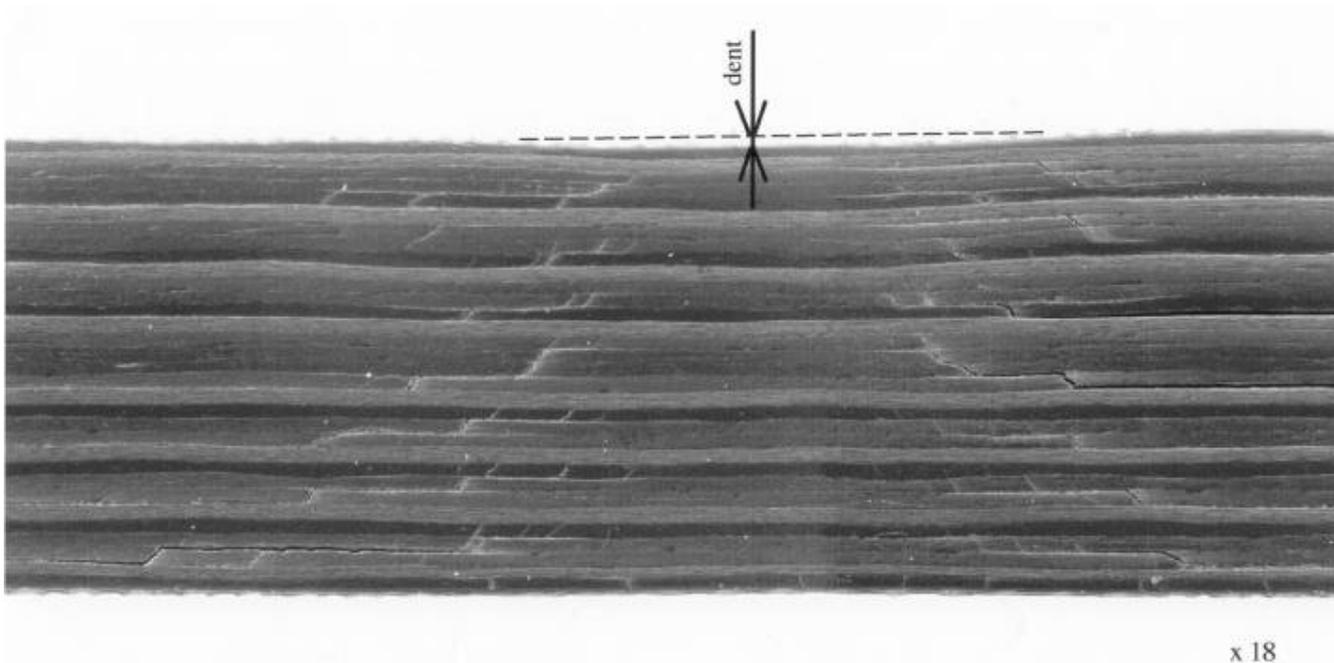
Material brittleness associated with poor through-laminate properties



LARGE STATIC STRENGTH REDUCTIONS MAY OCCUR BEFORE DAMAGE BECOMES DETECTABLE

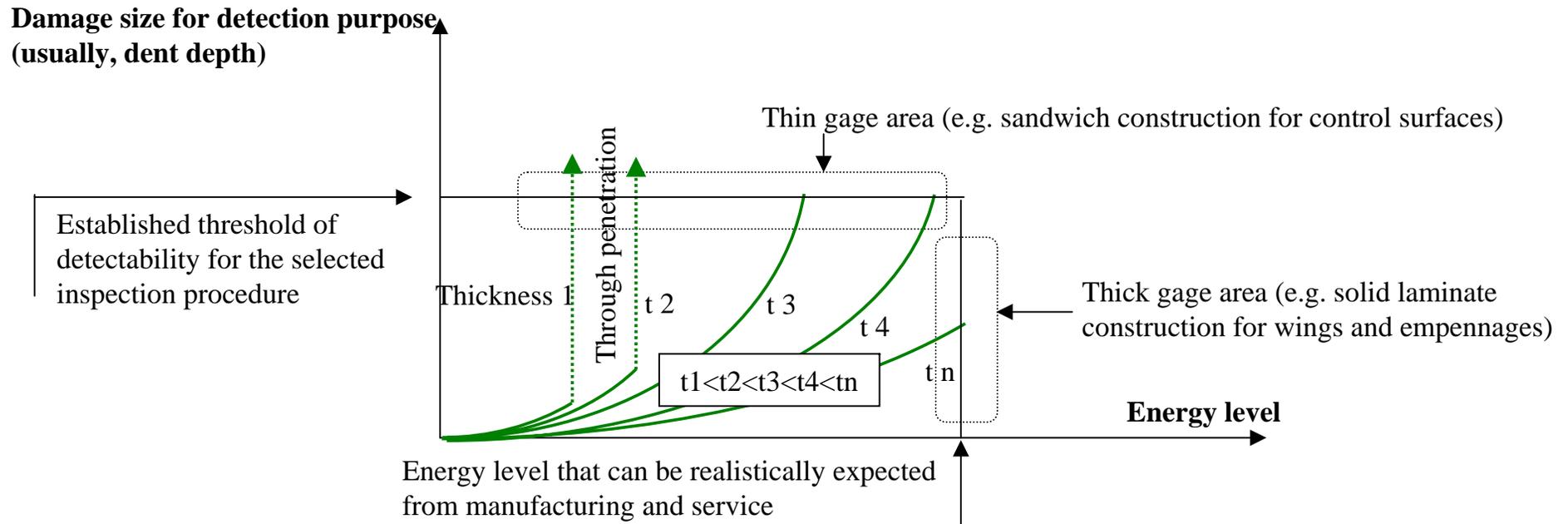
How damage develops, under a low velocity accidental impact

Material : T 800H / F 655-2, 32 plies
Impact energy : 12 joules
Dent depth : 0.1 mm



Allowing for low velocity impact damage in static strength substantiations

ACJ 25 603 § 5.8 : It should be shown that impact damage that can be realistically expected from manufacturing and service, but not more than the established threshold of detectability for the selected inspection procedure, will not reduce the structural strength below ultimate load capability.



Defining both thresholds. First : detectability threshold

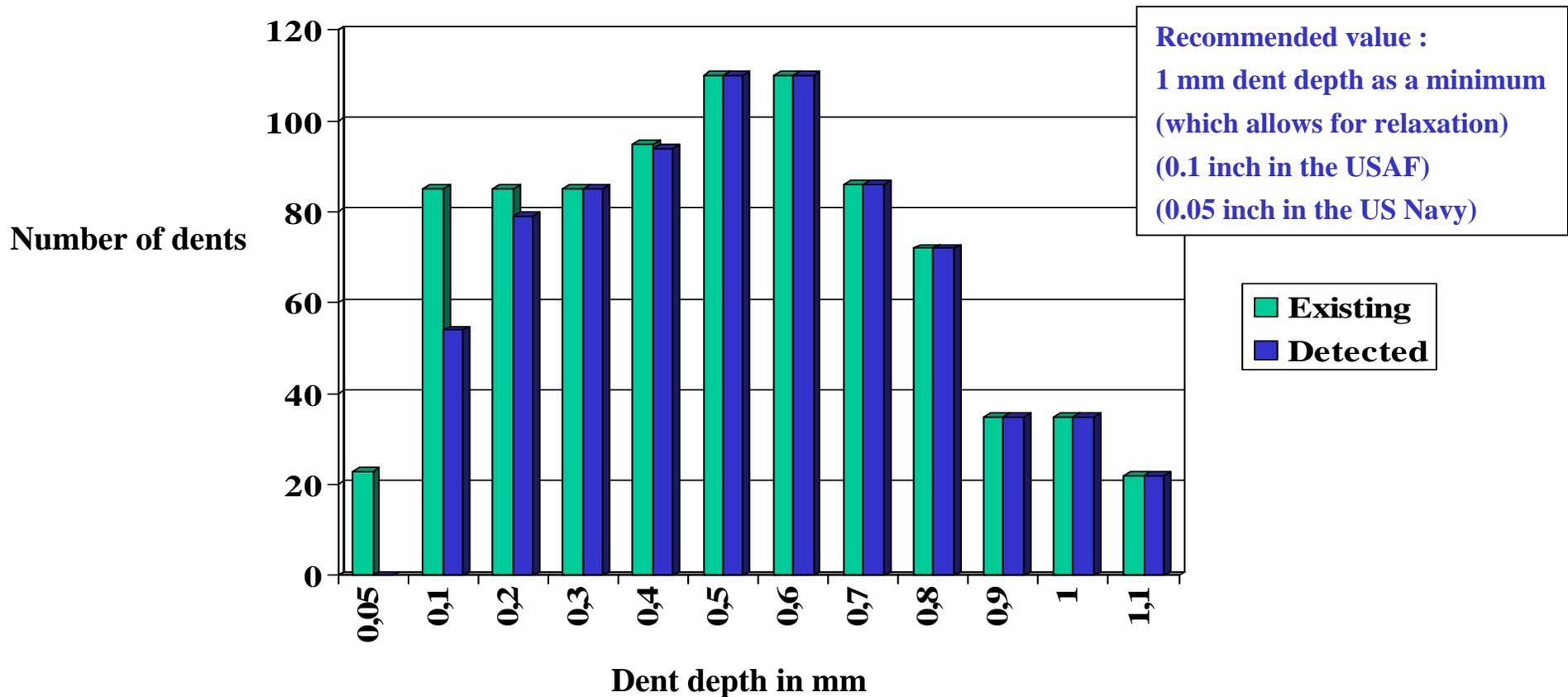
~~-Is it the minimum size that the most acute inspector is able to detect ?~~

Or

-the maximum size that a normal inspector may overlook?

Defining detectability threshold

Results of an investigation carried out at EADS - Louis Bleriot research centre



Defining both thresholds. Second : energy cut-off

A PROPOSAL ABOUT WHAT COULD BE CONSIDERED AS 'REALISTIC'

AT THE END OF LIFETIME, MOST OF THE STRUCTURES SHOULD NOT HAVE BEEN IMPACTED WITH A HIGHER ENERGY.

Let P_a the probability, per flight*, to encounter one impact with an energy $E > E_{co}$.

Then, $(1 - P_a)$ is the probability to have encountered either none impact or lower energy impacts.

$P = 1 - (1 - P_a)^n$ is then the probability to have encountered at least one damage with an energy $E > E_{co}$ after n flights.

Let 'Most' meaning 90 % of the population and $n = 50\,000$ flights, then $P_a = 2.1 \cdot 10^{-6}$ / flight.

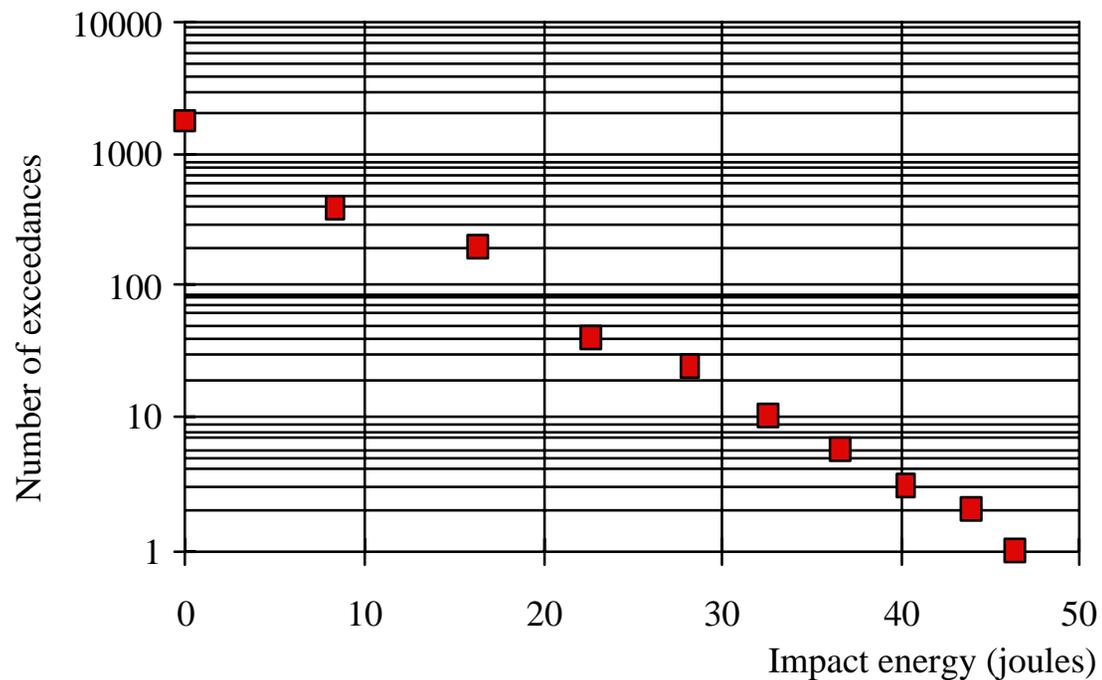
For the purpose of this analysis, one flight includes aircraft servicing and a shared part of the risk associated with the scheduled inspections.

But statistics on impact damage hazards are needed

Low velocity accidental impact damage statistics (very poor)

Results of a field survey carried out by Northrop / MCair (Report DOT/FAA/AR-96/111 or NAWCADPAX-96-262-TR)

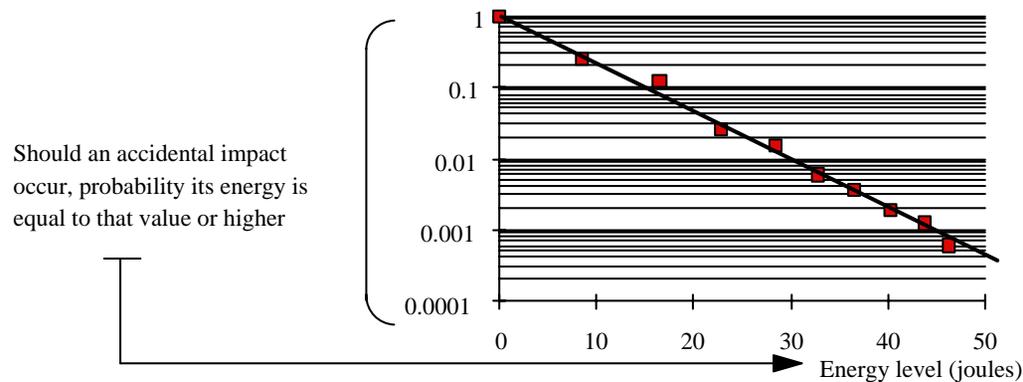
1644 impacts recorded on four different in-service aircraft types (F-4, F-111, A-10 and F-18)



Energy level has been drawn from the dent depth values through a calibration curve established on a F-15 wing.

How to use the Northrop/Mcair survey ?

Assumption : maintenance actions, with their associated tools and procedures, are not significantly different between civil and military aircraft.



Conversion (by Northrop) into a probability distribution (Weibull) :

- shape parameter : $\alpha = 1.147$
- scale parameter : $\beta = 8.2$

or conversion to a log-linear relationship :

probability (P_e) of exceeding a given level of energy :

$$\text{Log } P_e = - X(j) / 15$$

Probability (per flight hour) to encounter an accidental impact of a given energy value, or higher : $P_a = P_o \times P_e$, with :

P_o = probability of occurrence,

P_e = probability the energy is equal to that value, or higher (refer to Northrop survey).

Let us assume that accidental impact occurrence is reasonably probable ($10^{-5} < P_o < 10^{-3}$ /flight hour) according to JAR ACJ 25 1309 definitions).

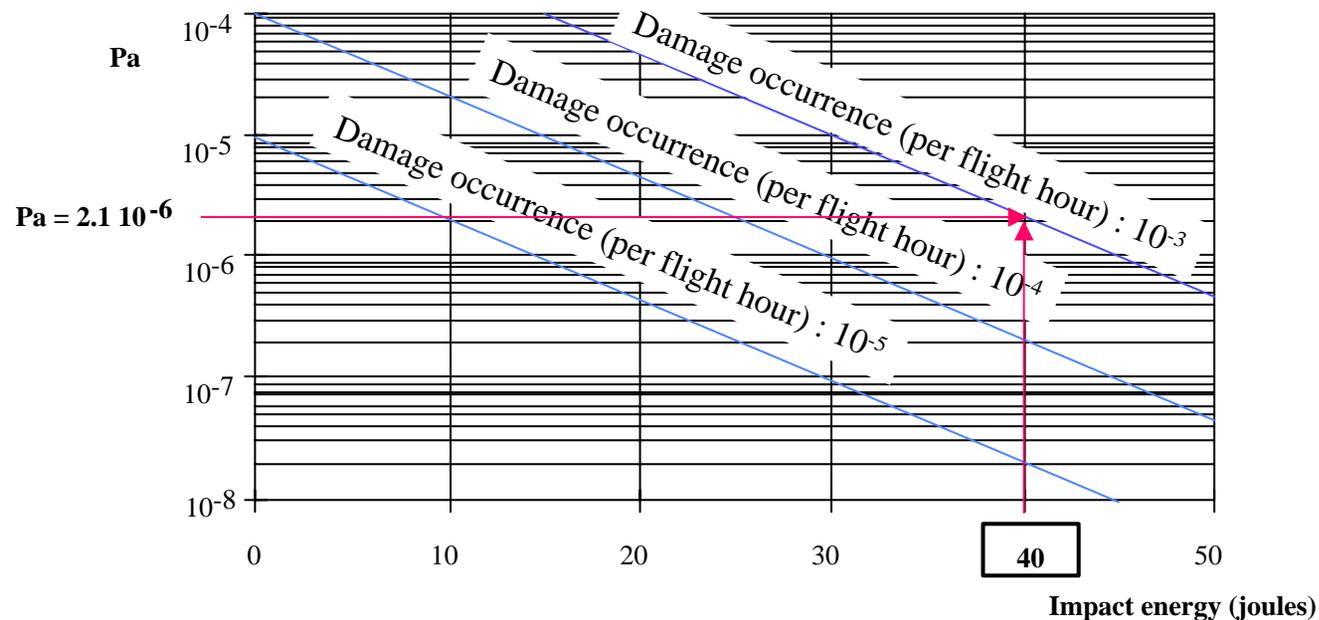
For a short-medium range aircraft ($n = 50\,000$ FH), if 'Most of the structures' means 90% of the population, the realistic level of energy should not be lower than : 40 joules (50 joules is used for most of JAR certified programmes, 137 joules is recommended in USA).

Derivation of the energy cut-off from the Northrop / MCAir survey

Summary of the assumptions :

90% of the structures will not have to be impacted by a higher level of energy at the end of lifetime.

Low velocity impact damage is at the lower boundary of reasonably probable events : 10^{-3} / flight hour.



General conclusion about the realistic level of energy

35 joules is widely used in most of the European programmes (Airbus and Falcon)

There is an exception at the horizontal tail plane root at Airbus : **140 joules**

Boeing use 100 feet-pounds, which is about **137 Joules**

Chapter 9 - Fatigue and damage tolerance

Regulatory requirements addressing ‘Fatigue and Damage Tolerance’

BASIC RULES (e.g. JAR or FAR 25)

§ 25.571 - DAMAGE-TOLERANCE AND FATIGUE EVALUATION OF STRUCTURE :

(a) General. An evaluation of the strength, detail design, and fabrication must show that catastrophic failure due to fatigue, corrosion or accidental damage will be avoided throughout the operational life of the aircraft.....

.....,inspections or other procedures must be established as necessary to prevent catastrophic failure,...

(b) Damage-tolerance (fail-safe) evaluation. The evaluation must include a determination of the probable locations and failure modes due to fatigue, corrosion, or accidental damage.....

.....The residual strength evaluation must show that the remaining structure is able to withstand loads (considered as static ultimate loads) corresponding to the following conditions.....

(c) Fatigue(safe life) evaluation. Compliance with the requirements of sub-paragraph (b) of this paragraph is not required if the applicant establishes that their application for particular structure is impractical.....

ACCEPTABLE MEANS OF COMPLIANCE (ADVISORY CIRCULAR AC 20-107A or AMC N°1 to CS 25.603)

§ 6 - PROOF OF STRUCTURE - FATIGUE/DAMAGE TOLERANCE :

The evaluation of composite structure should be based on the applicable requirements of FAR 23.571, 23.572, 25.571, 27.571 and 29.571. The nature and extent of analysis or tests on complete structure and/or portions of the primary structure will depend upon applicable previous fatigue / damage tolerant designs, construction, tests, and service experience on similar structures.....

.....The following considerations are unique to the use of composite material systems and should be observed for the method of substantiation selected by the applicant....

Examples :

- utilisation of the no- growth concept for damages,
- relation between the inspection interval and the residual strength in the situation of the no-growth concept.

Unlike CS 23 and soon CS 27 and 29, CS 25 does not include any fatigue and damage tolerance paragraph specific to composites (xx 573) CS 25.571 is essentially written from metallic structures experience

The origins of the Damage Tolerance philosophy

Damage Tolerance was introduced for the first time in 1978 in the civil regulatory requirements (FAR 25 amendment 45), at a time when all primary aircraft structures were made out of metals (aluminium alloys).

Damage Tolerance is basically a '**Safety by Inspection**' concept which has superseded former concepts the experience had shown they were insufficiently safe.

afe-Life Safety by retirement,

ail-Safe Safety by redundancy (multiple load path).

From the experience gathered with metallic structures in mind, Damage Tolerance evaluation of the structure must address the effects of :

Repeated loading (fatigue)

Environmental effects (corrosion)

The right definitions to bear in mind

MIL-HDBK-17-3F (17 June 2002) § 7.2 :

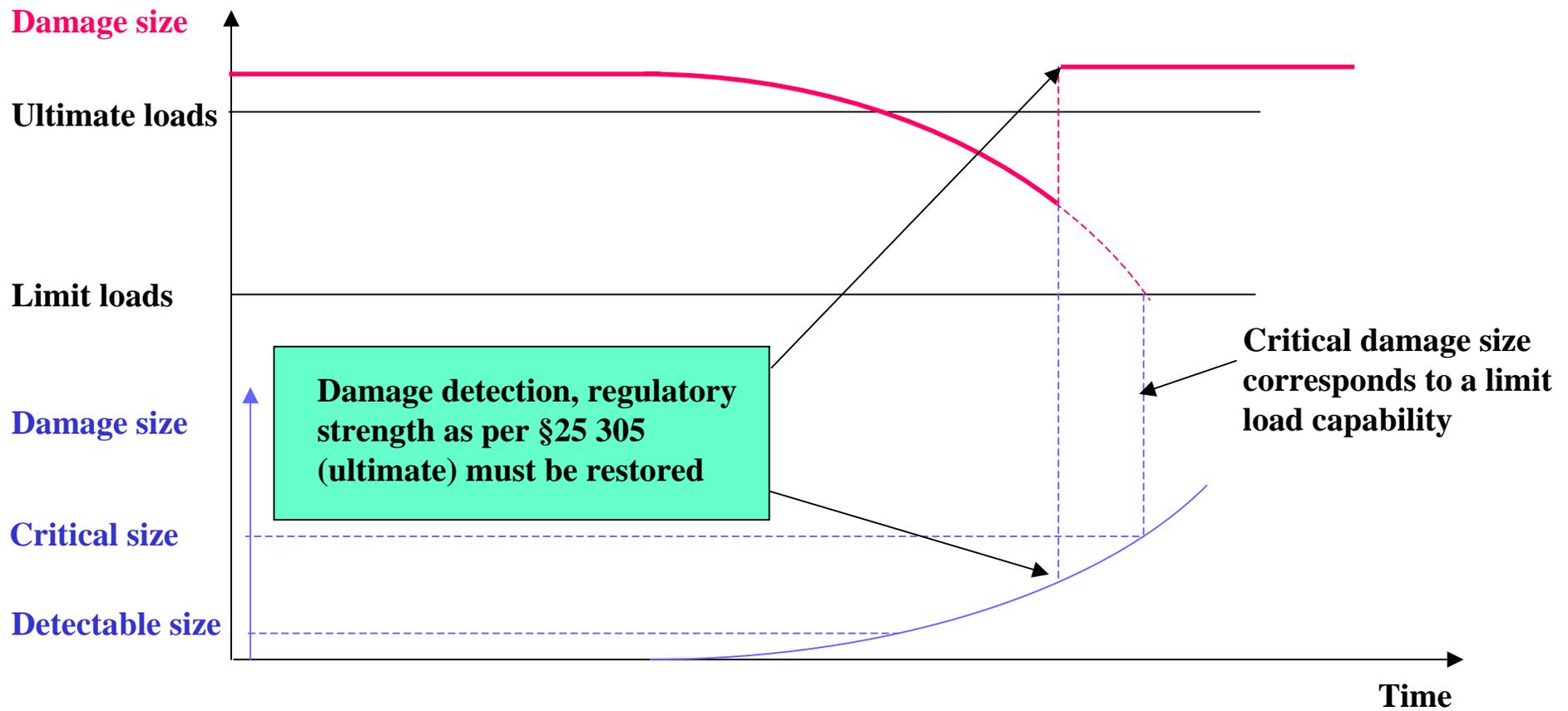
Damage tolerance provides a measure of the structure ability to sustain design loads with a level of damage or defect and be able to perform its operating functions.

Regulatory requirements (FAR/CS25) c.f. AC 25 571 1F (April 98) :

Damage tolerance is the attribute of the structure that permits it to retain its residual strength without detrimental structural deformation for a period of use after the structure has sustained a given level of fatigue, corrosion, accidental or discrete source damage.

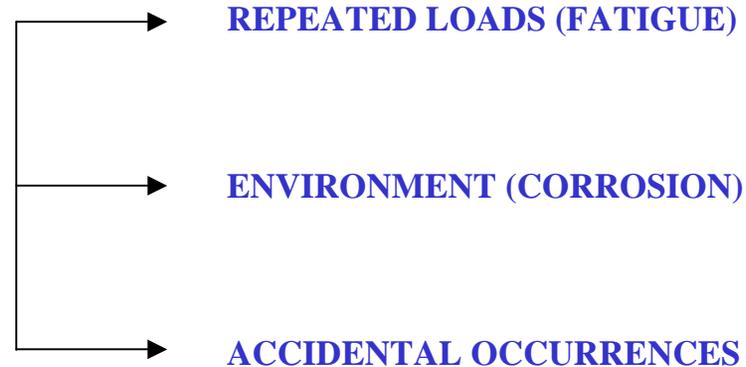
Damage tolerance is definitely a ‘Safety Issue’ not to confuse with durability which is an economical issue.

Damage tolerance principles based on the slow growth concept



Fatigue / Damage tolerance requirements, as per CS or FAR 25-571, are applicable to all structures, regardless the material (metallic or composite)

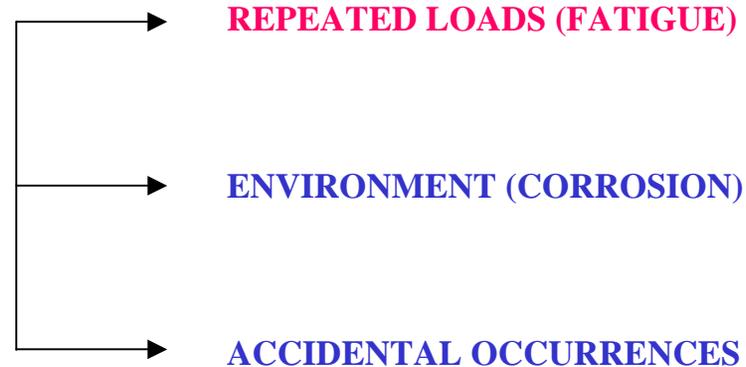
THE DAMAGE TOLERANCE
EVALUATION MUST TAKE INTO
ACCOUNT THE EFFECTS OF



**THE REMAINING STRUCTURE MUST BE ABLE TO WITHSTAND
REASONABLE LOADS UNTIL DAMAGE IS DETECTED**

Fatigue / Damage tolerance requirements, as per CS or FAR 25-571, are applicable to all structures, regardless the material (metallic or composite)

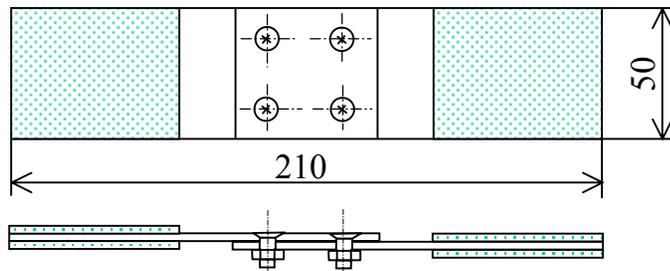
THE DAMAGE TOLERANCE
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THE REMAINING STRUCTURE MUST BE ABLE TO WITHSTAND
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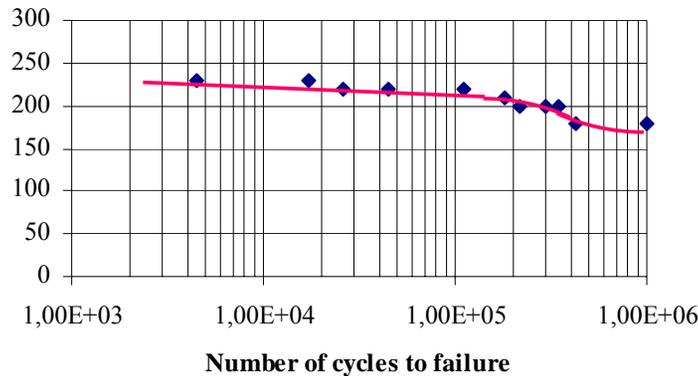
About composite sensitivity to fatigue - 1st example (single lap joints)

Single lap joint specimen
(Lay-up : 8 plies at 0°, 12 plies at +/-45°, 2 plies at 90°)

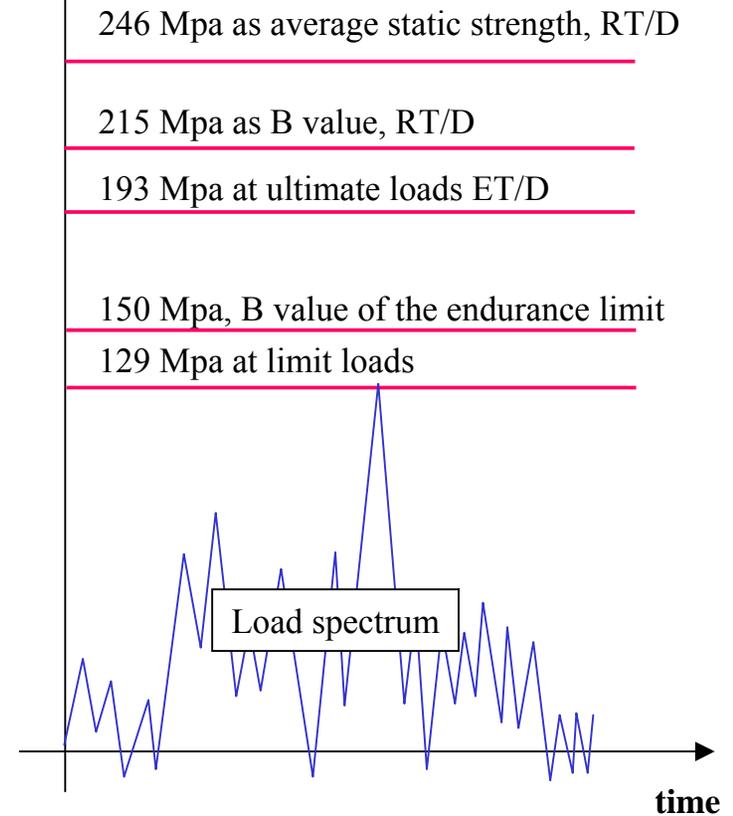


Static test results : Average gross stress at failure : 246 Mpa
Standard Deviation : 12 Mpa (with 8 specimens)

Zero-tension SN curve

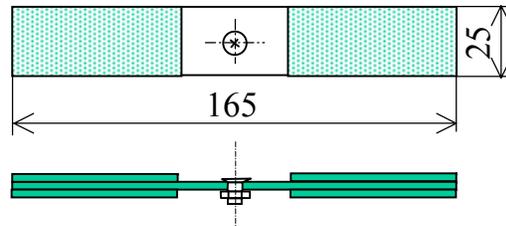


Gross stress

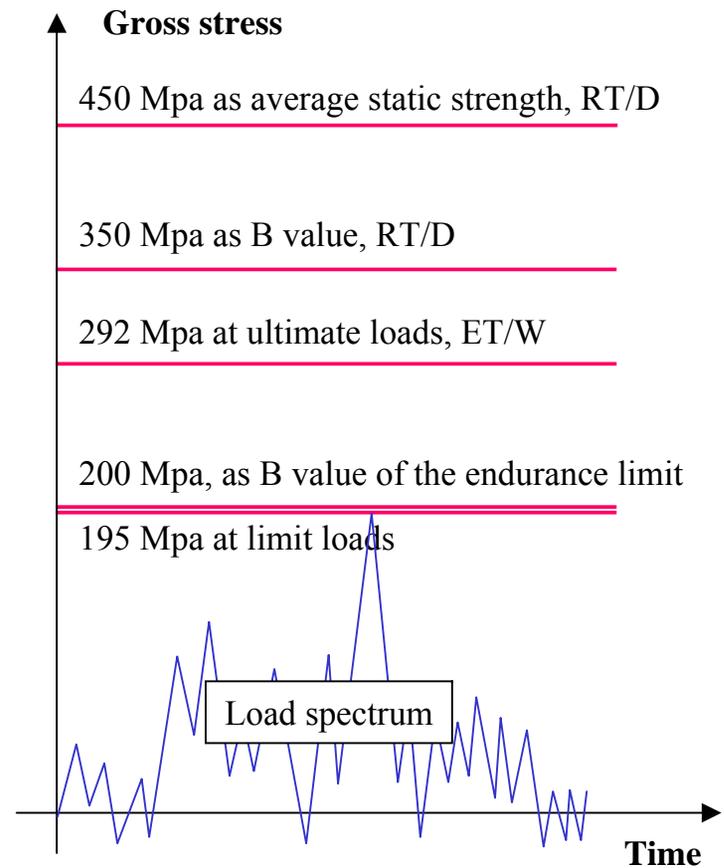
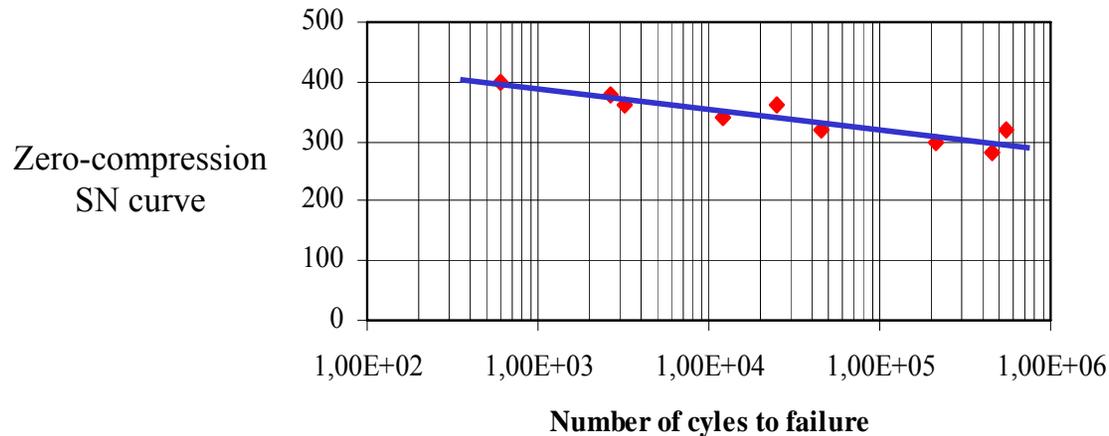


About composite sensitivity to fatigue, 2nd example
(solid laminate in compression)

Filled hole solid laminate specimen
(Lay-up : 8 plies at 0°, 12 plies at +/-45°, 2 plies at 90°)

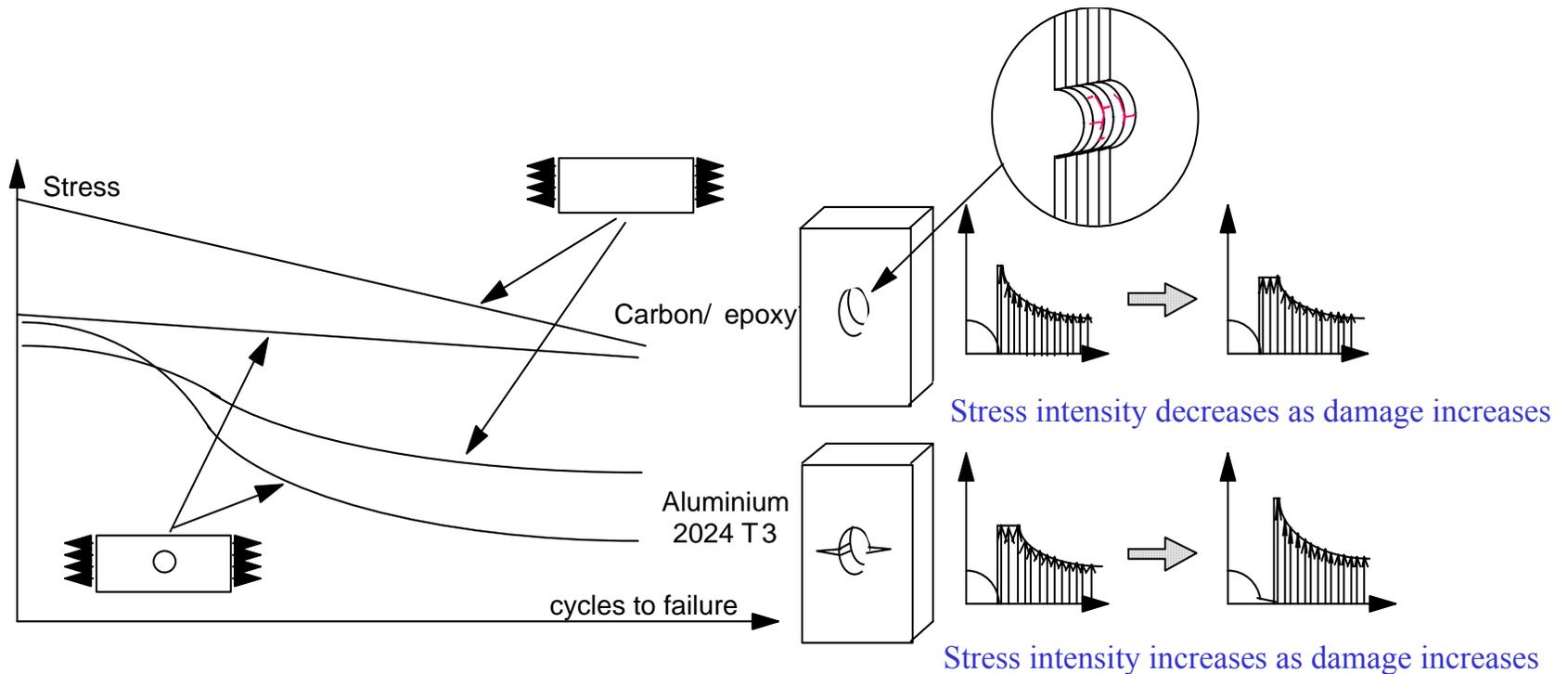


Static test results : Average gross stress at failure : 450 Mpa
(compression) Standard deviation : 33 Mpa (with 8 specimens)



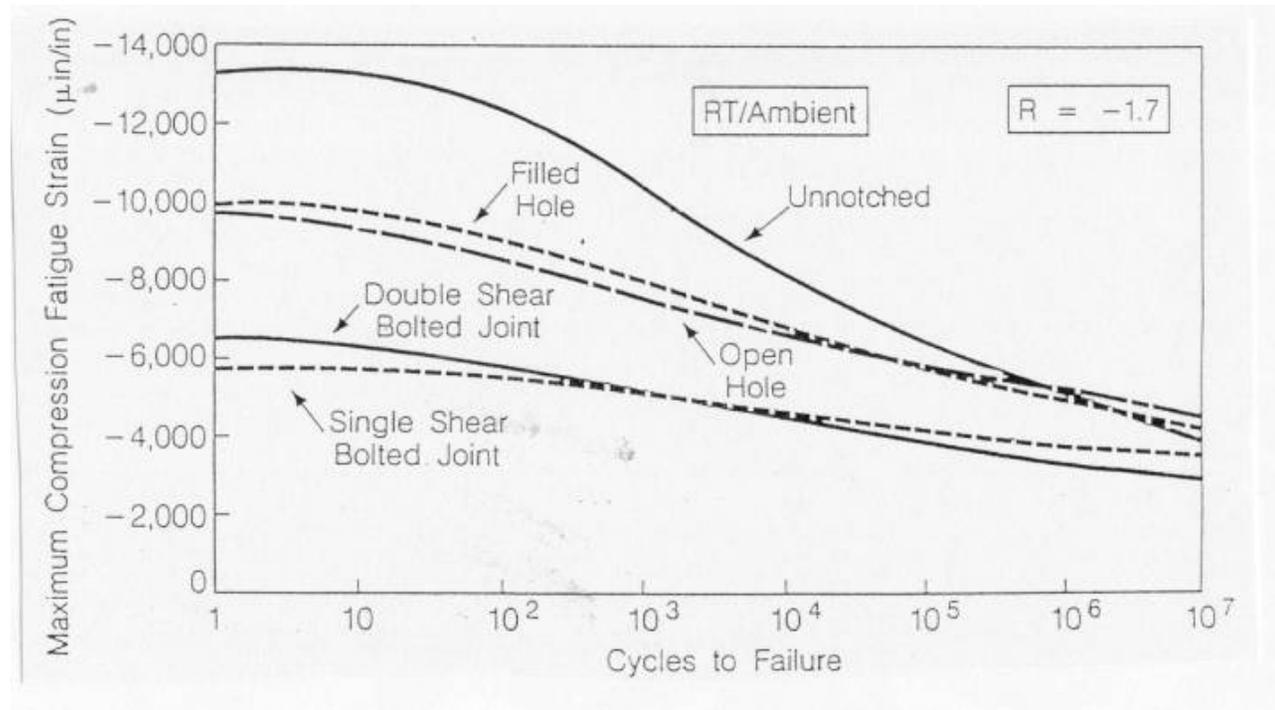
A simple comparison of composite and metallic fatigue behaviour

Actual tension S-N curves obtained on 1.5 mm thick plates in metal and composite



*The stacking sequence of the composite was such to have a Young modulus similar to the aluminium one.

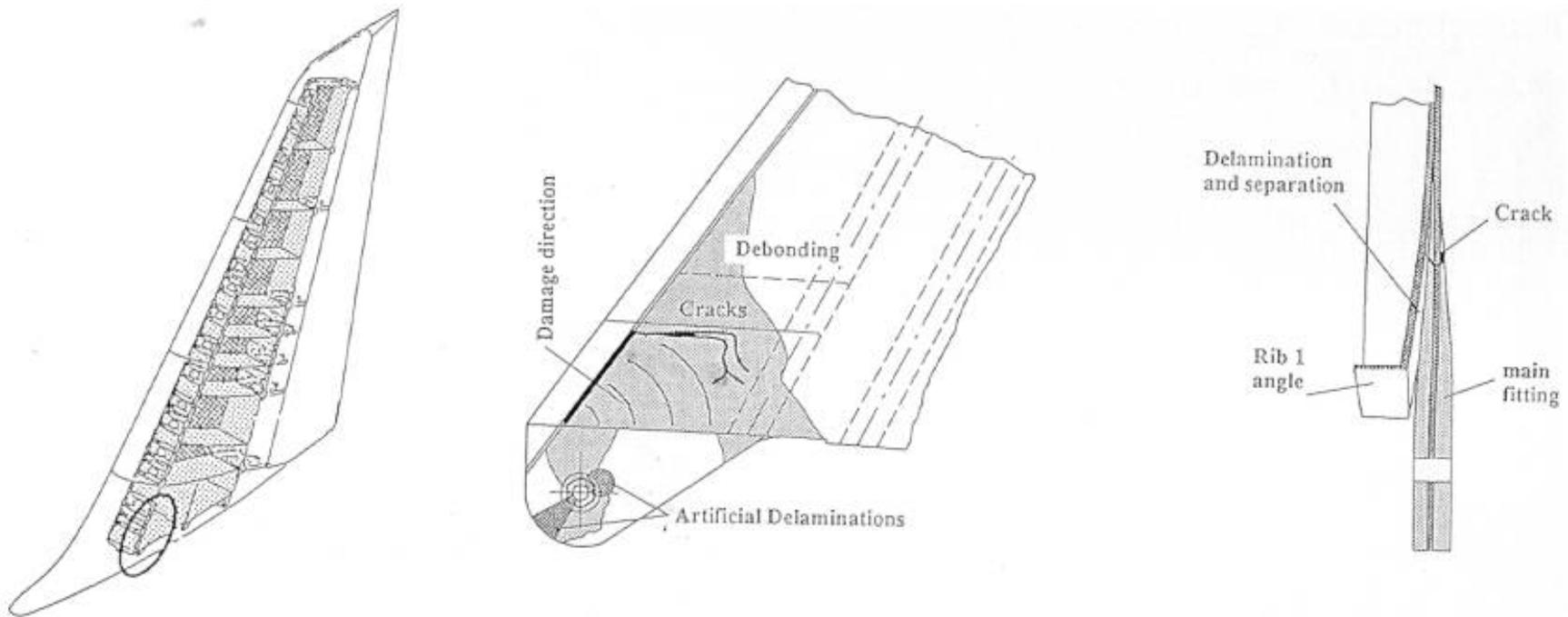
Various S-N curves shapes associated with some generic design features



Reference : 'Qualification of Primary Aircraft Structures' par Robin Whitehead, 14^o ICAF symposium, 1987
In the presence of a stress raiser (hole, fastener), to size a structure with respect to static strength requirements should impose service loads sufficiently low should to fatigue problems

IT DOES NOT APPLIES TO BONDED JOINTS, ROTOR AND PROPELLER BLADES, etc.

An example of fatigue damage that occurred on a full-scale fatigue test



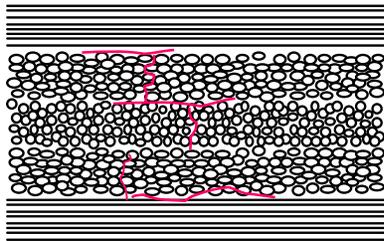
Damage occurred at 37,500 simulated flights, with a load enhancement factor of 1.15

Examples of fatigue damages that can be anticipated with composites

Intrinsic phenomenon, cannot be detected by NDT

Discrete phenomenon, can be detected by NDT

MATERIAL DEGRADATION

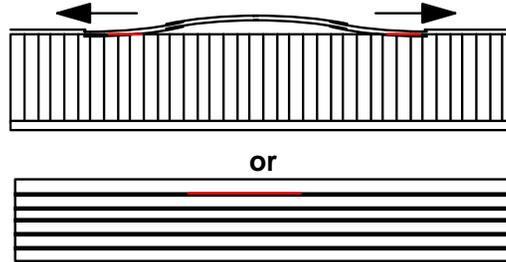


Trans. or interlaminar cracking



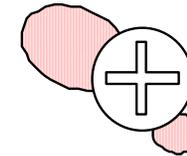
Fiber failure

MANUFACTURING FLAW EXTENSION



or

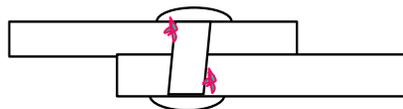
EDGE DELAMINATION



IMPACT DAMAGE EXTENSION



BORE CRUSHING



STRINGER PEELING

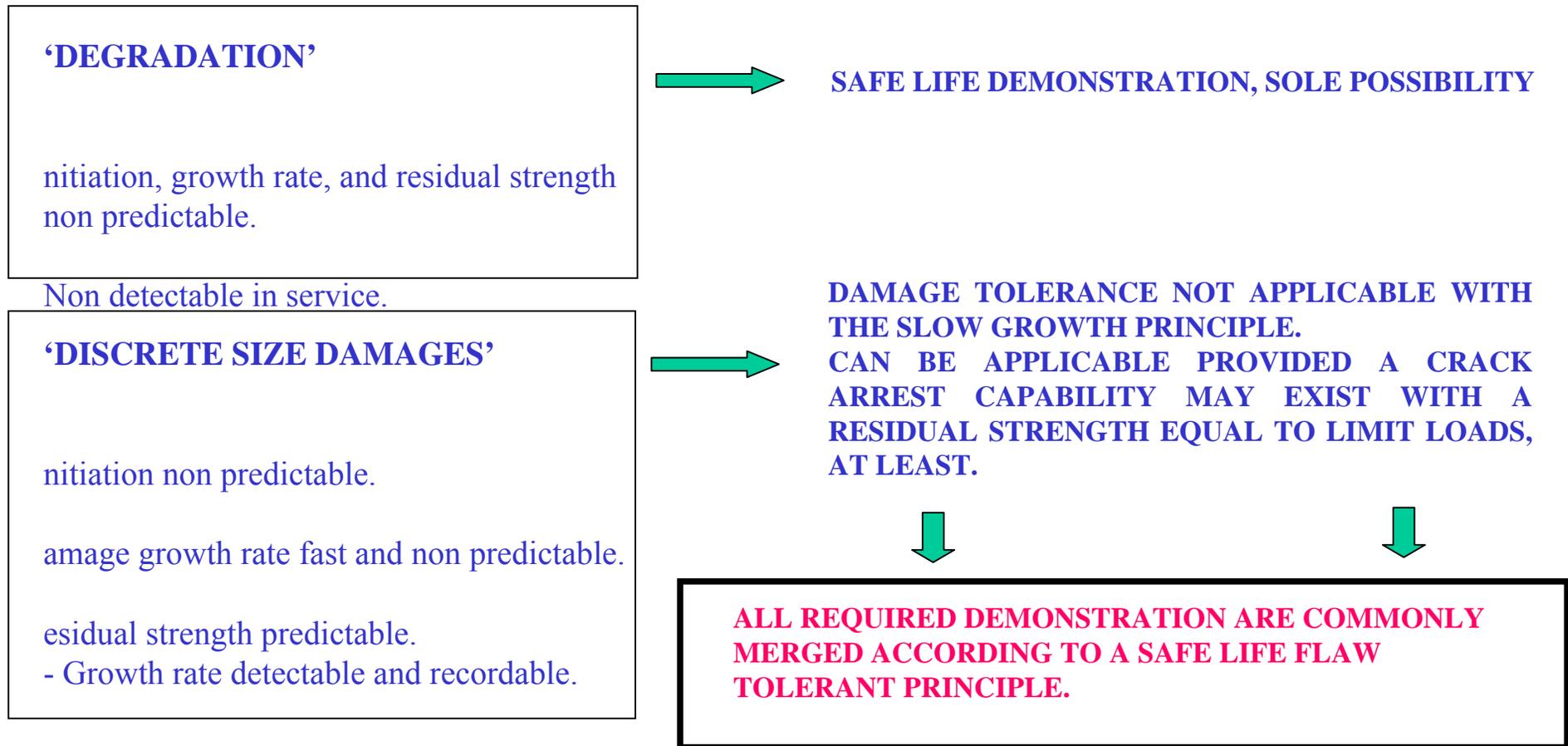


Certification philosophy with respect to composite fatigue

GENERAL STATEMENT : DESPITE COMPOSITE REPUTATION TO BE INSENSITIVE TO FATIGUE, NO MAJOR APPLICATION HAS BEEN CERTIFIED, IN EUROPE TILL AIRBUS A330/340, WITHOUT A FULL-SCALE FATIGUE TEST.

FATIGUE DAMAGE ARE ROGUE EFFECTS THAT MAY OCCUR AT DESIGN HOT SPOTS (MAINLY WHERE 3D STRESSES EXIST). ONLY A FULL-SCALE STRUCTURE INTEGRATING ALL DESIGN FEATURES SHOULD BE ABLE TO REVEAL THESE FATIGUE SENSITIVE AREAS.

Certification philosophy with respect to composite fatigue (Cont'd)



Principe of the Safe-Life, Flaw Tolerant, structure demonstration

TO PROVE THAT A STRUCTURE REPRESENTATIVE OF THE MINIMUM QUALITY - THAT MEANS WITH MAXIMUM TOLERATED MANUFACTURING DEFCTS AND DAMAGES - WILL BE ABLE TO WITHSTAND ULTIMATE LOADS ALL ALONG ITS SERVICE LIFE.

DUE TO THE LACK OF :

- CALCULATION MODEL ABLE TO PREDICT RESIDUAL STRENGTH,
- NDT METHODS ABLE TO REVEAL SOME MATERIAL DEGRADATION,

ULTIMATE LOADS CAPABILITY AFTER FATIGUE IS TO BE DEMONSTRATED BY TESTS

The differences in the Safe-Life approaches

FOR METALS :

The structure must be free of any detectable flaw until the end of lifetime.

Demonstrated through a full-scale fatigue test associated with an end-of-test inspection.

FOR COMPOSITES :

The structure must be free of any CRITICAL FLAW' DAMAGE OR DEGRADATION until the end of lifetime.

FULL-SCALE FATIGUE TEST + NDT + RESIDUAL STATIC TEST UP TO ULTIMATE LOADS



With a structure representative of the minimum quality



In the most adverse environmental conditions

Fatigue spectrum development for analysis and test purpose

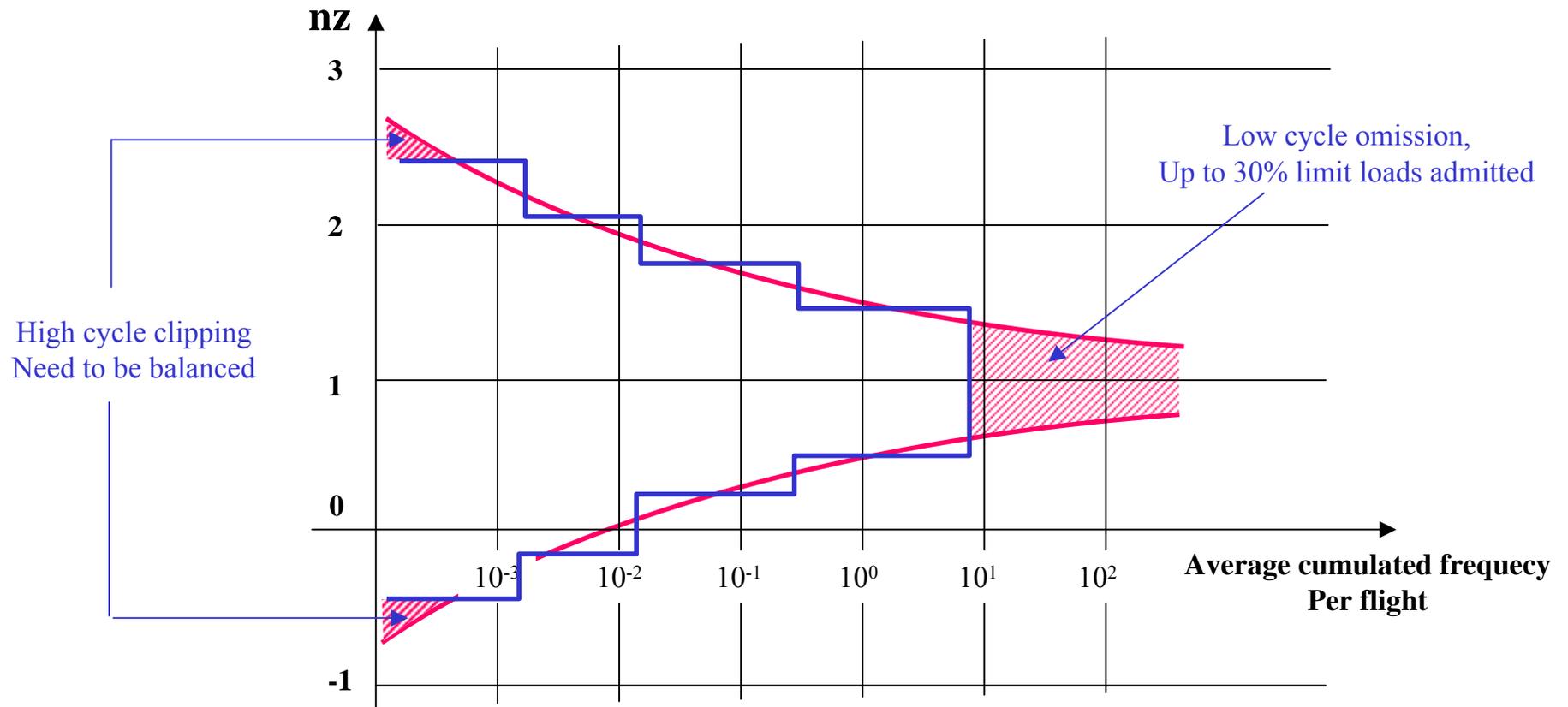
TRUNCATION LEVEL :

- Unlike metallic materials, high loads always assumed to be fatigue damaging and then cannot be ignored.
- In spectrum stepping (for simulation) high loads clipping is balanced by Limit Loads applications (most often, fatigue and static substantiations are performed with the same test article).

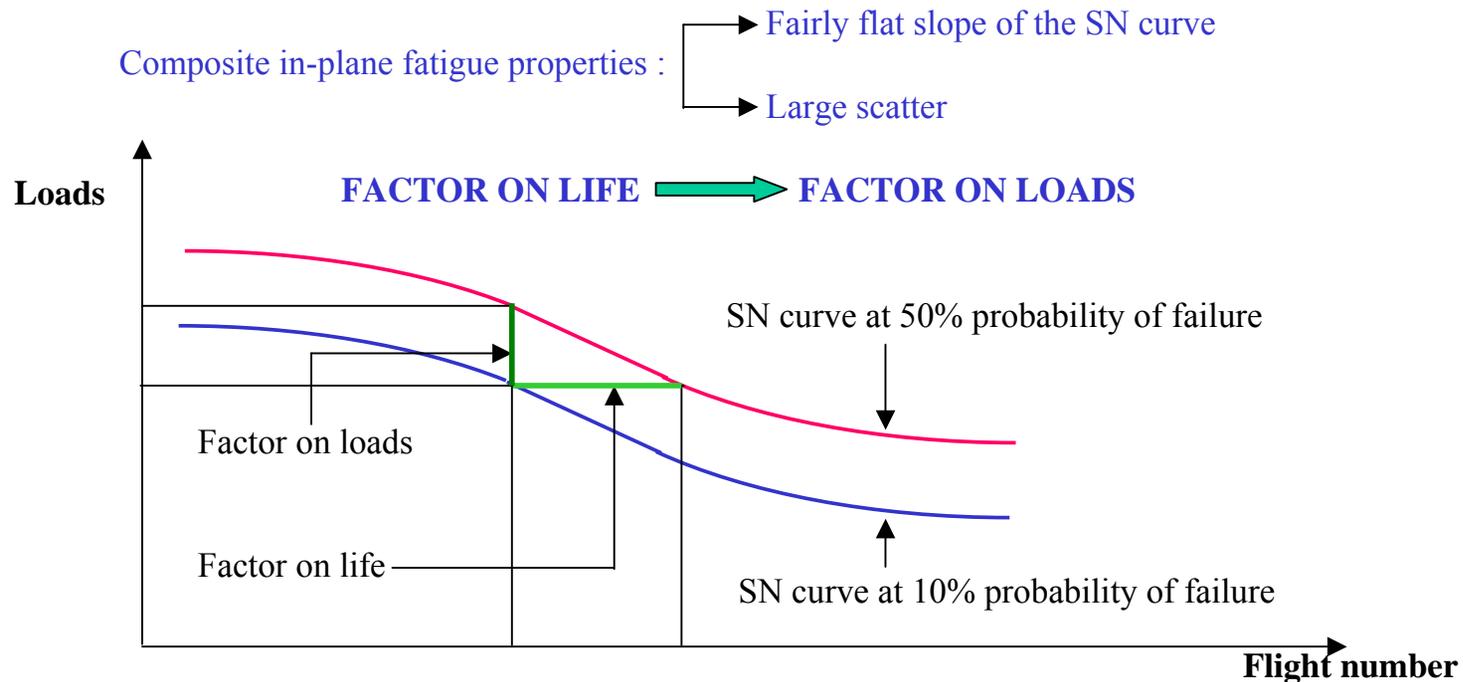
OMISSION LEVEL :

- Less important than for metallics (commonly 30% Limit Loads).

Fatigue spectrum development for analysis and test purpose (Cont'd)



Material scatter considerations



THE SCATTER FACTOR IS SELECTED IN SUCH A WAY TO COVER THE DIFFERENCE BETWEEN SN CURVES AT 50 AND 10% PROBABILITY OF RUPTURE, RESPECTIVELY.

THEN ULTIMATE LOAD CAPABILITY WILL BE DEMONSTRATED FOR A FATIGUE DEGRADED STRUCTURE, REPRESENTATIVE OF 90% OF THE POPULATION (WITH 95% CONFIDENCE).

Results of American FAA/DoD investigations on composite mechanical property scatter

Test variables : laminate lay-up, specimen geometry, loading mode, failure mode, test environment, spectrum variation and shape

REFERENCES :

- Whitehead, R.S., Kan, H.P., Cordero, R., Saether, E.S., "Certification testing methodology for composite structures. Volume 1 : Data analysis. Volume 2 : Methodology development" Northrop Corp. NADC-87042-60 Report. October 1986.
- Badaliane, R., Dill, H.D., "Compression fatigue life prediction methodology for composite structures", NADC-83060-60 volumes 1 & 2, September 1982.
- Whitehead, R.S., Schwartz, M.G., "The role of fatigue scatter in the certification of composites", ASTM, Williamburg, March 1982.

71 static test cases (1500 points), 120 fatigue test cases (2925 points) have been analysed

Results of American FAA/DoD investigations on composite mechanical property scatter (main findings)

- The ratio between fatigue and static scatter is higher for composites than for metals.
- Composite fatigue properties scatter is significantly higher than for light alloys.
- Composite static strength scatter is not significantly influenced by such parameters as : the loading mode, the specimen geometry, environment and the laminate lay-up.
- Composite fatigue properties scatter is not significantly influenced by the stress level, the laminate lay-up and the failure mode
- Composite fatigue properties scatter may be influenced by R ratio, specimen geometry and environment.
- Composite fatigue properties scatter in compression-compression is significantly higher than in tension-compression.
- Worst environment conditions (hot/wet) lead to a higher scatter than test performed at room temperature with as-received specimens.

COMPOSITE MECHANICAL PROPERTIES COMPLY WITH A WEIBULL PROBABILITY LAW

FOLLOWING SHAPE PARAMETERS (ALPHA)	= 20 in static strength (25 for metals) = 1.25 in fatigue life (7.5 for metals)	CAN BE ASSUMED TO REPRESENT THE MODAL VALUES
------------------------------------	--	--

The Weibull probability law

Cumulative survival probability function $F(X_o) = P(X \leq X_o) = 1 - e^{-\left(\frac{X_o}{\beta}\right)^\alpha}$

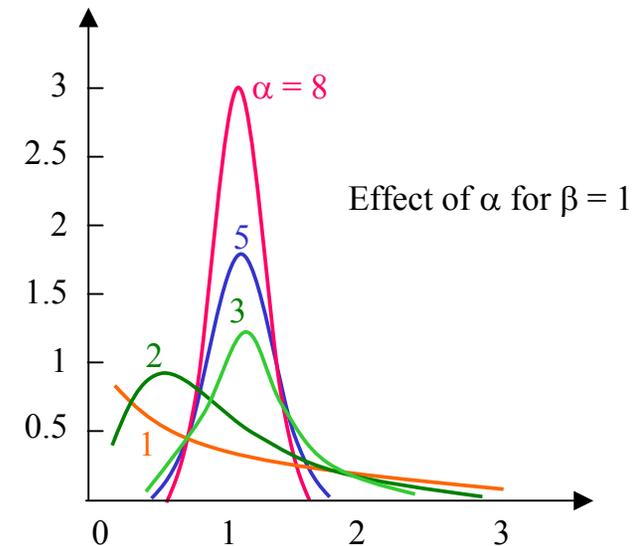
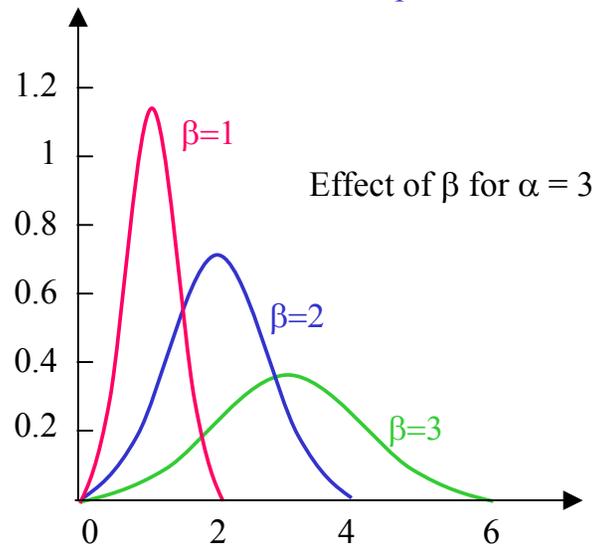
With :

x = Random variable

α = shape parameter (the higher α is, the less scattered the population)

β = characteristic value or scale parameter

Probability density function $f(x, \alpha, \beta) = \frac{\alpha}{\beta} \left(\frac{x}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^\alpha}$



Derivation of the scatter factor

Reference : NLR report TP 90068U : the use of load enhancement factors in the certification of composite aircraft structures, by J. Laméris

FACTOR ON LIFE

$$NF = \frac{\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)}{\left(\frac{-\ln(p)}{X_\gamma^2(2n)/2n}\right)^{1/\alpha_L}}$$

FACTOR ON LOADS

$$LEF = \frac{\left(\Gamma\left(\frac{\alpha_L + 1}{\alpha_L}\right)\right)^{\alpha_R}}{\left(\frac{-\ln(p).N^{\alpha_L}}{X_\gamma^2(2n)/2n}\right)^{1/\alpha_L}}$$

With :

$$\Gamma = \text{gamma function} = \int_0^{\infty} e^{-t} t^{(x-1)} dt$$

α_L = shape parameter modal value for the random variable 'Fatigue life'

n = number of test specimens

p = reliability level required at the γ level of confidence (=0.9 if it is a 'B' value)

$X_\gamma^2(2n)$ = chi 2 function at 2n degrees of freedom at the confidence level $\gamma = 0.95$

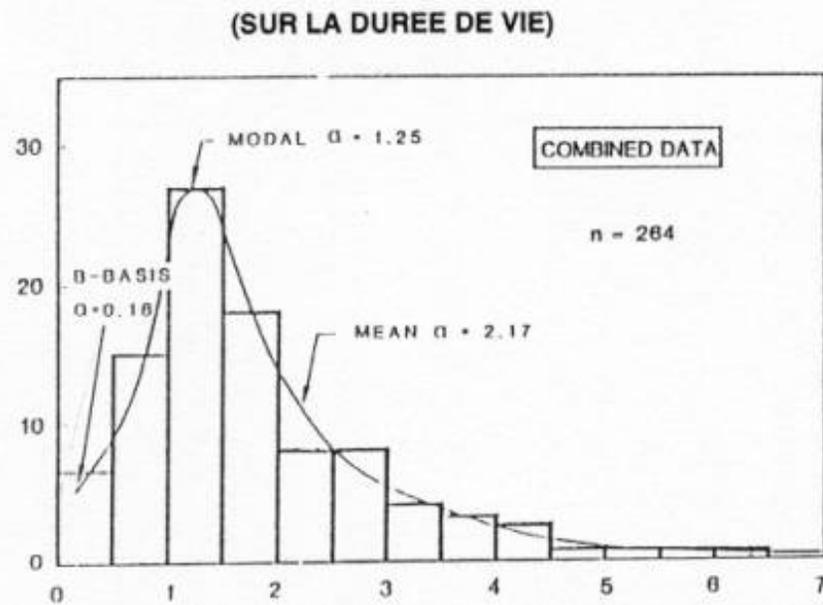
α_R = shape parameter modal value for the random variable 'Static strength'

N = test duration

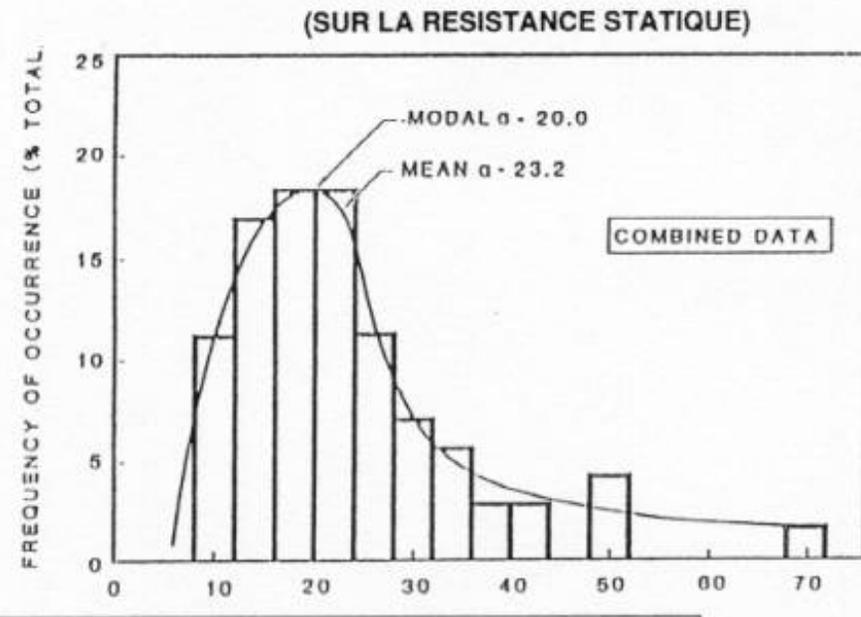
Derivation of the scatter factor (Cont'd)

Reference : NLR report TP 90068U : the use of load enhancement factors in the certification of composite aircraft structures, by J. Laméris

**MODAL VALUE OF THE SHAPE PARAMETER
(ON LIFETIME)**



**MODAL VALUE OF THE SHAPE PARAMETER
(ON THE STATIC STRENGTH)**



Typical factors used to cover scatter in fatigue

On the basis of the former assumptions :

- the safety factor must cover the difference between the SN curves at respectively 50% and 10% (B value) probability of failure,
- the Weibull probability law is the most representative of the composite statistical behaviour in fatigue,
- scatter is conservatively covered by assuming $\alpha = 20$ in static and $\alpha = 1.25$ in fatigue.

Calculations lead to : 13.3 on life or 1.17 on loads

Coefficients used for Airbus certification (1.15 on loads associated with 1.5 lives) lead to an equivalent level of confidence.

On the basis of fatigue results on materials and technological specimens actually representative of the structure under certification, lower factors can be accepted by the certifying agency.

Example of the ATR 72 outer wing : 1 life with 1.10 on the loads

Comparing metal / composite approaches to manage the fatigue issue

METAL

Fail-Safe design as far as possible.
Hunting for sharp angles and any stress raisers.

Stressing of all fatigue sensitive areas :
-for crack initiation,
-for crack propagation,
-for residual strength.

Economic Repair Life demonstration
(sensitivity to fatigue damage initiation).
Damage Tolerance demonstration
(assessment of crack growth rate and residual strength).

Scheduled inspection programme established for all structural significant items.

DESIGN LEVEL PRECAUTION

SIZING, STRESS CALCULATION

TEST SUBSTANTIATION

IN-SERVICE INSPECTION

COMPOSITE

Hunting for 3 D stresses (shape, stacking sequence).

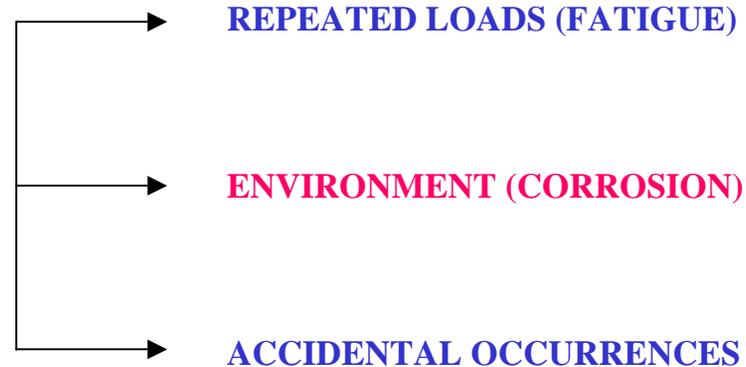
No fatigue calculation (except for propeller blades)

Fatigue demonstration of a flaw tolerant structure,
i.e. testing structure sensitivity to damage growth
(residual strength after fatigue)

No fatigue dedicated inspection only zonal
Inspection.

Fatigue / Damage tolerance requirements, as per CS or FAR 25-571, are applicable to all structures, regardless the material (metallic or composite)

THE DAMAGE TOLERANCE
EVALUATION MUST TAKE INTO
ACCOUNT THE EFFECTS OF



THE REMAINING STRUCTURE MUST BE ABLE TO WITHSTAND
REASONABLE LOADS UNTIL DAMAGE IS DETECTED

Allowing for corrosion/ageing

CORROSION :

Organic matrix composites are totally insensitive to corrosion, however, galvanic corrosion may be generated on the metal parts which are in contact with them.

Design level precautions : use interposition (insulating) materials (fibreglass, mastic, putting).

In-service inspection : zonal control.

AGEING (HUMID AGEING) :

Ageing is taken into account through the induced degradation due to moisture ingress.

Design level precautions :

- Design values and allowables are generated allowing for most adverse conditions.
- Fatigue is commonly demonstrated with a structure at least representative of a minimum aged condition (60% of the moisture content target).

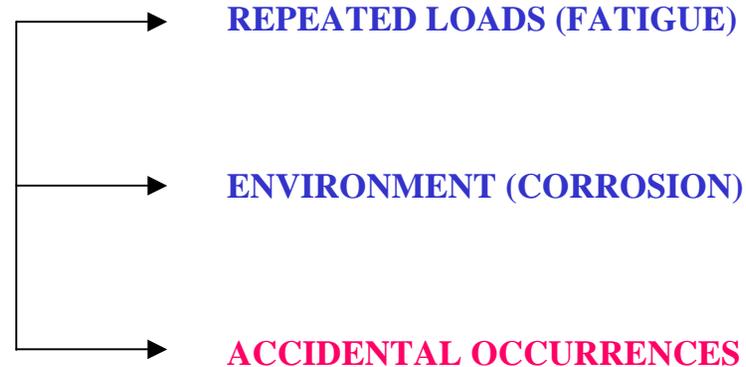
In-service inspection :

- Solid laminate : no control possible.
- Sandwich : zonal, NDT special, tap-check, ultrasonic.

CAUTION : UNLIKE SOLID LAMINATE CONSTRUCTION WHICH HAS, SO FAR, DEMONSTRATED A GOOD BEHAVIOUR IN REGARD TO HUMID AGEING, SANDWICH CONSTRUCTION PROVED TO BE MORE QUESTIONABLE IN THIS RESPECT.

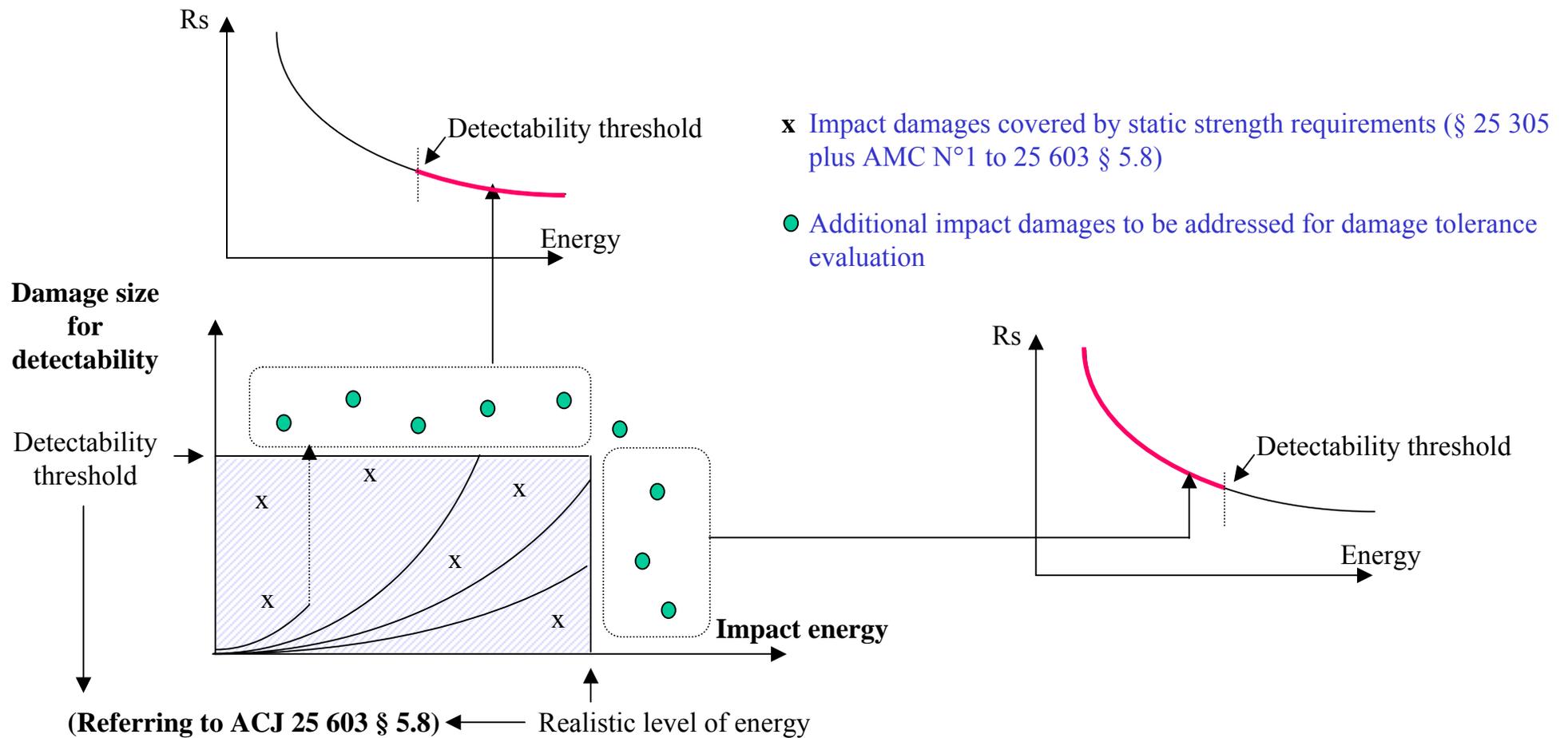
Fatigue / Damage tolerance requirements, as per CS or FAR 25-571, are applicable to all structures, regardless the material (metallic or composite)

THE DAMAGE TOLERANCE
EVALUATION MUST TAKE INTO
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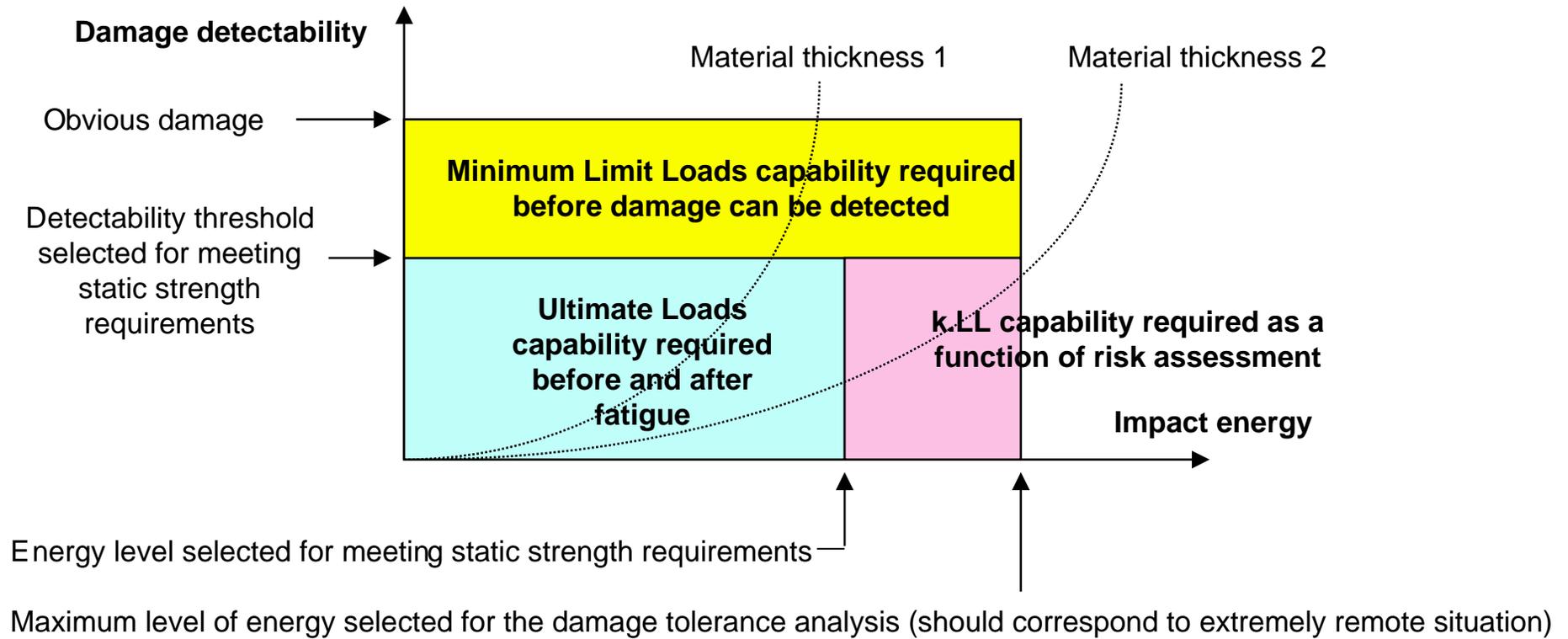


THE REMAINING STRUCTURE MUST BE ABLE TO WITHSTAND
REASONABLE LOADS UNTIL DAMAGE IS DETECTED

The domain of Damage Tolerance evaluation



Regulatory loads for Damage Tolerance evaluation



Fatigue / Damage Tolerance evaluation, acceptable means of compliance proposed by the AMC N°1 to CS 25.603

§ 6.2 Damage tolerance (fail-safe) evaluation.

6.2.1 : Structural details, elements, and subcomponents of critical structural areas should be tested under repeated loads to define the sensitivity of the structure to damage growth. This testing can form the basis for validating a no-growth approach to the damage tolerance requirements. The testing should assess the effect of the environment.....

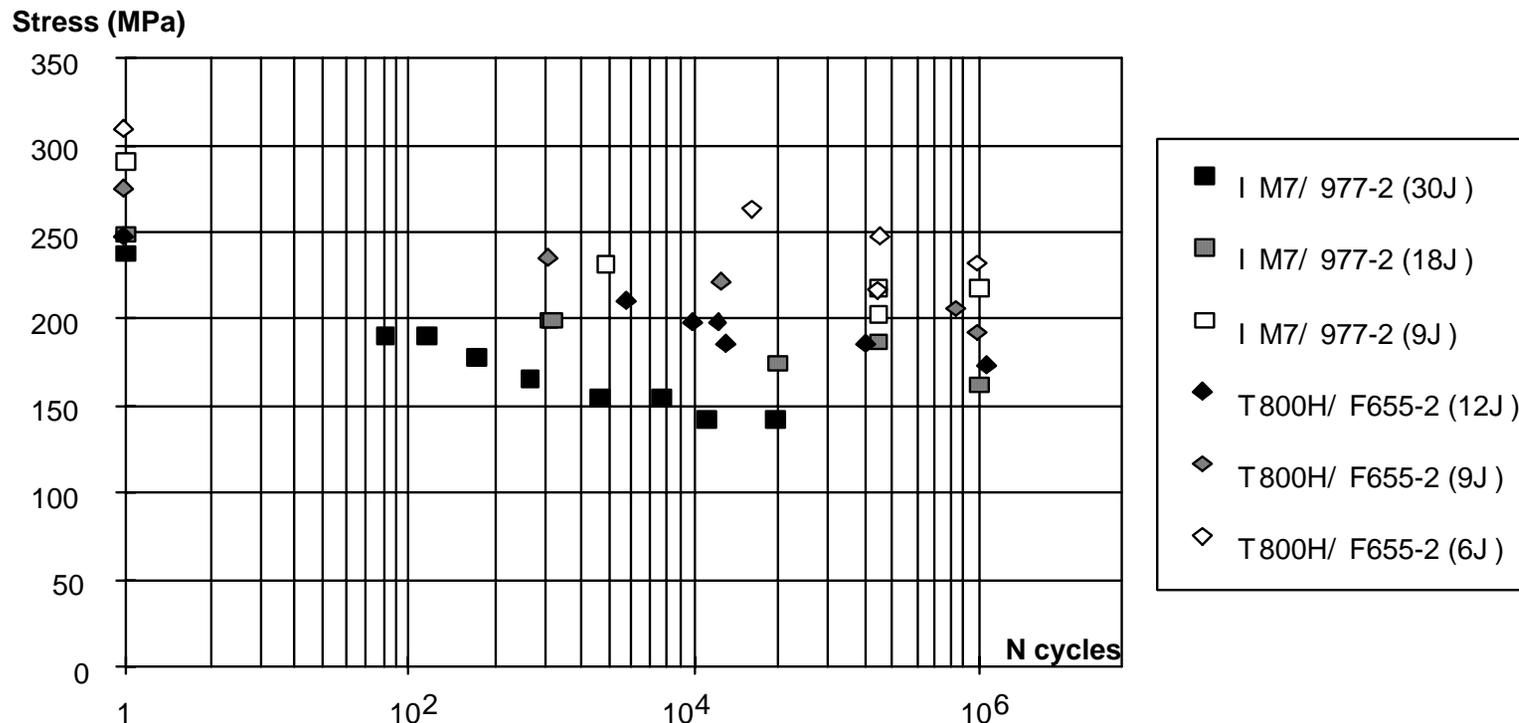
.....The repeated load testing should include damage levels (including impact damage) typical of those that may occur during fabrication, assembly, and in service, consistent with the inspection techniques employed.

6.2.2 :

.....The number of cycles applied to validate a no-growth concept should be statistically significant, and may be determined by load and/or life considerations. 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.....

Fatigue behaviour of impacted solid laminates in compression-compression, R = 10

Real world stacking sequence, impact at BVI D level

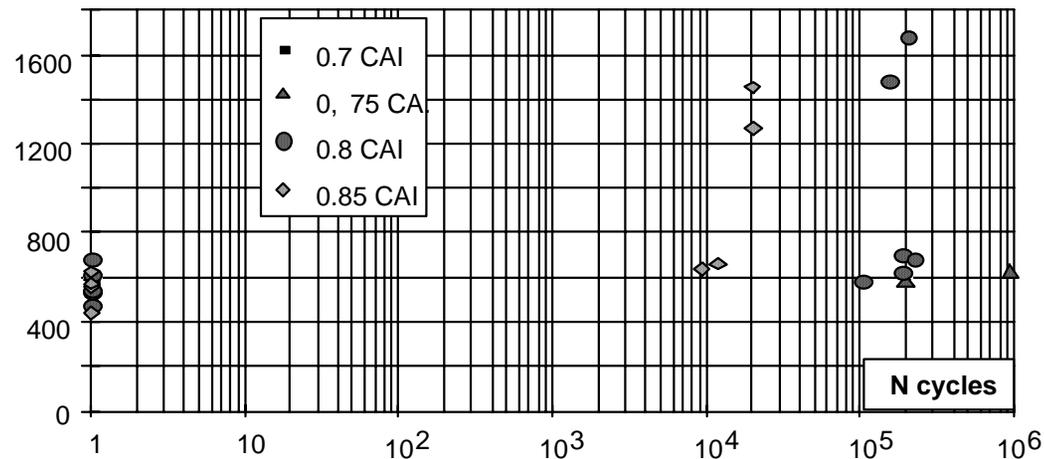


Fatigue behaviour of impacted solid laminates Damage growth or not growth ?

Example : T800/F655-2 material, impacted at 6 joules (around the BVID).

Constant amplitude fatigue testing at various ratios of the compression after impact (CAI) strength

Delaminated area (mm^2)

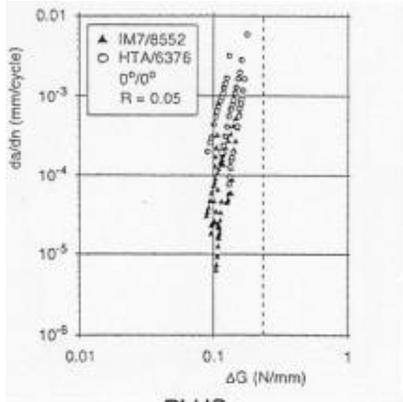


LESSONS LEARNED :

- High constant amplitude stress values (>0.75 CAI) are there required to obtain any damage extension :
- **THE NO-GROWTH APPROACH IS THEN THE MORE LIKELY SITUATION**
- When damage can develop, growth rate is very high.

Growth or no-growth approach ?

Test results have shown that slopes of da/dN versus ΔG curves are very high (example : FFA results obtained in the framework of a GARTEUR programme):



PLUS :

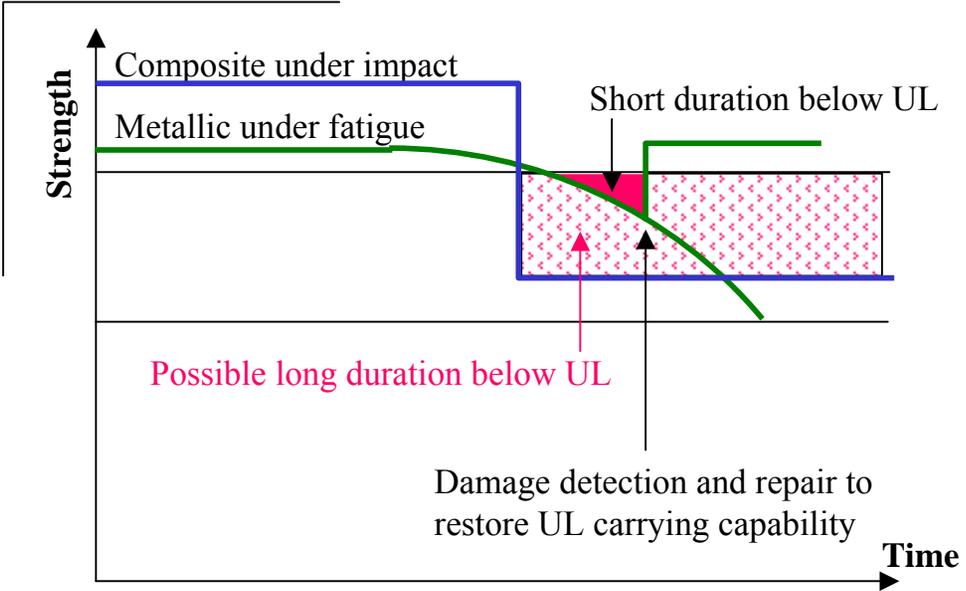
There are not validated tools to predict damage growth in composites

THEN :

DAMAGE TOLERANCE SUBSTANTIATION BASED ON DAMAGE STABLE GROWTH SHOULD NOT BE ACCEPTED BY CERTIFICATION



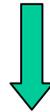
THERE IS A NEED FOR A PROBABILISTIC APPROACH



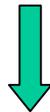
AMC N°1 to CS 25.603 § 6-2-4 : ‘In selecting the intervals, the residual strength associated with the assumed damage should be considered’
But also the probability of occurrence.

The problem of selecting inspection intervals
(for accidental damage likely to reduce static strength below ultimate loads)

THE LARGER STRENGTH REDUCTION IS, THE EARLIER DAMAGE SHOULD BE DETECTED



THE MORE LIKELY DAMAGE MAY OCCUR / THE EARLIER IT SHOULD BE DETECTED



NEED FOR A PROBABILISTIC APPROACH

Probabilistic approach principle for accidental damage associated with the no-growth concept

THE PROBABILITY OF ENCOUNTERING THE COMBINATION OF A DAMAGE REDUCING THE STRUCTURE STATIC STRENGTH DOWN TO ($k \times LL$) AND A GUST OR A MANEUVER OF THE SAME INTENSITY MUST BE EXTREMELY IMPROBABLE (10^{-9})

*Figure (per flight hour) drawn from CS 25 1309 for the definition of extremely improbable.

Probabilistic approach, an example of application

LET :

Pa = probability to have an accidental damage at the end of a unity of aircraft utilization (e.g. one flight hour).

n = inspection interval expressed with same unity of aircraft utilization.

The probability to have at least one accidental damage at the last flight preceding the inspection is :

$$1 - (1 - Pa)^n$$

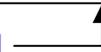
$$\approx n \cdot Pa \text{ (first term of the development, if } n \cdot Pa < 0.1)$$

Pr = probability of occurrence of the flight load (e.g. gust), the intensity of which combined with the accidental damage of probability **Pa** would lead to a catastrophic failure.

The combination of both events should be extremely remote :

$$Pr \cdot n \cdot Pa \leq 10^{-9}$$

maximum risk at the last flight of the interval



*This example is based on an analogy with the failure of a system interacting with structural performances.

Probabilistic approach, an example of application (Cont'd)

Gust and maneuver statistics show an approximately log/linear relationship between probability of occurrence and intensity, within the interval Limit Loads – Ultimate Loads

Examples for the rudder and the vertical fin of the A 340 (Airbus assumptions)

Gust probabilities :

- of Limit Loads : 10^{-5}

-of Ultimate Loads : $2.23 \cdot 10^{-9}$

Maneuvers probabilities :

-of Limit Loads intensity : $3 \cdot 10^{-5}$

-of Ultimate Loads intensity : $9.9 \cdot 10^{-9}$

Probabilistic approach an example of application (Cont'd)

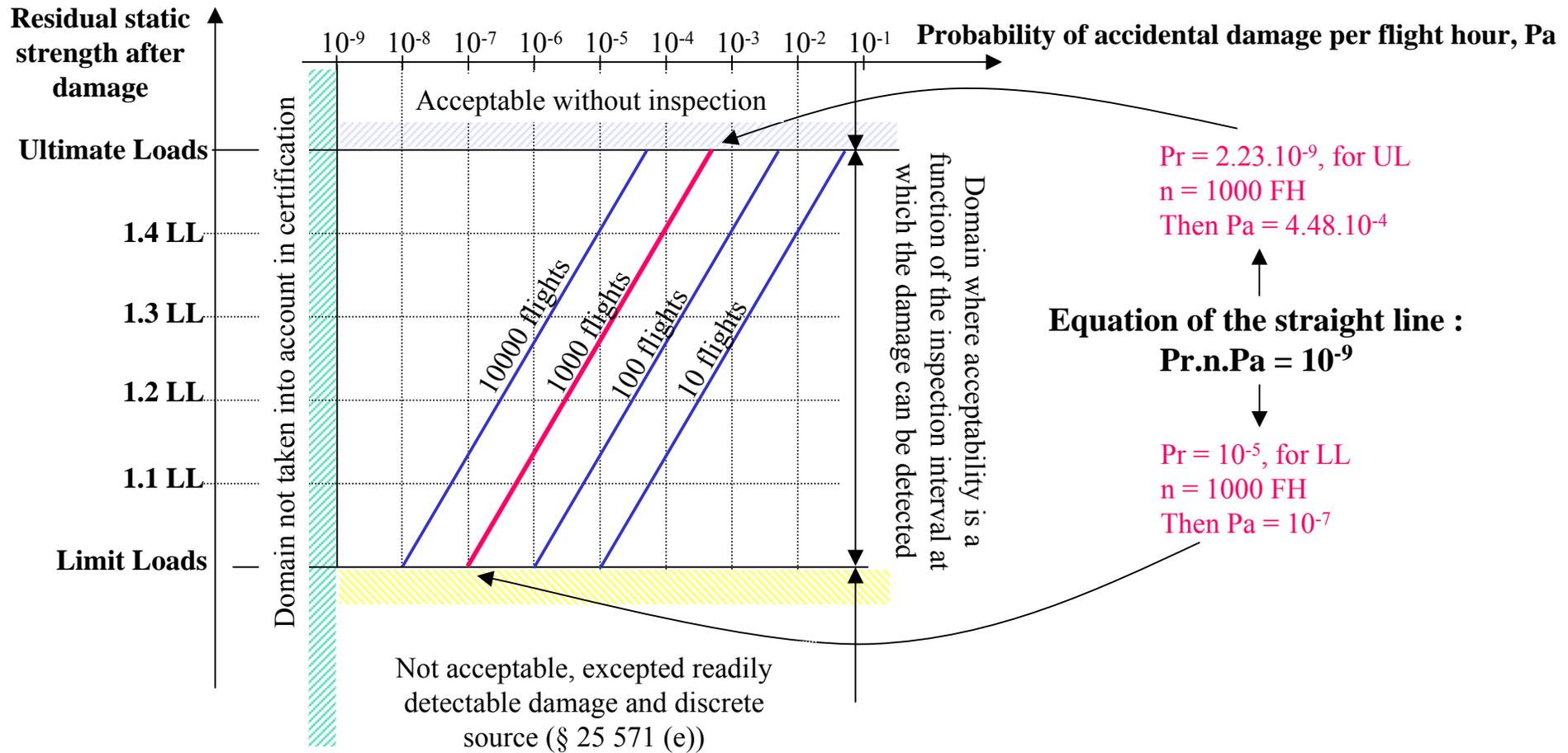
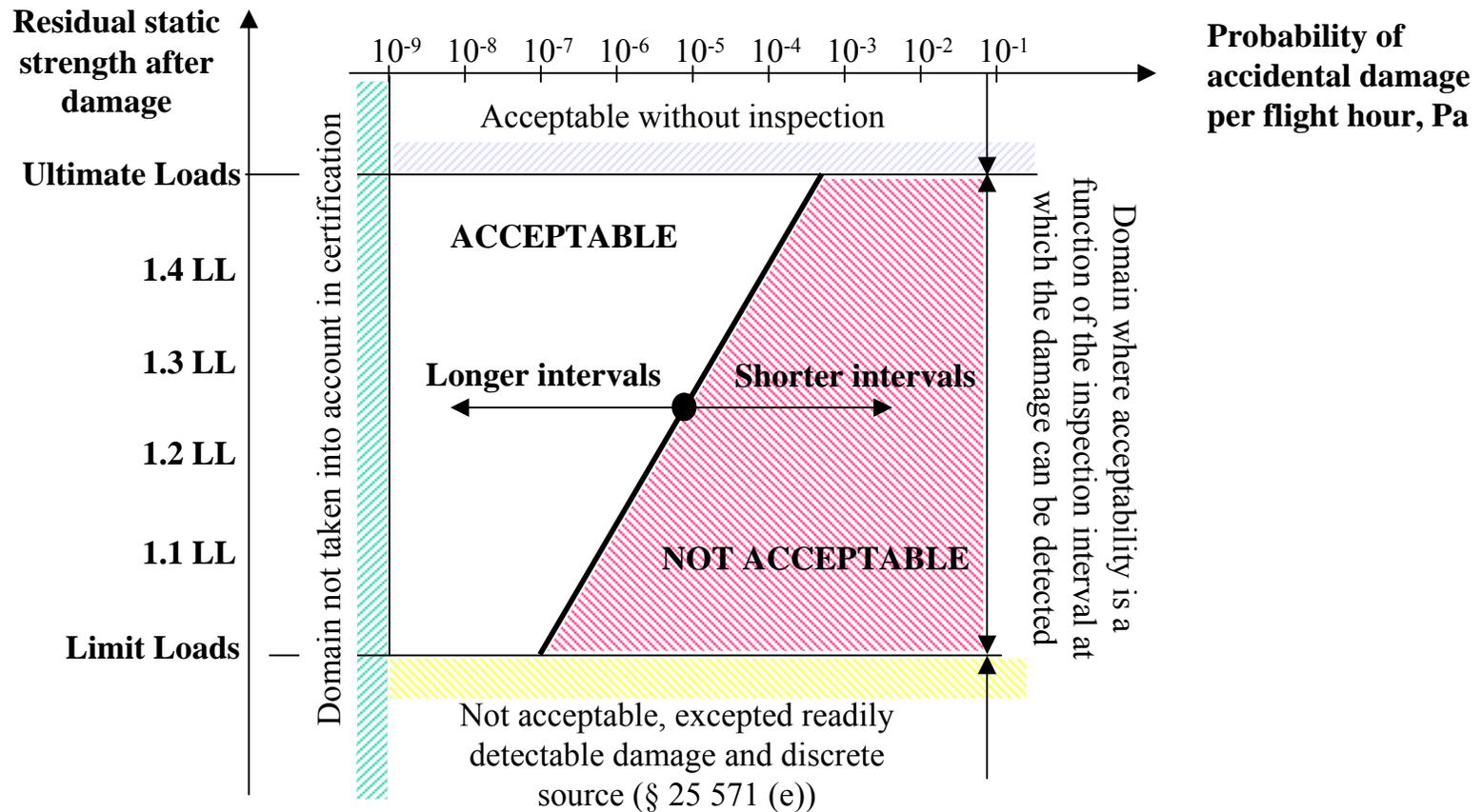


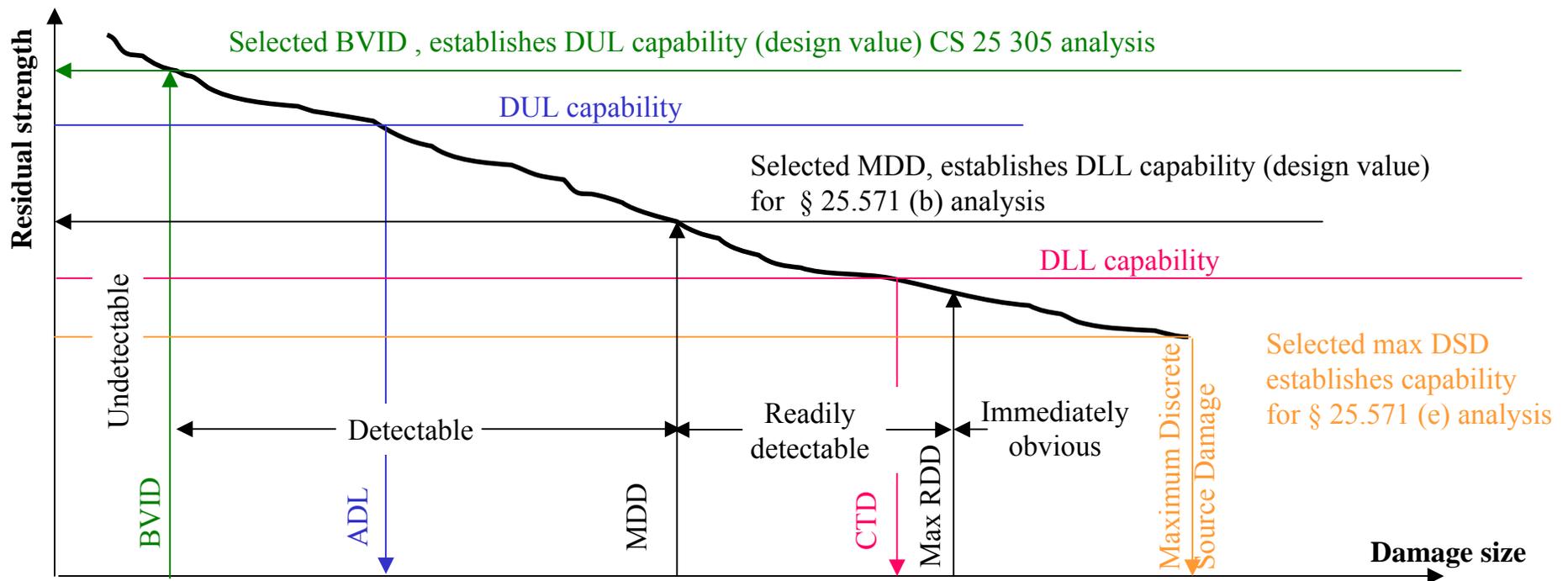
Illustration of the probabilistic approach with the assumption of a log-linear relationship between the probability of gust occurrence and intensity between LL and UL



Implementation of a probabilistic approach to comply with damage tolerance requirements

- The fundament of structure airworthiness requirements is of a deterministic nature.
- A probabilistic approach can be accepted, only, if there is no possible way to show compliance through a deterministic approach.
- Such probabilistic approach for composites has been, so far, used to a limited extent.
- Assuming conservative energy levels for showing compliance with Ultimate Loads static strength requirement can naturally provide an acceptable damage tolerance capability.
- In addition to that, there is a need to demonstrate the ‘large damage capability’ of the structure, in simulating by analysis the consequences of large cuts in the structure.

Compliance with static strength and damage tolerance requirements Deterministic method (Boeing)



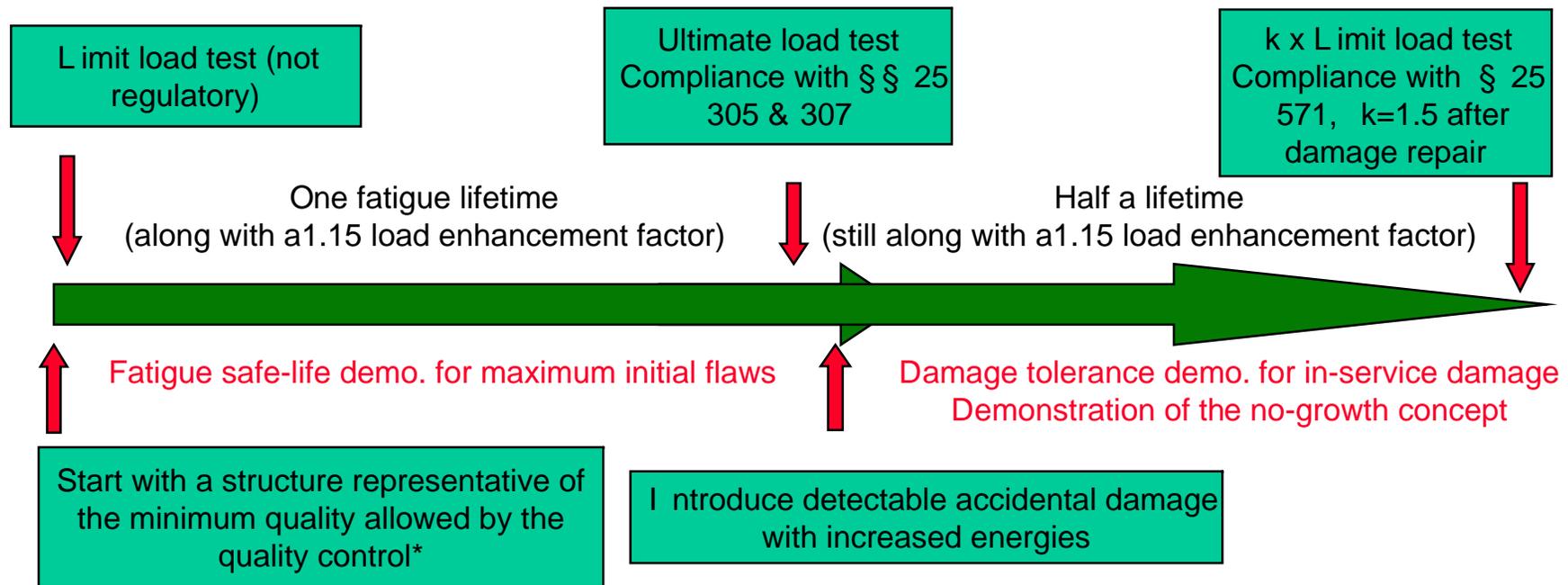
ADL : Allowable Damage Limit (damage size and state which reduces strength to design ultimate loads).

CTD : Critical Damage Threshold (damage size and state which reduces strength to design limit loads).

MDD : Maximum Design Damage.

RDD : Readily Detectable Damage.

Current practice for composite Static and Fatigue /DT demo. with a single test article



- Residual static strength is demonstrated allowing for worst environmental conditions
- Fatigue test performed on a quasi-moisturised structure (60% of the maximum moisture content, condition more and more relaxed)

-* Artificial manufacturing defects representative of voids, porosities, delaminations must be deliberately introduced in the most stressed areas, along with tolerable low velocity accidental damage

Chapter 10 – Lightning strike protection

Regulatory requirements addressing ‘Lightning strike protection’

BASIC RULES (e.g. CS or FAR 25)

ACCEPTABLE MEANS OF COMPLIANCE

CS 25.581 : LIGHTNING PROTECTION

AMC 25.581 : Lightning protection

(a) The aeroplane must be protected against catastrophic effects from lightning. (See CS 25x899 and AMC N°1 to CS 25.603).

(1) External metal parts.....

(b) for metallic components.....

(2) External non-metallic parts.

(c) For non metallic components, compliance with sub-paragraph (a) of this paragraph may be shown by :

2-1 External non-metallic parts should be so designed and installed that
a - They are provided with effective lightning diverters which will safely carry the lightning discharges described in EUROCAE document ED-84 (including Amendment N°1 dated 06/09/99) titled : Aircraft Lightning Environment and Related Test Waveforms, or equivalent SAE ARP5412 document.

(1) Designing the components to minimize the effects of a strike; or

b - Damage to them by lightning discharges will not endanger the aeroplane or its occupants, or

(2) Incorporating acceptable means of divert the resulting electrical current so as not to endanger the aeroplane.

c - A lightning strike on the insulated portion is improbable because of the shielding afforded by other portions of the aeroplane.

Where lightning diverters are used the surge carrying capacity and mechanical robustness of associated conductors should not at least equal to that required for primary conductors.

Concerns radomes

2-2 Where unprotected non-metallic parts are fitted externally to the structure, etc. etc.

Regulatory requirements addressing ‘Lightning strike protection’ (Cont’d) : The Advisory Circular AC 20-53A

TITRE : Protection of Airplane Against Fuel Vapor Ignition Due To Lightning

Purpose

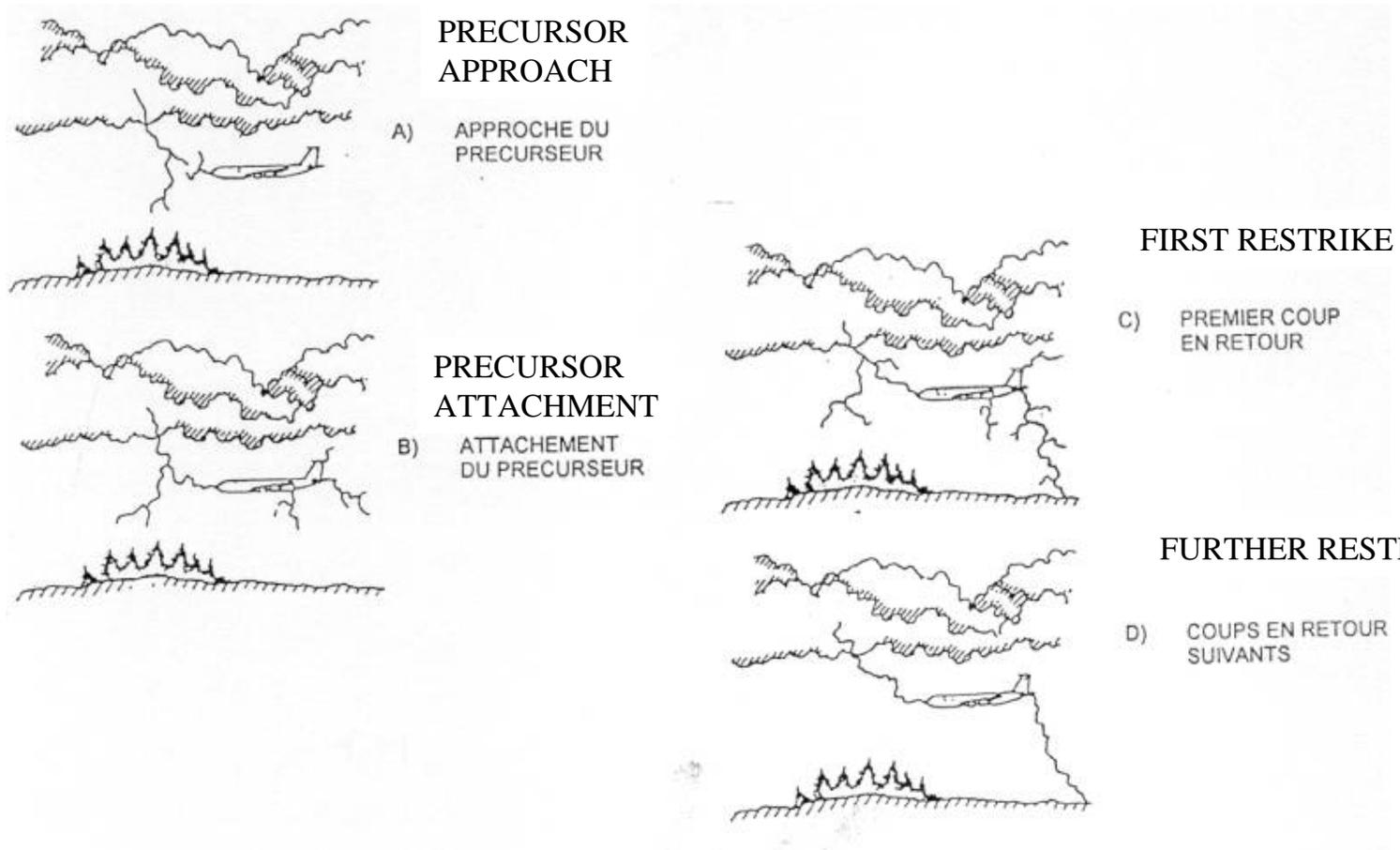
This advisory circular (AC) provides information and guidance concerning an acceptable means, but not the only means, of compliance with part 23 or 25 of the Federal Aviation Regulation (FAR), applicable to preventing ignition of fuel vapors due to lightning. Accordingly, this material is neither mandatory nor regulatory in nature and does not constitute a regulation. In lieu of following this method, the applicant may elect to establish an alternate method of compliance that is acceptable to the FAA for complying with the requirements of sections 23 954 and 25 594.

For what concern rotorcraft :

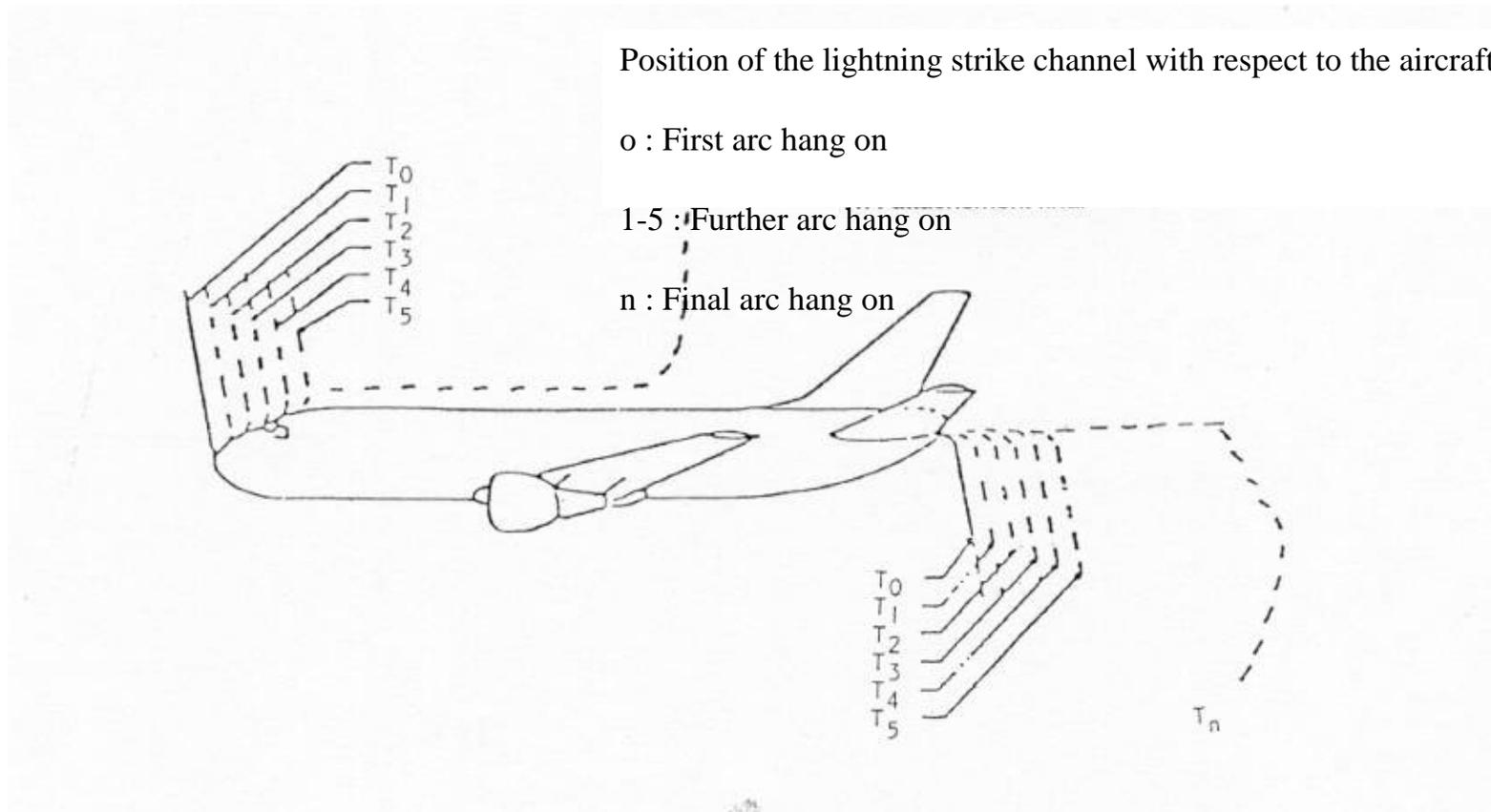
The AC 20-53A does not specifically refer to rotorcraft..

The § 29 610 of the FAR 29 code does not mention any advisory circular.

How an aircraft can be struck by lightning



How a lightning strike can sweep on an aircraft



Composite attributes with respect to lightning strike

CONCERN : MATERIAL ELECTRICAL RESISTANCE 1000 TIMES GREATER THAN ALUMINIUM ONE.

RECALL : Statistically, a transport category aircraft may suffer a lightning strike once a year.

CONSEQUENCES :

DIRECT EFFECTS :

- local destruction of the material that may sometimes lead to large skin puncture (thermomechanical damage).

These damages must comply with § 25-571, discrete source case (typically 70% Limit Loads for maneuvers and 40% Limit Loads up to V_c for gusts).

- arcing, sparking or hot spot inside a fuel tank.

INDIRECT EFFECTS :

- induced perturbations in wiring and equipments, due to the low electromagnetic screening properties of the structure.

Compliance with the required robustness of the equipments with respect to electromagnetic radiations (HIRF) has to be shown

Composite structure zoning against lightning strike direct effects

ZONE 1 : Surfaces of the vehicle for which there is a high probability of initial lightning flash attachment. Typically the wing and empennage tips, the nacelles, the tail cone.

ZONE 2 : Surfaces of the vehicle across which there is a high probability of lightning flash being swept by the airflow from a zone 1 point of initial flash attachment.

ZONE 3 : All of the vehicle areas other than those covered by zone 1 and 2 regions. In zone 3, there is a low probability of any direct attachment of the lightning flash arc. However, zone 3 may carry substantial electric currents by conduction between some pair of initial or swept stroke attachment points.

Zones 1 and 2 may be further separated in 'A' and 'B' regions.

A : Low probability of lightning arc channel hang on.

B : High probability of lightning arc channel hang on.

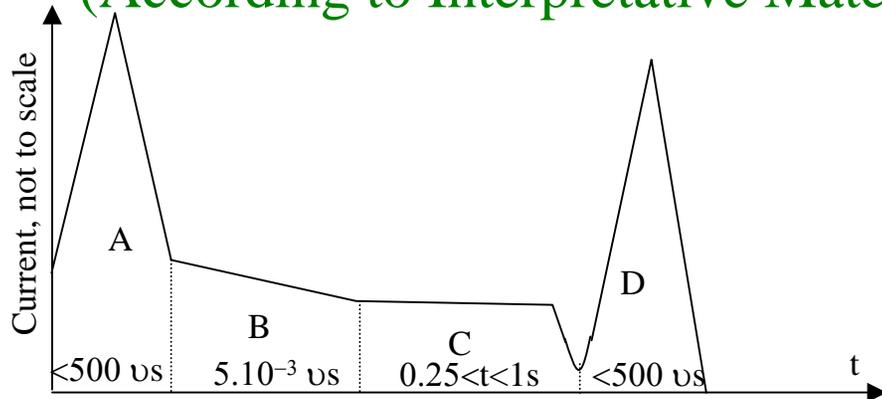
Zone 1A : Typically the leading edges.

Zone 1B : Typically the trailing edges.

Zone 2B : Typically the surfaces directly aft zone 1.

Current waveform for simulation purpose

(According to Interpretative Material S31, Airbus A330/340 certification)



Current component

A
Initial stroke

Peak amplitude = 200 kA +/- 10%
Action integral = $0.25 \times 10^6 A^2 s$ +/- 20%
Time duration < 500 μs

B
Intermediate Current

Maximum charge transfer = 10 coulombs
Average amplitude = 2kA +/- 10%

C
Continuing Current

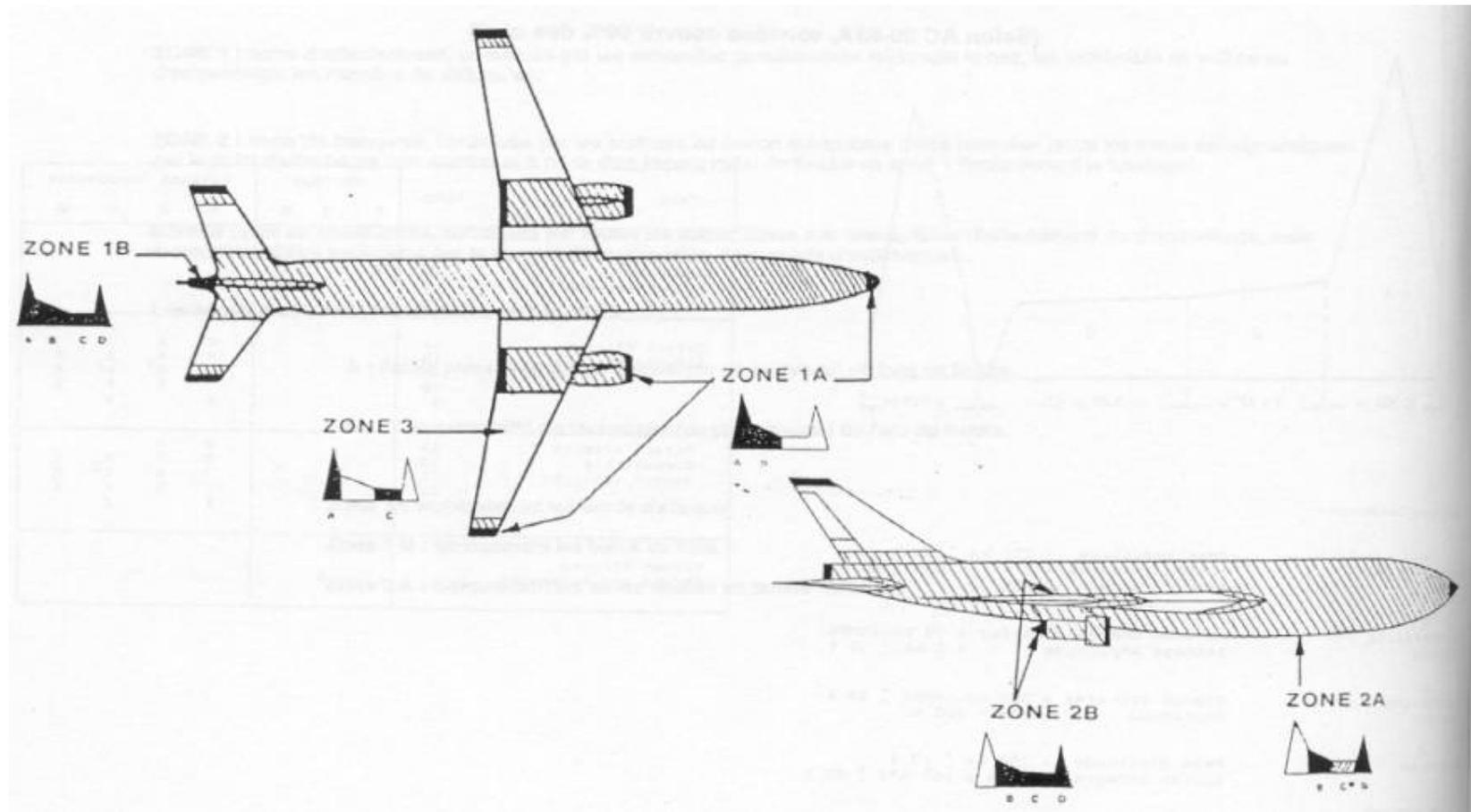
Charge transfer = 200 coulombs +/- 20%
Amplitude = 200, 800 A

D
Restrike

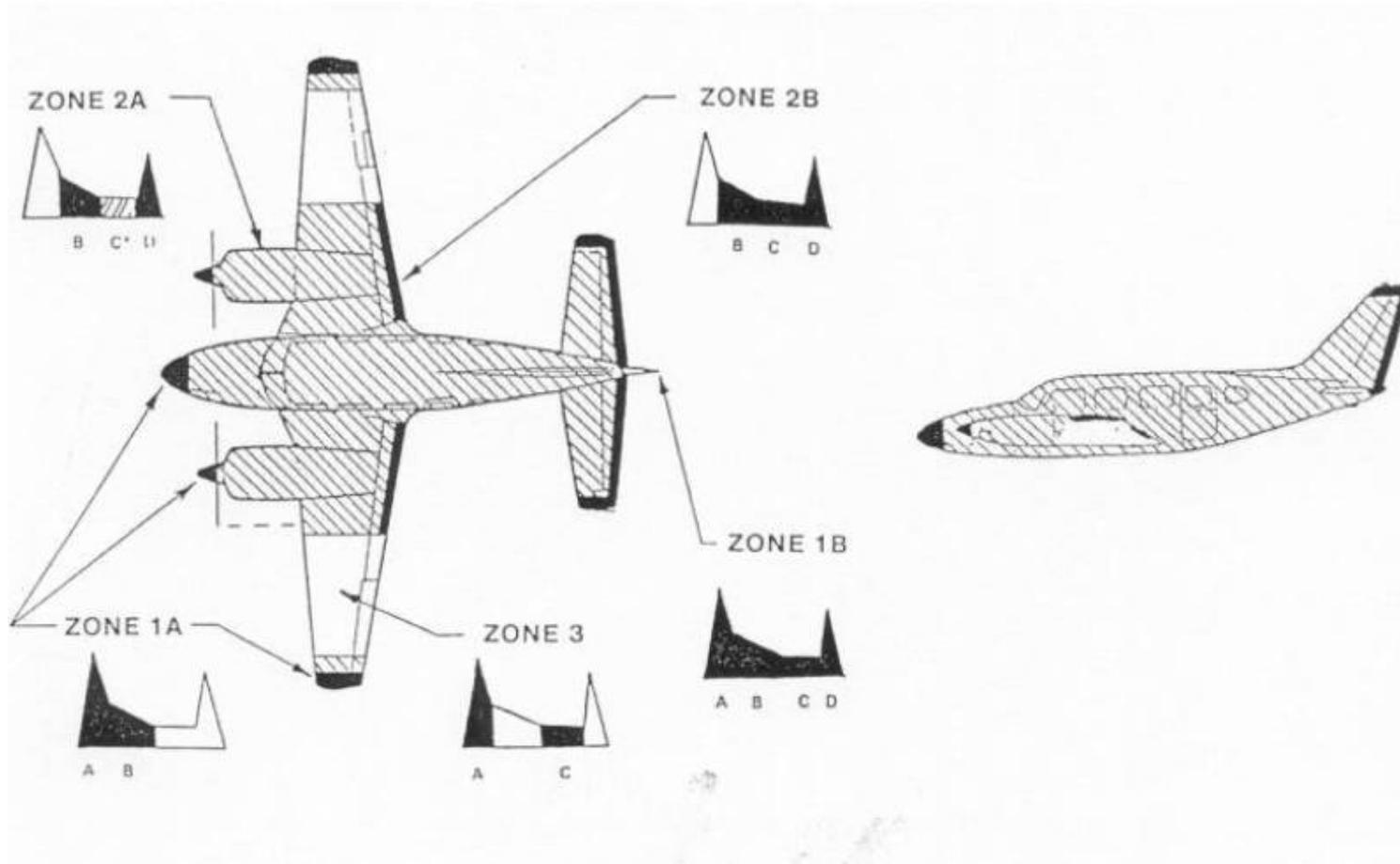
Peak amplitude = 100kA +/- 10%
Action integral = $0.25 \times 10^6 A^2 s$ +/- 20%

Test	Zone	Voltage			Current Components			
		A	B	D	A	B	C	D
Full size Hardware Attachment point	1A, 1B	x		x ¹				
Direct effects Structural	1A 1B 2A 2B 3				x	x		
Direct effects combustible Vapor ignition	1A 1B 2A 2B 3				x	x	x	x
						x ²	x ²	x
						x	x	x
					x		x	
Direct effects Corona and streamers			x					

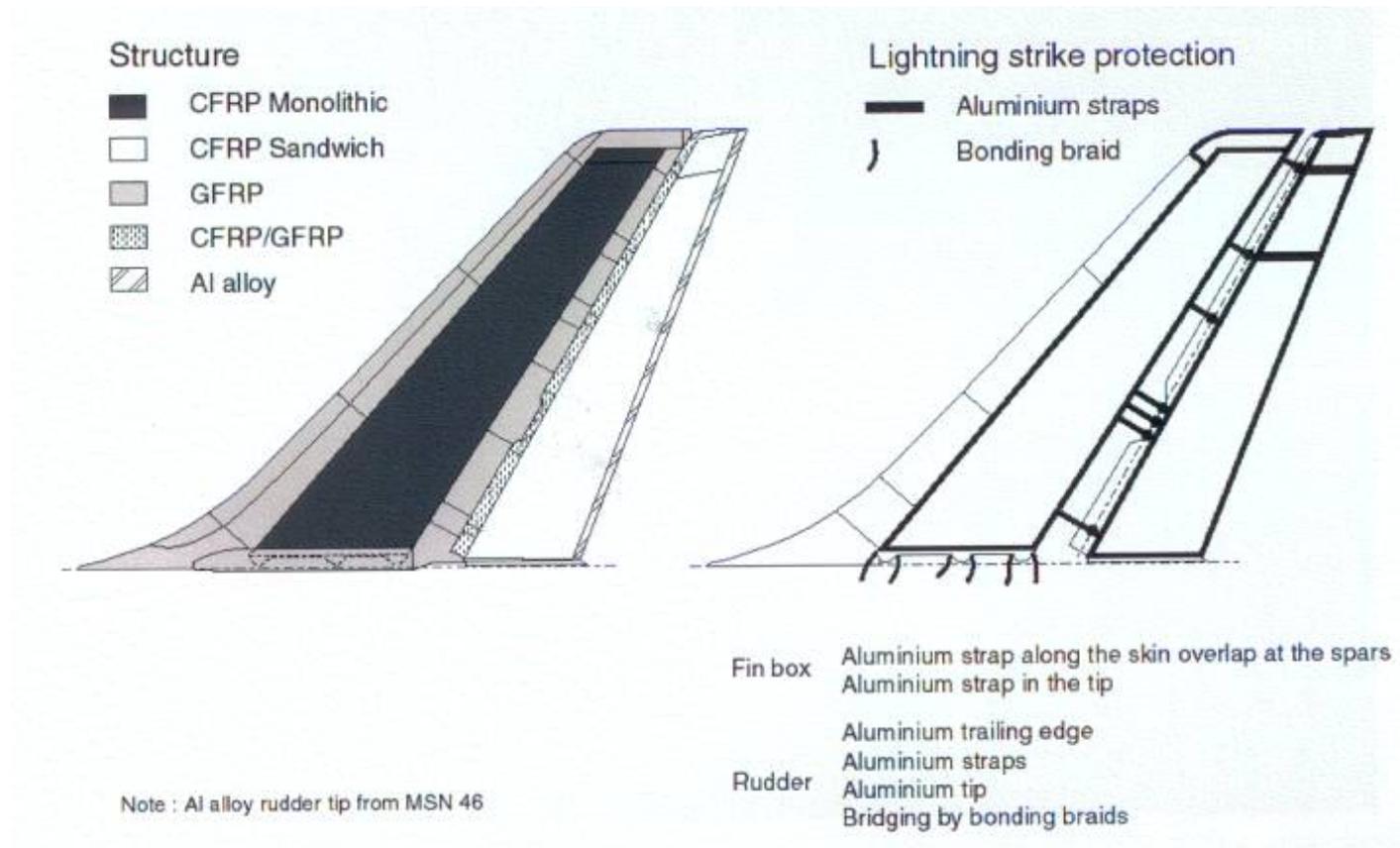
Example of zoning for a JAR 25 aircraft (Ref. : AC 20-53A)



Example of zoning for a JAR 23 aircraft (Ref. : AC 20-53A)



Example of protection against direct effects (Airbus courtesy)





Chapter 11 – Continued airworthiness, inspection and repairs

Regulatory requirements addressing continued airworthiness and repairs

BASIC RULES (FAR or JAR 25)

§ CS25.1529 : Instructions for continued airworthiness

Instructions for Continued Airworthiness in accordance with appendix H must be prepared.



Appendix H establishes that the aircraft must have a maintenance manual together with associated procedures. Moreover, a specific 'Airworthiness Limitation Section' is required. This section is intended to specify the inspection intervals or retirement lives in fatigue in accordance with CS 25.571.

ACCEPTABLE MEANS OF COMPLIANCE (AMC N°1 to CS 25.603)

§ 8.7 INSPECTION AND MAINTENANCE

Maintenance manuals developed by manufacturers should include appropriate inspection, maintenance and repair procedures for composite structures.

§ 8.8 SUBSTANTIATION OF REPAIRS

When repairs procedures are provided, it should be demonstrated by analysis and / or test that methods and techniques of repairs will restore the structure to the airworthy condition.

Airworthiness Limitations (ALI's) applicable to composite structures

In relation to fatigue safe life :

Unlike some helicopter rotating parts, or propeller blades, CS 25 composite structures do not require fatigue limitations.

In relation to environmental effects :

Zonal inspection, visual or detailed, for those possible corroded parts on metallic matching surfaces, or sandwich structures. Special inspection in case of finding.

It is not at all usual to check the moisture ingress of solid laminates.

In relation to accidental damages :

Limitations are linked to the damage detectability threshold assumptions accounted for in the damage tolerance evaluation, plus the result of a hazard analysis if a probabilistic approach has been used for this evaluation.

Airworthiness Limitations (ALI's) applicable to composite structures (Cont'd)

In relation to accidental damages (cont'd) :

The selection of the scheduled inspection procedure ‘ **General visual** ’ or ‘ **Detailed** ’ establishes the detectability threshold to be accounted for in this procedure:

- If ‘ **detailed** ’ : around 0.5 mm dent depth (Airbus has justified 0.3mm, which means 1mm initial to take dent relaxation into account).
- If ‘ **General visual** ’ : around 2 mm dent depth (Airbus has justified 1.3mm, which means 2.5 mm initial to take dent relaxation into account).

Up to this damage size, Ultimate loads capability must have been demonstrated.

Effectively, any structure definitely released after such inspection is reputed to meet the regulatory loads as per 25 301 et 305.

On the other hand, any damage that might decrease the residual strength below limit loads should be detectable before next flight.

Inspection of composite structures in service

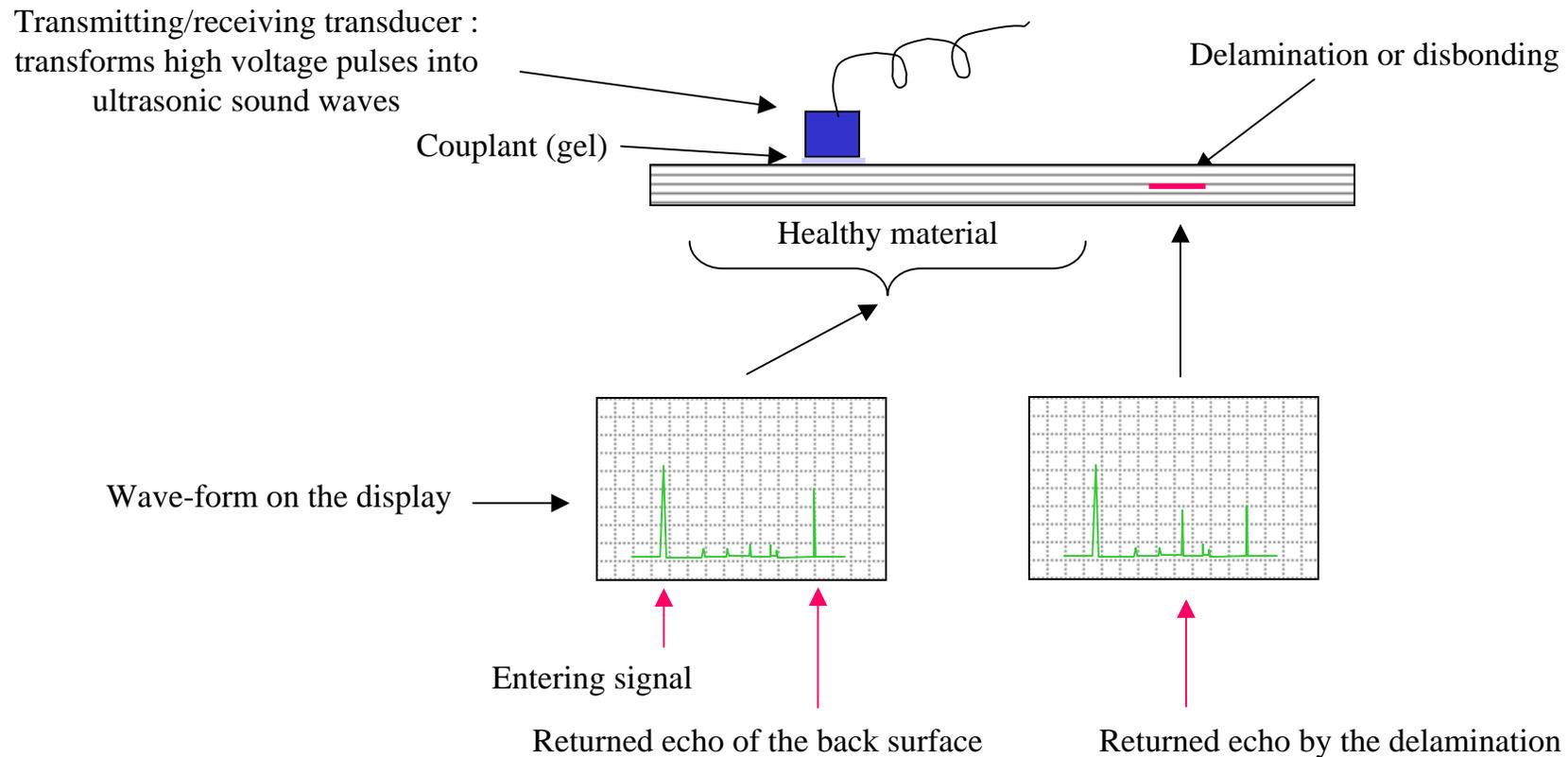
Composite structure damages that may be expected in service and their appropriate inspection methods :

Accidental impact by foreign objects : Recommended inspection method : zonal inspection visual general and detailed, plus local ultrasonic if there is a finding.
(Except on rotorcraft rotating elements, fatigue damages (disbondings, delaminations) should not be expected).

Liquid ingress in thin-skinned sandwich structures (may occur with porous facesheets due to an insufficient thickness) : Recommended method : Sonic (audio) tap-check plus radiography if there is a finding.

Corrosion (may concern only metallic structures directly in contact with the composite) : Recommended method zonal inspection visual general and detailed, plus local special (ultrasonic, radiography, eddy currents) if there is a finding.

Ultrasonic inspection principles of composite structures The pulse-echo technique



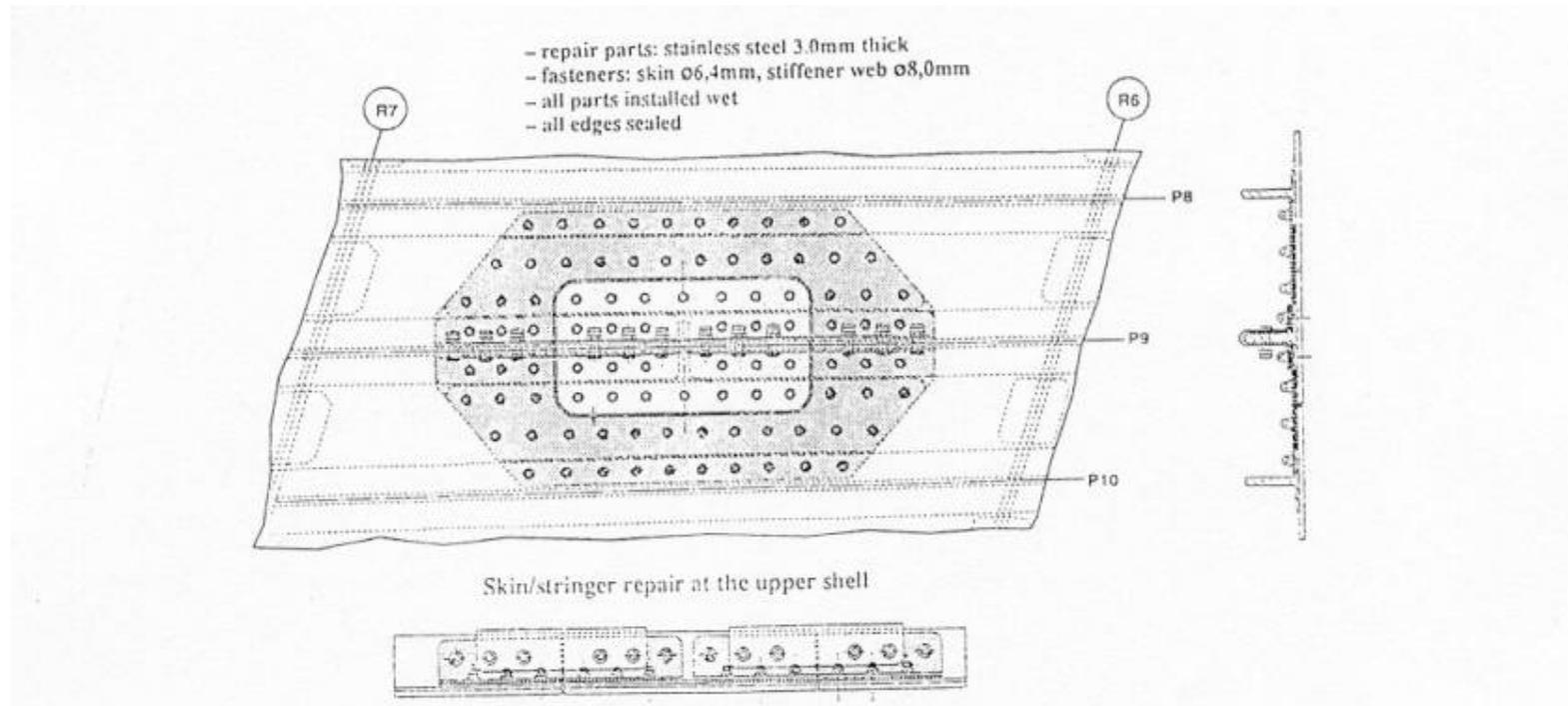
Composite structures repairs, recommendations drawn from AC 29-2B, but expandable to JAR 25 aircraft

... In general, no composite repair should be attempted which is out of the scope of repairs stated in an approved Structural Repair Manual (SRM) without an engineering design approval by a qualified FAA / Authority representative (DER or staff engineer). The following minimum criteria should be met in any acceptable composite repair :

- (i) The repair should be permanent.
- (i) The repair should restore the structure to the required strength and stiffness.
- (iii) The repair should restore all functional requirements.
- (iv) The repair should have negligible weight penalty.
- (v) The repair should be aerodynamically compatible.
- (vi) The repair materials should be compatible in all essential aspects with the parent materials.

IT IS STRONGLY RECOMMENDED TO INTRODUCE REPAIR SOLUTIONS IN THE PYRAMID OF TESTS (BUILDING BLOCK APPROACH) AND AT THE HIGHEST LEVELS OF THIS PYRAMID.

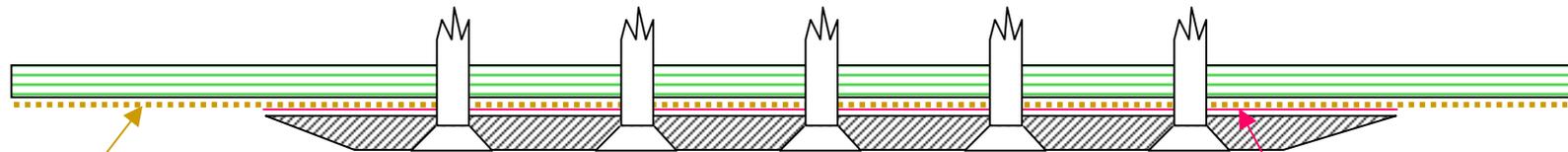
Examples of repair solutions for composites (solid laminate construction)



‘Heavy repair’ on a self-stiffened panel, ref. DASA Hambourg, AGARD CP 550

Examples of repair solutions for solid laminate composite construction, repair by outer doubler

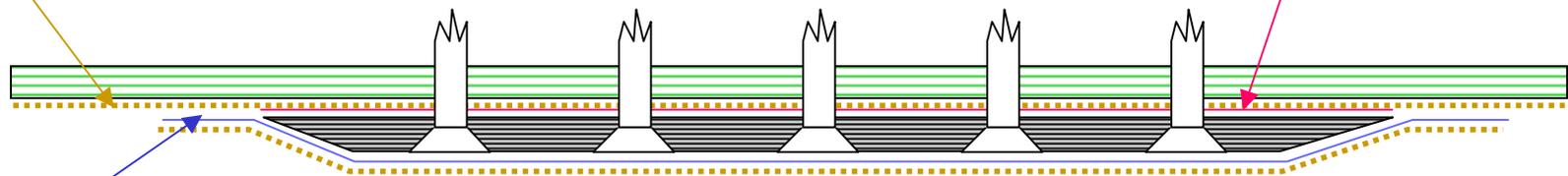
Outer doubler **METALLIC**



Fastener 'wet' installation

Lightning strike protection, if there is a need

Outer doubler in **COMPOSITE**



Fastener 'wet' installation

Adhesive

PR

Reference AEROSPATIALE, Programme ATR 72

Examples of repair solutions for sandwich construction

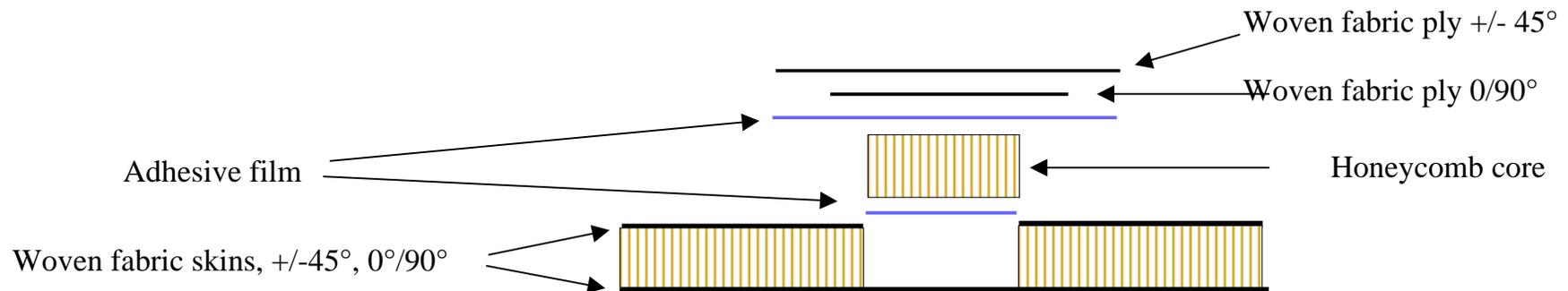
In principle the repair must provide a reinforcement equivalent to the damaged one

Case N°1 : Outer bonded patch, cured out or in place, **with** honeycomb restoration

Selecting the same resin system (or prepreg) than the parent skin of the sandwich structure is, in general, only possible if the component can be removed from the aircraft and then repaired out of place using an autoclave with the same curing cycle. If not :

- check the material health and the mechanical performances that can be achieved through a vacuum bag curing process of the same material,
- or select an other resin system compatible with this manufacturing process.

In both cases, the compatibility between the adhesive and the resin system has to be checked.



Examples of repair solutions for sandwich construction (Cont'd 1)

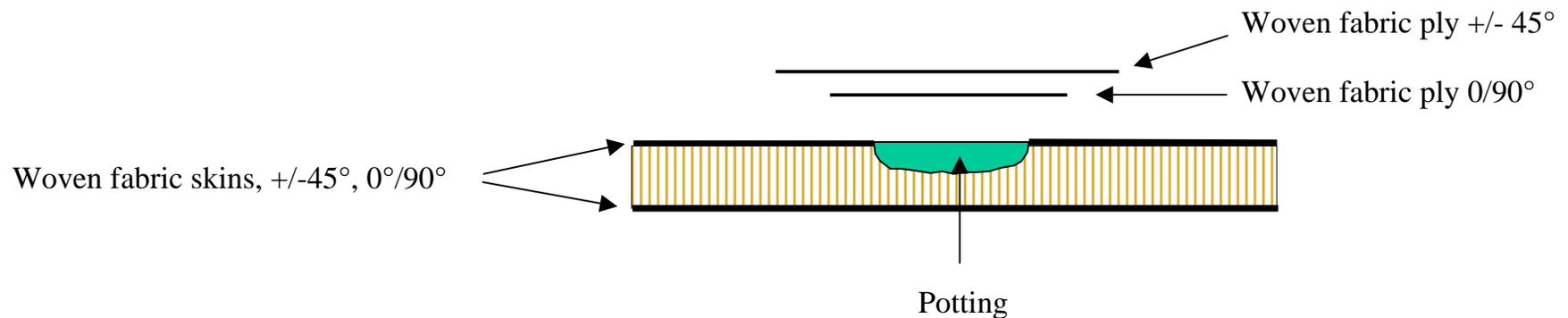
In principle the repair must provide a reinforcement equivalent to the damaged one.

Case N°2 : Outer bonded patch, cured in place, **without** honeycomb restoration

This repair method, more 'rustic' than the one referenced in case N°1, requires either prepregs with low temperature and low pressure (atmospheric) curing cycles, or a wet layup process.

The potting resin (or adhesive) is cured in advance and its surface made flush with the skin level.

The compatibility between the resin used for potting and the prepreg one has to be checked.



Examples of repair solutions for sandwich construction (Cont'd 2)

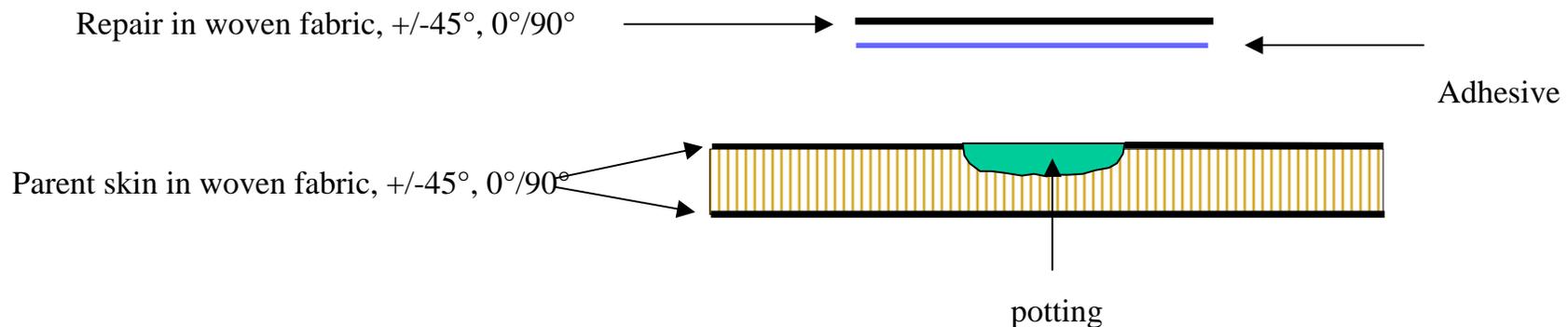
In principle the repair must provide a reinforcement equivalent to the damaged one.

Case N°3 : Outer repair by a pre-cured patch, **without** honeycomb restoration

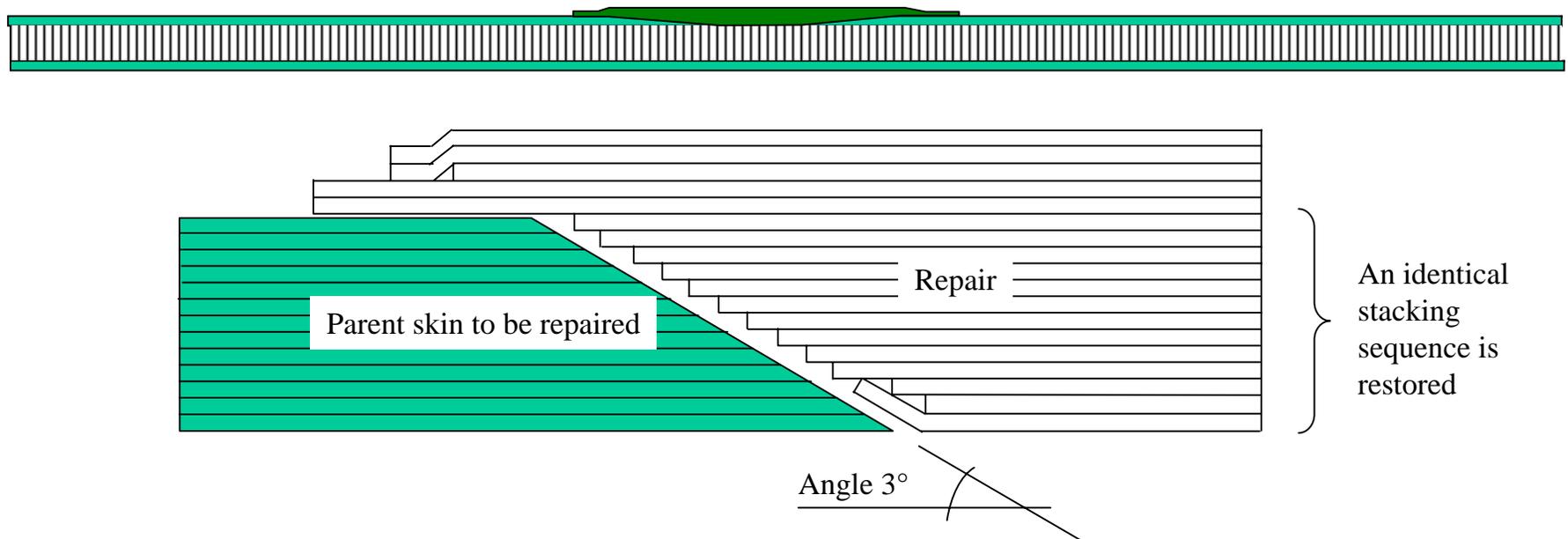
This method allows to use the same repair material as the one used for the parent skins. Provided an adequate adhesive selection, the original performances of the repaired part against adverse environmental conditions (elevated temperature and moisture effects) can be fully restored.

The paste (resin or adhesive) used for potting is cured in advance and made flush with the skin level.

The compatibility between the the resin used for potting and the adhesive has to be checked.

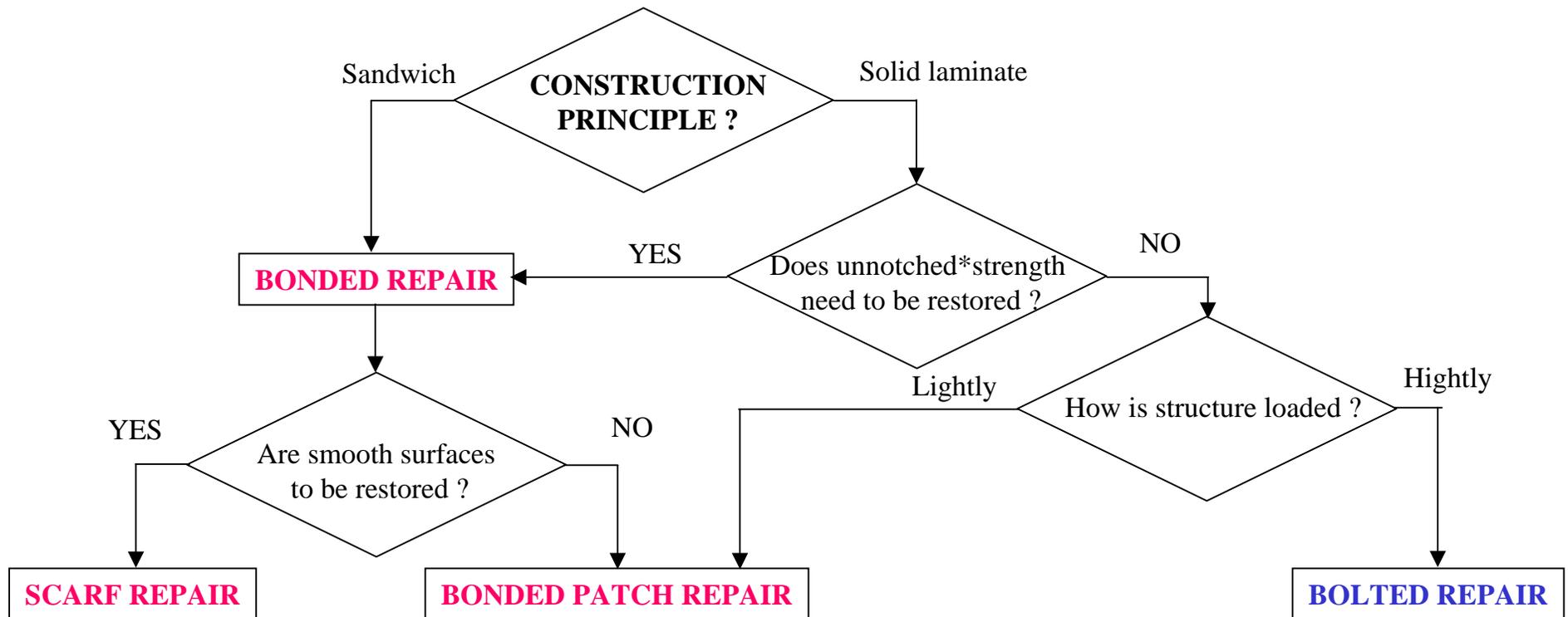


Examples of repair solutions for sandwich construction (Cont'd 3)
'Scarf' repair on an heavily loaded structure



Reference DSTO, Australie AGARD CP 550

An overview of selection criteria for repair techniques



* unnotched strength does not need to be restored in mechanically fastened boxes, but has to be restored in rotorcraft rotating elements for instance.

Recommendation summary

- Bonded repairs, for those damages reducing structure strength below ultimate loads capability, should be avoided (unfortunately not applicable on sandwich construction).
- With bolted repairs, stiffness compatibility (between the patch and the parent skin) should be considered in order to avoid stress raiser effects at the repair bounds. Pre-cured composite patches should be preferred, rather than those out of steel (too stiff).
- When a bonded repair solution is unavoidable, most often the selected adhesive is a medium range (120°C) curing system. In this respect, it may be difficult to restore the original component strength under the most adverse environmental conditions. The same remark applies to patches that are cured in place.

AIRWORTHINESS AUTHORITIES APPRECIATE THAT REPAIR SOLUTIONS ARE SUBSTANTIATED BY TESTS AND INTRODUCED FOR THIS PURPOSE IN THE FULL-SCALE TEST ARTICLES.

NEVERTHELESS, DESIGN 'ROBUST' TO AVOID REPAIR NEEDS, MAINLY WITH SANDWICH CONSTRUCTION.

Chapter 12 – Quality assurance

Regulatory requirements addressing ‘Quality Assurance’

BASIC REQUIREMENT (CS 21)

CS 21.139 : Quality System.

(a) The production organisation must show that it has established and can maintain a quality system. The quality system must be documented. This quality system shall be such as to enable the organisation to ensure that each product, part or appliance produced by the organisation or by its partners, or supplied from or subcontracted to outside parties conforms to the applicable design data and is in condition for safe operations, and thus exercise the privileges set forth in JAR 21.163. [See ACJ N° 1 to 21.139(a) and ACJ N°2 to 21.139(a)].

(b) The quality system must include -

(1) As applicable within the scope of approval, control procedures for those elements shown in Appendix B; [See ACJ 21.139(b)(1)] and

.....

Appendix B Quality System

The quality system must include, as applicable within the scope of approval, control procedures for the following elements as required by JAR 21.139(b)(1).

(a) Document issue, approval, or change.

(b) vendor and subcontractor assessment, audit and control.

© Verification that incoming products, parts, materials, and equipment, including items supplied new or used by buyers of products, are as specified in the applicable design data.

.....

Acceptable means of compliance addressing 'Composite quality Assurance'

AMC N°1 to CS 25-603 § 8.5 Quality Control

An overall plan should be established and should involve all relevant disciplines (i.e. engineering, manufacturing and quality control). This quality control plan should be responsive to special engineering requirements that arise in individual parts or areas as a result of potential failure modes, damage tolerance and flaw growth requirements, loadings, inspectability, and local sensitivities to manufacture and assembly.

AC 21-26 : Quality control for the manufacture of composite structures (26 June 1989).

Content

- 1 - Purpose
- 2 - Related FAR sections
- 3 - Related Reference material
- 4 - Definitions
- 5 - Quality control system
- 6 - Material and process specifications
- 7 - Materials
- 8 - Manufacturing controls
- 9 - Final acceptance
- 10 - Storage and handling

Composite materials main attributes with respect to quality assurance (non comprehensive list)

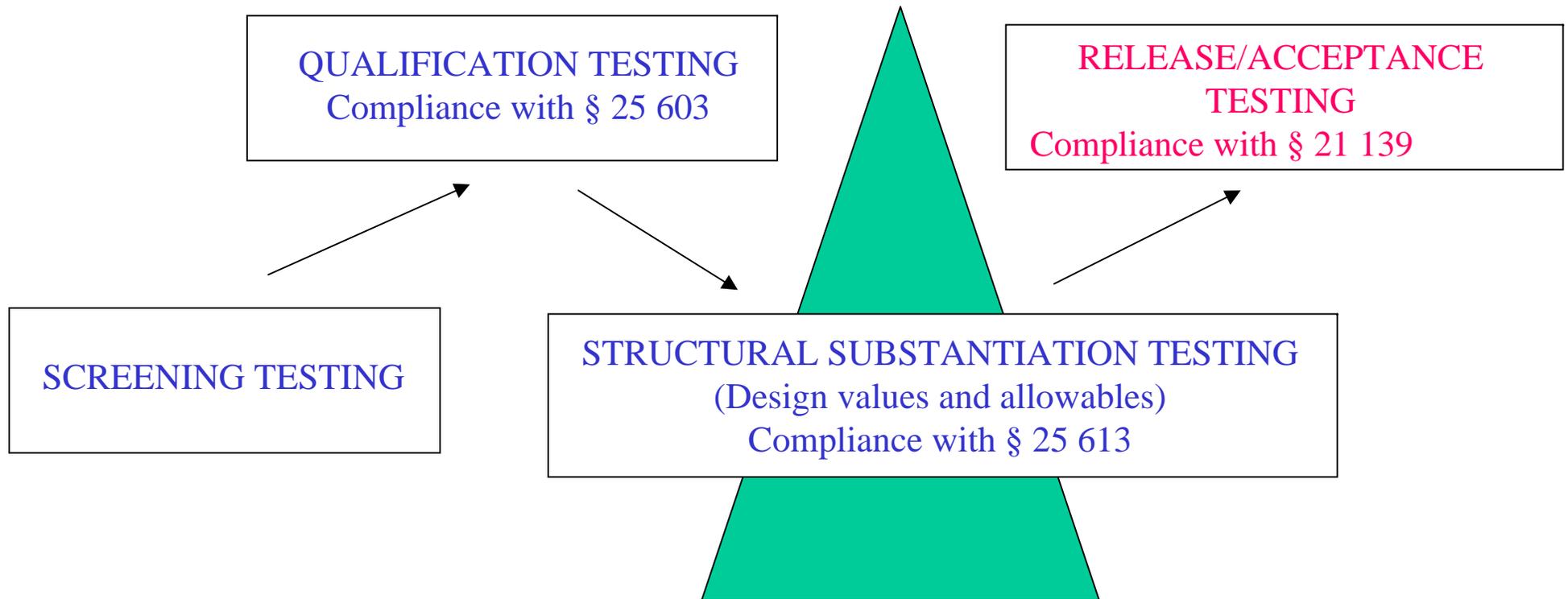
- Raw materials (with thermoset resin systems) are perishable and need to be stored in cold chambers or freezers. Dedicated procedures for storing and destoring should be established, and historical records maintained.
- Physico-chemical control of the constituents (fibre and matrix) is most often not efficient enough to detect engineering properties deviations.
- Engineering properties are accessible with difficulty through the testing of simple and cheap specimens.
- Various possible contamination sources for prepreg during processing and for surfaces dedicated to further secondary bonding. There is a need to take care of peel-ply release agent possible transfer. Such ancillary product must therefore be considered as a structural material (need for a qualification procedure and an incoming product control).
- Difficulty to check, after hand lay-up, that a stacking sequence conforms to the specification .
- Risk of manufacturing induced defects (porosity, voids, foreign objects) that require a hundred per cent inspection for critical parts.
- Vulnerability of cured parts during handling and storage (sensitivity to low velocity impact damage, mainly along the edges).

Quality control system main coverage

THE QUALITY CONTROL SYSTEM SHOULD INCLUDE PROCEDURES THAT WILL ENSURE :

- **the quality of incoming materials,**
- **the control of the in-process manufacturing methods,**
- **the evaluation of the end product for conformity to design requirements.**

Incoming material quality assurance



PURPOSE OF RELEASE/ACCEPTANCE TESTING : TO VERIFY THAT A LOT OF MATERIAL CONFORMS TO THE QUALIFIED REFERENCE

Incoming material quality assurance

Release/Acceptance testing is carried out against an **INDIVIDUAL PRODUCT SPECIFICATION** which has been developed from qualification data.

In general, most of release/acceptance testing is performed at the supplier 's and a copy of supplier laboratory test report showing actual test results should accompany each batch of purchased material.

But refer to AC 21-26, § 7 MATERIALS (a) :

' however, a material supplier 's test report alone should not be considered adequate documentation to substantiate that materials satisfy all specification requirements '

As a consequence, adequate batch controls (repeating at least the release test matrix) should be performed at the purchaser 's on a sampling basis.

Incoming material quality assurance (Cont'd)
 An example of release test matrix (Ref. Airbus AIMS 05-01-000 Part 2)

UNCURED PROPERTIES (3 specimens per batch)	TEST METHOD
<ul style="list-style-type: none"> - Prepreg areal weight - Fiber areal weight - Resin density - Fiber density - Volatile content - Resin content - Physico/chemical definition - Resin flow - Tack 	<ul style="list-style-type: none"> EN 2557 EN 2559 ISO 1183 A ISO 1119 EN 2558 EN 2559 (See next page) EN 2560 tbd between the supplier and the purchaser
<p>CURED PROPERTIES (6 specimens per batch)</p> <ul style="list-style-type: none"> - ILSS (UD 0°) at room temperature and 120°C - Tensile strength and modulus (UD 0°) at RT - Open hole tensile strength (lay-up 50/40/10) at RT 	<ul style="list-style-type: none"> EN 2563 EN 2561 A or B AITM 1.0007

Incoming material quality assurance (Cont'd)
Physico/chemical characterization of the resin system

METHOD	AIRBUS in-house corresponding standard
<p>- HPLC (High Performance Liquid Chromatography) Involves the liquid-phase separation and monitoring of separated resin components.</p>	AITM 3-0001
<p>- DSC (Differential scanning calorimetry) Monitor material enthalpy change as a function of temperature.</p>	AITM 3-0002
<p>- IR (Infrared spectroscopy) Identifies polymers and polymers precursors, yields both qualitative and quantitative information concerning a polymer sample's chemical nature.</p>	AITM 3-0003
<p>- Gel time</p>	AITM 3-0004
<p>- Viscosity</p>	AITM 3-30004

Statistical processing of incoming control test data.

IDENTIFICATION OF THE ISSUE :

- Let us consider one mechanical property among those which have been selected for the incoming control test matrix (e.g. tension strength, ILSS, etc.).
- Qualification testing, performed with a large amount of specimens, has provided the random variable main features associated to this mechanical property (probability law with the best fit, estimate of the mean and standard deviation).
- This mechanical property is checked through a reduced sample size (in general from 3 to 5 specimens) in the incoming control procedure.

QUESTION :

What are the acceptance limits to accept (or reject) one batch ?

In practice, these limits may be applied to :

- (a) : the mean value of the test sample,
- (b) : the mean value of the test sample,
- (c) : a combination thereof,
- (d) : the mean value and the standard deviation.

The following methods are detailed in the reference : *Statistical Tests for Batch Acceptance, Notes for Mil-HDBK-17 Coordination Group, TUCSON, 6 April 1997.*

Author : Mark G. Vangel : Statistical engineering Division, National Institute of Standards and Technology
Normal population and no batch-to-batch variability are assumed in these methods.

Control of the in-process manufacturing methods

- Prior to the start of production, **manufacturing processes should be qualified** by demonstration that the combination of materials, tooling, equipment, procedures, and other controls making up the process will produce parts having consistent material properties that conform to design requirements.
- Once the manufacturing process has been established **it should not be changed** unless a comparability study and necessary testing of differences has been completed.
- All **pertinent process variables** (curing cycles, processing room conditioning) **should be adequately controlled and traced**. Records should be made available on request.
- **Tolerance limits** (e.g. curing temperature) of the process **should be established** and substantiated.
- After initial process qualification, testing (process control panels, etc.) for conformity to design requirements should continue on an appropriate frequency.
- A programme **to train and / qualify operators**, as appropriate, should be established. This programme should measure operator performance to production standards.
- For sandwich construction with pre-cured skins, and other secondary bonding situations, appropriate procedures to guarantee the faying surface cleanliness should be established. **Traveller specimens following the whole manufacturing process should be used and tested for final acceptance.**

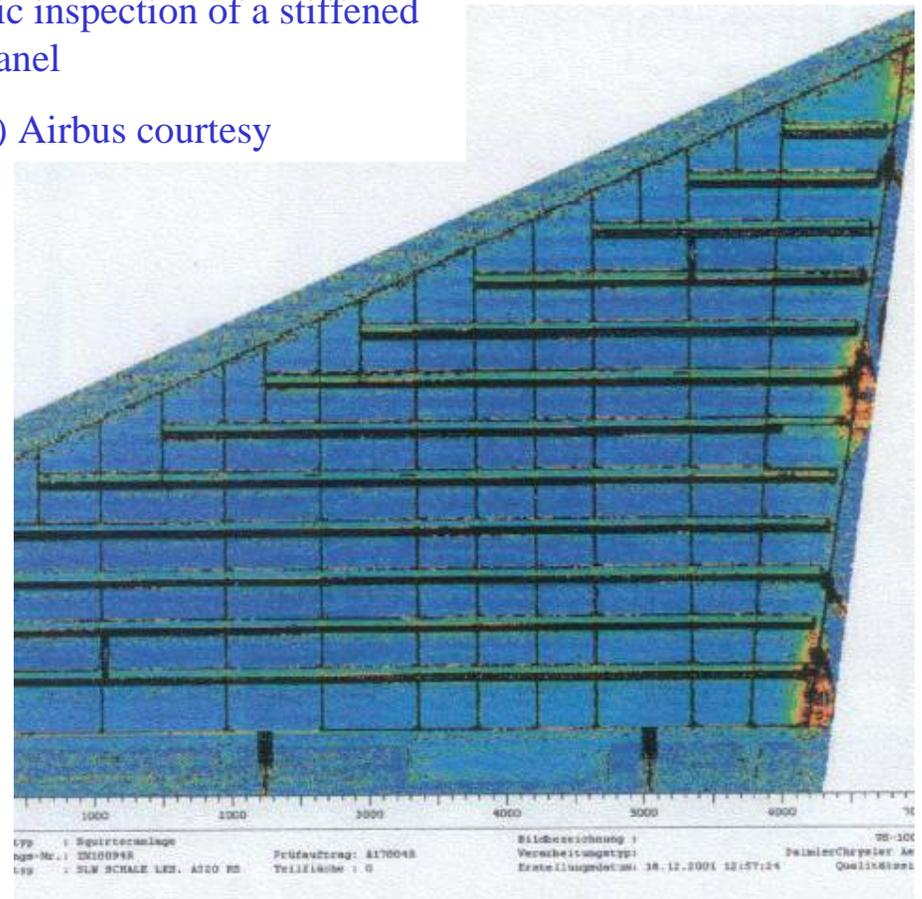
Evaluation of the end product for conformity to design requirements

- Final acceptance procedures provide an added assurance that the complete structure meets its functional and design requirements.
- Geometry checks and non destructive inspections are the main parts of the end-product control.
- As far as non destructive inspection is concerned, **ultrasonic inspection** is the most efficient and widely used method at the production line.
- Shearography, thermography, and tap-check are appropriate for an overall control of large bonded surfaces. Should any finding be detected by these methods an ultrasonic inspection would be used in order to precisely identify the damage.
- X-ray radiography and tomodensitometry are restricted to very thick parts when other methods are no longer appropriate.

End product control

A hundred per cent Ultrasonic inspection of a stiffened skin panel

(Squirter technique) Airbus courtesy



The table below gives most of the notes taken during the “ Certification of Structures en Materiaux Composites” April 2007 Training. The handouts of the English course were not yet ready at that time and were given by the instructor as courtesy.

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
1-4	1-4	0.5% for the passengers = If you die in a transport accident, there is 0.5% probability that it is in an aircraft
2-2	2-2	For the A340-600 Composite Bulkhead, a special condition has been added to the certification requirement. It consists in an impact on the pressurized bulkhead.
2-6		Flutter: one of the last difficulties on the A380 (solved).
2-9	2-3	Emergency landing (drop test) for the 787 has been done by analysis and test on the lower portion of the structure. One of the driver for the A350 hybrid fuselage (Al frames with CFRP skin)
2-18	2-12	Shall understand the consequences and effects of the parameters (or deviation) (geometry, processes, etc.) on the behaviour. Analyses supported by tests.
2-20	2-14	On A380, the belly fairing is considered primary structure considering its size (J.R. “It is big as a canal boat”)
3-2	3-3	Problems with Airbus rudder stiffeners (initially co-cured). Disbond of the stringers due to the peel ply. The peel ply used for the certification was not the same as in the manufacturing. Newer peel ply has contaminated the interface. This problem has been responsible for the addition of fasteners at each stinger/rib junction. Financial consequence in terms of millions of Euros. Mix of R&D and Certification pgm = DANGER
3-4 to 3-6	3-5 to 3-7	Summary of the Airbus Certification Plan and Composite Summary plan
3-6	3-7	Comparison Calculation-Tests: graph of Analyses results versus Test results (points close to a line with a slope = 1 + or - 8 to 10%)
4-3	4-3	Bullets 1 and 4 are the weak points of the A320 Air Transat Rudder problem.
4-4	4-4	Today, nobody would present such design. Stringer/Skin junction always over a solid laminate section.

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
4-5	4-5	<p>Travelers: the problem is with economical pressure and the sub-contacting, those procedure are usually not well followed.</p> <p>Rudder of the F7X is a RTM multi spar design. The controls are performed only in the zone highly stressed.</p>
4-6	4-6	<p>Rafale in Afghanistan: lightning protection on the first set of A/C was obtained using aluminium mesh. On the boat, corrosion occurred at the fastener heads. Aluminium oxide creates crack in the 5254 resin.</p>
4-7	4-7	<p>In sandwich structure, the water ingress is mainly due to the pressure cycling (ground-altitude-ground).</p> <p>Aramid (Kevlar) has the tendency to crack at the interface fibre/matrix when submitted to thermal cycling. Water is then trapped there.</p> <p>For sandwich structures, permeability obtained with co-curing is usually less than with two curing cycles.</p>
5-4	5-4	<p>In general, the new resins have better impact resistance but they are more affected by the humidity.</p>
5-7	5-8	<p>The % of absorbed humidity at saturation depends on the conditioning temperature (Henry's law).</p> <p>Resin 914 absorbs water</p>
5-10	5-10	<p>Conditioning temperature = 70 C in Europe Conditioning temperature = 82 C in America</p>
5-14	5-13	<p>Conventionally, the maximum temperature is determined at a given time after the takeoff.</p> <p>For upper surfaces $T \approx 70-80$ C For lower surfaces $T \approx 50-60$ C</p>
5-16	5-16	<p>Since accelerated conditioning may act as a secondary curing, it is necessary to evaluate the effect separately (temperature)</p>
6-4	6-4	<p>Impact sensibility: Impact resistance and damage tolerance</p> <p>Static: OHT (open hole tension)</p> <p>Environment: FHC (filled hole compression) and bearing</p>
6-5	6-5	<p>Spec: Material definition stable with time. No excessive deviation with time.</p>

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
6-8	6-8	<p>During the Falcon 10 wing testing, a rupture occurred at the holes at the structural rib (gear) at 1.35 LL → traumatism</p> <p>For the Rafale, a material with very good strength in presence of holes was selected (remembering the Falcon experience). This material was a catastrophe because all the other properties were low.</p>
7-2	7-2	<p>25.603 must be completed before to start 25.613</p> <p>A bolted joint (1 row of bolts) that it is net section critical (opposed to bearing critical) is considered single load path (no repartition in case of problem) → A-Value.</p>
7-5	7-5	<p>There are as much allowable as different materials (or even batches of material)</p> <p>Design value: Published value that considers for example the different sources of materials and/or materials for replacement etc.</p>
7-9	7-9	<p>Kb: is the coefficient linked to 90% for B-Basis</p> <p>Conf: is the coefficient linked to the confidence (95%)</p>
7-11	7-11	<p>Outliers: points that are apart from the majority of the points. If there is an explanation why those points are outside the trend, those points can be removed from the analysis.</p>
7-18	7-16	<p>In conclusion, the variability between batches may induce unrealistic B-Basis values (particularly with Stat17). The variability between batches must be low first.</p>
7-20	7-18	<p>In the Selected Rupture Criterion, the value for Rl and Rlt are derived using best fit through B-Basis experimental values (<u>uni axial and bi-axial</u> tests)</p>
8-2	8-2	<p>Paragraph 25.303: for Pressure case, Limit = 1.3 Δ P and Ultimate = 2 Δ P</p>
8-4	8-2	<p>According to J. Rouchon, it is acceptable to apply a Δ T superior to the real Δ T to compensate for a lower humidity saturation than the reality.</p>
8-7	8-6	<p>A340: coefficient on the applied load to simulate environment effects. In the case of hybrid structures, metallic components must be oversized. In general, the ultimate loads are applied on the subcomponents individually for hybrid structures.</p>

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
8-12	8-10	<p>The strength variability of FRP supporting realistic loading (multi-axial compared to tension) is less than initially anticipated.</p> <p>In Russia, for the composite structures an additional coefficient is used. This coefficient is 1 if the variability is less than 0.08, is 1.08 if VAR < .10, is 1.25 if VAR < 0.15, is 1.57 if VAR < .20, is 1.97 if VAR < 0.25.</p>
8-14	8-11	<p>A350XWB: hail is a concern for the fuselage</p> <p>Impact damage in composite is similar to the micro crack in brittle steel. Damages are difficult to detect while the strength reduction associated with those damages is large. Sizing usually made with max strain = 2500 to 3500 micro def.</p>
8-16	8-13	<p>For laminate thk from 2 to 7 mm, impact creates delaminations through the whole thickness. For laminate thicker than 7 mm approx., impact creates delaminations in the first layers only → res. strngth remains high.</p> <p>A350XWB keel beam thk around 2-3 cm.</p>
8-19		Impactor head > or = to 0.5"
8-23	8-19	<p>Based on the Limit Load probability 10E-5/FH, Airbus has suggested to use the same probability for the BVID Energy cut-off (Eco). Using J. Rouchon graph, Eco = 30 J. Since J. Rouchon has suggested 40 J, a compromised was reached for 35 J. Even the Eco=135J for the H-Stab root may be dropped to 90 J.</p>
8-28	8-20	<p>According to J. Rouchon, if the structure is not highly loaded in compression, the BVID requirement is not used (Ex. -1500 micro def, no BVID req.).</p> <p>ATR72: Upper wing skin ruptured at 1.47 Limit Load. The inspection technique has been therefore changed to lower the BVID size.</p>
9-2	9-2	<p>In addition CS 25.571 requirements about the load cycling effect, environment effects and the accidental damage effects, the FAR25.571 includes the Manufacturing Defect Effects.</p>
9-3	9-3	<p>A380 aileron made from sandwich with rohacell foam cured in one shot → Damage Tolerance problems</p>

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
9-10	9-10	Load cycling may increase the strength by creating micro damages relaxing locally the stiffness.
9-12	9-12	<p>On the A310, one row of fasteners at the stringers run out at the base of the V-stab → not fatigue problem.</p> <p>When a problem occur, the tracability becomes very important. Two composite material suppliers for the blade of the Super Puma helicopter. One day, problems occurred with the blade made from the material of one supplier. Since no tracability systems were put in place, each blade was tested.</p>
9-19	9-19	Usually on composite, the load truncature is performed at 30% limit load. A Swedish study showed that truncature at 50% limit load is still OK.
9-26	9-26	<p>The weak points of the LEF derived here:</p> <ol style="list-style-type: none"> 1) old material systems 2) fatigue curves obtained with design details that differ from what is done today (Ex. bolted joint were used, stringer run-out not used to establish the fatigue curves). In additions, the tests were conducted to rupture. 3) Unknowns concerning the neglected loads.
9-30	9-27	<p>Hybrid Structures → 2 test articles A380 (empennage): Fatigue Composite → replace metal structure (Ex : Centre Rib) → Fatigue Metal</p> <p>The A320 fatigue loading was less severe that the A319 loading. To rely on the A320 test for the certification, the static load (not required) applied before the first life were converted in fatigue equivalent.</p> <p>It seems that it is now a common practice to add some high loads at the end of the load cycling to get some provision for future program or potential load increases.</p> <p>Fatigue problems on doors stiffened by omega stiffeners. Cracks developed in the corner of the omega (corner not in contact with skin). The problem was solved by closing the omega.</p>
9-32	9-30	Accidental damage is the first concern.
9-34	9-32	Obvious damage = 1 to 2 mm dent (permanent)
9-40	9-38	Probabilistic approach for the composite is inspired by the approach developed for the load alleviation systems.

French Presentation: Chapter-Slide	English Presentation Chapter-Slide	Notes
9-45	9-42	Damage tolerance applies to: primary structures that support high compressive load and are not thin or thick. (thin → impact penetration, thick → no significant damage)
	9-43	This slide does not exist in the April 2007 French version
9-49	Does not exist	Curves that look similar correspond to residual strength of laminate of different thickness (left = thinner, RH = thicker)
11-3	11-3	J. Rouchon asked for traveler specimens on one type of A/C to be weighted periodically because some conformity problems (relative to humidity) occurred during the certification.
11-7	11-7	The V-Stab of the A310 AA787 was repaired in the zone that failed. However, the rupture did not go through the repair. What would happen if the repair did not restore the original strength but only M.S. = 0.
11-8	11-8	This is an example of heavy repair that is too stiff and attracting additional load.
11-12	11-12	Usually the repair are cured at the same temperature and pressure that the initial skin. This must be considered in the sizing.
11-13	11-13	According to J. Rouchon, a bonded repair is acceptable if: <ul style="list-style-type: none"> 1) it is the only possible repair 2) if the repair disbond, it becomes obvious