Impulsvortrag *bei* ***Carbon Composites e.V.***
IHK Schwaben, Augsburg, April 3, 2009, 13.00 Uhr
Arbeitsgruppe “Engineering”

Development, Dimensioning and Design Verification of Load-carrying Structural Components

(Übersichtsvortrag zu *Auslegung und Nachweis* als ingenieurdiszipline-verbindendem Element)

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<u>Übersichtsvortrag</u> : **Orientierungshilfe / Mittel**

zur Festlegung gewünschter Arbeiten

als Bausteine notwendiger

interdisziplinärer Zusammenarbeit

und **um *Schnitt*stellen**

zu den werkstoff-, fertigungs- und prüfungsorientierten

Arbeitsgruppen

in *Verbindungs*stellen umzuwandeln

- Direkte Kommentare im Vortrag erwünscht !

- Wunschpunkte für die weitere Arbeit notieren !

- Vortrag wird an das E-Mail-Protokoll angehangen

Zielvorstellung

Sinnvolle Überlappung der Arbeitsgruppen
zum gemeinsamen Nutzen

Materials & Processes	Dr. Schröder
• Engineering	Prof. Cuntze
• Materialien	Hr. Radmann
• Herstellverfahren	Hr. Frick
• Automatisierung	Hr. Scheitle
• Werkstoff- und Bauteilprüfung	Prof. Busse
• Bearbeitung, Fügen und Montage	Dr. Schröder

Engineering zielt primär auf Bauteile / Strukturen und hat Entwicklungsprozeß + Zertifizierungsprozeß im Blick

Über mich:

1964:	**Diplom**	***Statiker***
1968:	**Dr.-Ing.**	***Strukturdynamik***
1978:	**Dr.-Ing. habil.**	***Mechanik des Leichtbaus***
1968- 1970:	**frühere DLR**	***Finite Element Analyse***
1970-2004:	**MAN-Technologie**	
1980-2002:	**Dozent an der Universität der Bundeswehr**	
jetzt:	**Ingenieur, Unruheständler + Simulant**	

Theoretical works in the areas:

Finite Element Analysis,

Structural and Rotor dynamics,

Structural reliability and Development policy,

Strength failure modes and hypotheses (isotropic + composites),

Composites fatigue,

Damage mechanics and Fracture mechanics.

Development, Dimensioning and Design Verification of Structural Components

Contents of Presentation: *ungefähr*

1. **Development, Design Requirements, and Design Verifications**
2. **Loadings and Dimensional Load cases**
3. **Design Aspects**
4. **Safety Concept and Design Factors of Safety**
5. **Modelling and Analysis**
6. **Material Failure Conditions**
7. **Input of Appropriate Properties**
8. **Material & Structural Testing and NDI**
9. **Margin of Safety, Reserve Factor**

Some Definitions

Safety Concept

Concept that implements structural reliability (safety is a wrong term) in design

(design) Factor of Safety (FoS)

Factor by which design limit loads (DLL) are multiplied in order to account for uncertainties of the verification methods, uncertainties in manufacturing process and material properties

Failure Modes (material, structural and others)

Yield initiation, fracture, degradation, excessive wear, fibre fracture, inter fibre fracture, delamination, instability, or any other phenomenon resulting in an inability to sustain environmental ‘loadings’ (not only loads)

Service life of Structural Component

Starts with the manufacture of the structure and continues through all acceptance testing, handling, storage, transportation, service, repair, re-testing, re-use

1 Development, Dimensioning, and Design Verifications

1.1 Development Phases and Associated Topics

Phase		DESIGN	Design Analysis	Test
1	concept	conceptual	sizing	
2	design development	preliminary	dimensioning	design development tests
3		critical (final)	analytical design verification	
4	qualification	accepted		experimental design verification
5	production			

certification of product

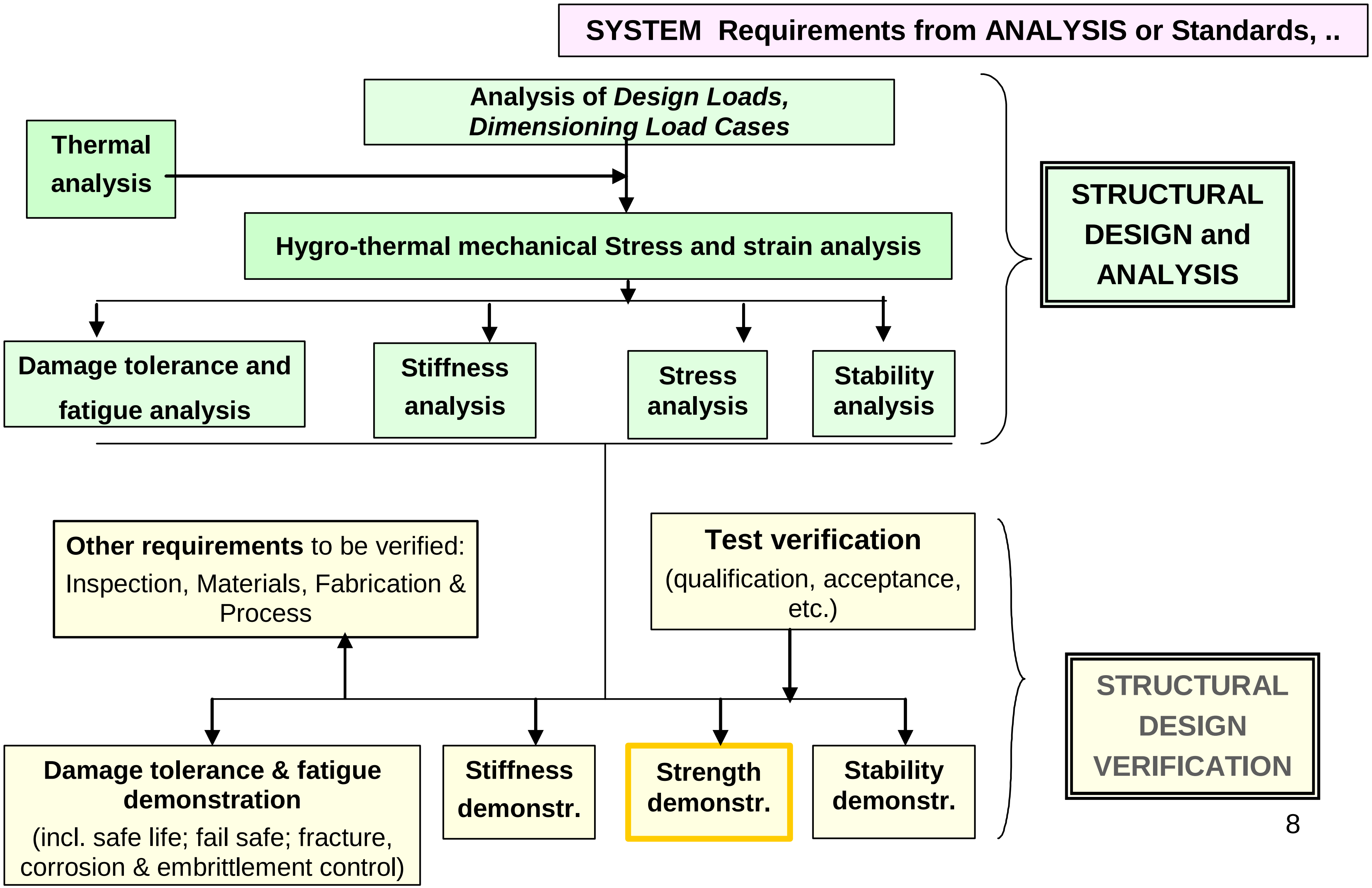
Development: Process phases from defining requirements until product delivery

Designing: Iterative process in the development of the structural component whereby various concepts are evolved and evaluated against a set of specified design requirements and constraints from manufacturing etc

Design Verification: Process, whereby a structural design is comprehensively examined an qualification-tested to ensure that it will perform in the required way, bef and during operational use.

Übertragbarkeit ??

1.2 Design Analyses and Design Verifications: *Flow diagram* [ESA/ECSS]



1.3 Some Aspects when Designing

*** Design requirements:**

- **Functional Requirements (*What must be done?)* and**
- **Operational Requirements (*How absolutely must it be done?)***

*** During Conceptual and Preliminary Design, supported by trade studies, the feasibility and estimation of cost and risk is established**

(In each later phase of the development a design change would cost about one magnitude more)

*** Structural integrity must be provided during design development, manufacture (production), and service (operation).**

1.4 Design Requirements

Design must fulfill many of the following *design requirements:*

- ***mass, production cost and life cycle cost, geometry, …***
- ***environmental loadings*** *(loads, temperature, moisture, chemical, impact, ..)*

  limits of deformation, lifetime, leakage, eigenfrequency,

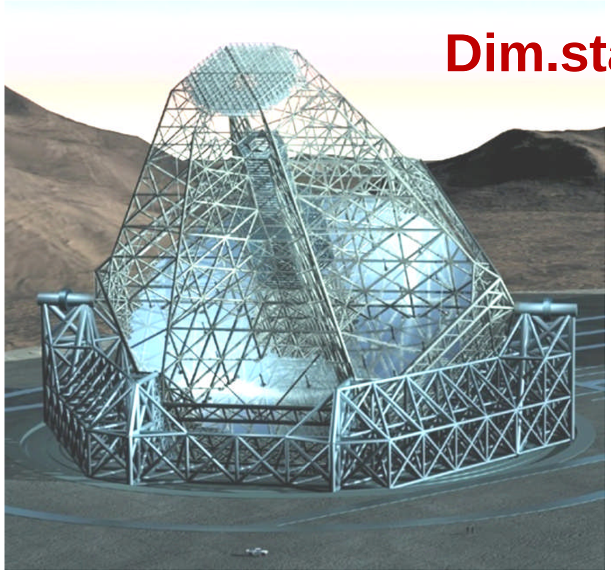
  strength , stiffness , dimensional stability , buckling,

  connections, interfaces, support conditions …
- ***manufacturability , repairability , testability , inspectability,***

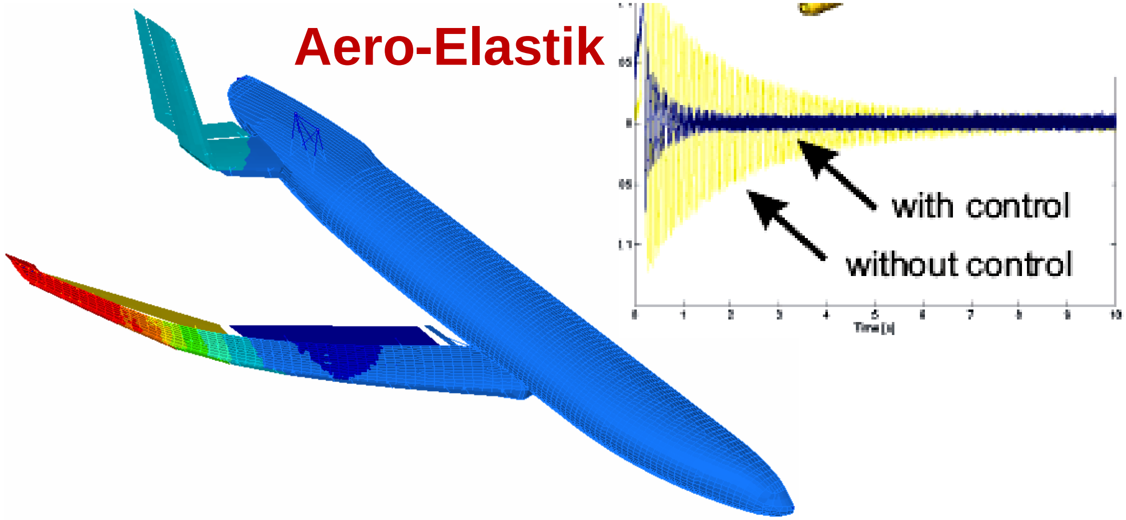
  (RAMS) reliability + availability + maintainability + safety .

Funktion und Systemverhalten, z.B.:

Dim.stab.

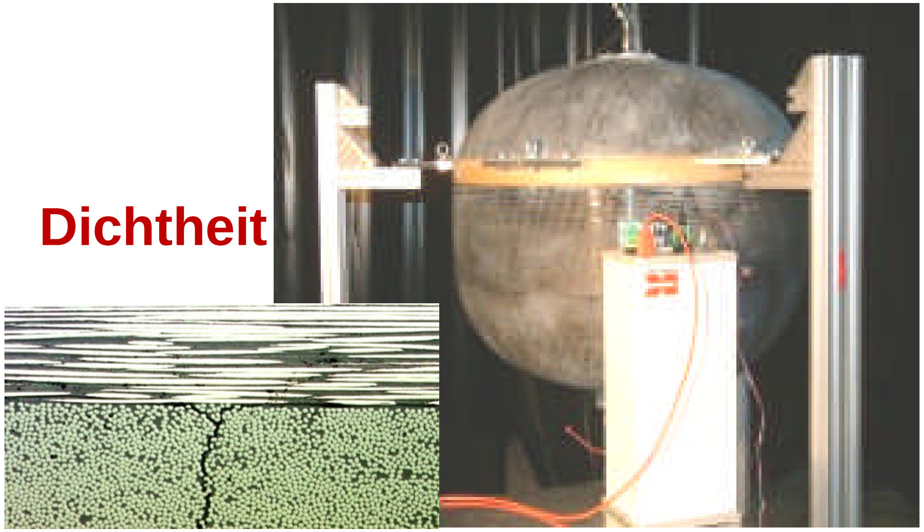


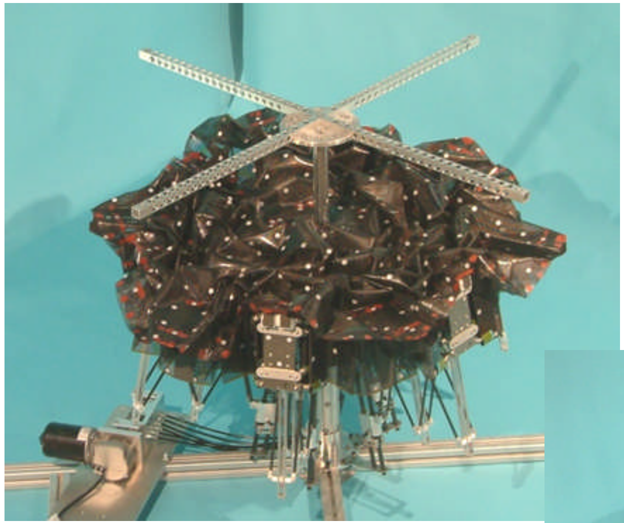
Aero-Elastik

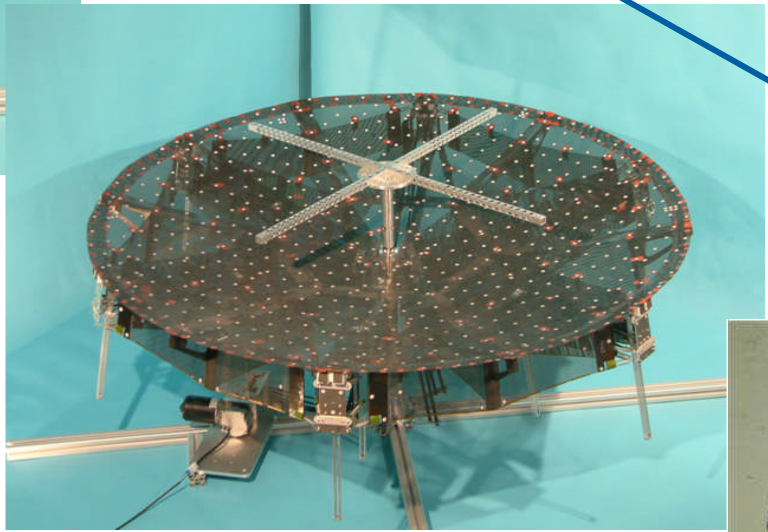


Aktorische /sens. Funktionen

Dichtheit



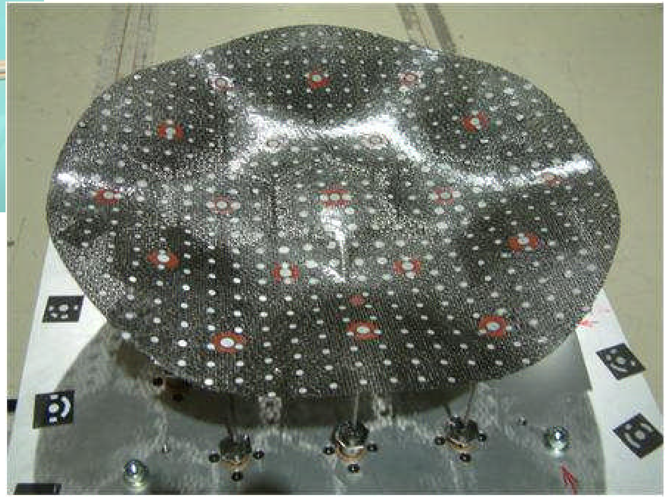




Entfalten

+

Formvariabilität



- sehr niedr. CTE
- gute RF performance
- hohe Formadaptivität
- extremer Leichtbau

2 Loadings and Dimensioning Load Cases

2.1 Load Analysis

Main task is:
Establishment of load events the structure is likely to experience (= load history)

Includes the estimation of all external + internal loadings of the structural component :
- thermal,
- mechanical (static, cyclic, and dynamic) and
- acoustical environment as well as of the
- corresponding lifetime requirements (duration, number of cycles)

Loadings are specified by
a Technical Specification from the customer, or an authority or
a common standard (EN, DIN, Betonkalender, ...)

Result:
Set of Combinations of Loadings termed *Load Cases*,
including the design driving *Dimensioning Load Cases*

Involves a Worst case scenario wrt. combinations of loadings, temperature and moisture, and undetected damage.

2.2 Dimensioning Load Cases

From the numerous *Load Cases*

the design driving ***Dimensioning Load Cases (DimLC)*** are to be sorted out:

- for ductile behaviour the : Yielding-related Load Cases,
- for brittle behaviour the : Ultimate-related Load Cases (for CFRP).

A minimum set of DimLCs is searched in order to:

- support fast engineering decisions in cases of 'input' changes

- avoid analysis and analysis data evaluation overkill and

- better understand structural behaviour (as hidden aspect).

Which *LC* is a *DimLC* can be often <u>firstly</u> recognized after the analysis of the conceptual design !

3 Design Aspects

3.1 Some special Aspects

* All designed products should be manufacturable, testable, and maintainable

* Materials used must have known, reliable, and reproducible properties and shall have proven resistance to the environment envisaged

* It has to be shown by:

- Analyses that the *design meets the requirements*,

- Manufacturing with Quality Assurance that the *structural product meets the requirements*,

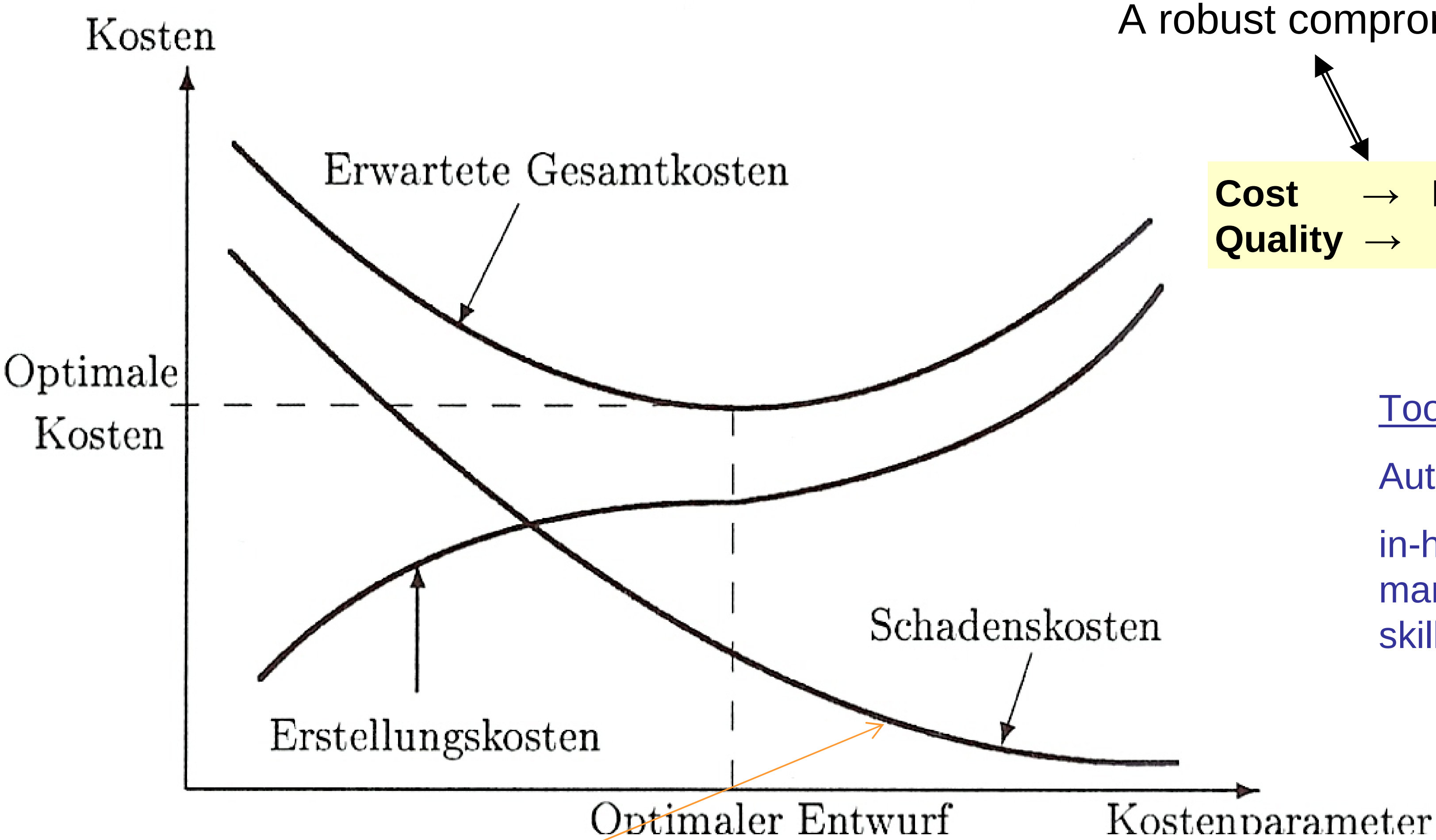
- Structural Test that the *requirements are verified*.

What is a good fulfilment of the requirements ?

A380 wing 97% or with the following pressure vessel video clip

3 Design Aspects

3.2 Design–to-Cost and Design-to-Quality



Searched:

A robust compromise of

Cost → Minimum
Quality → Maximum

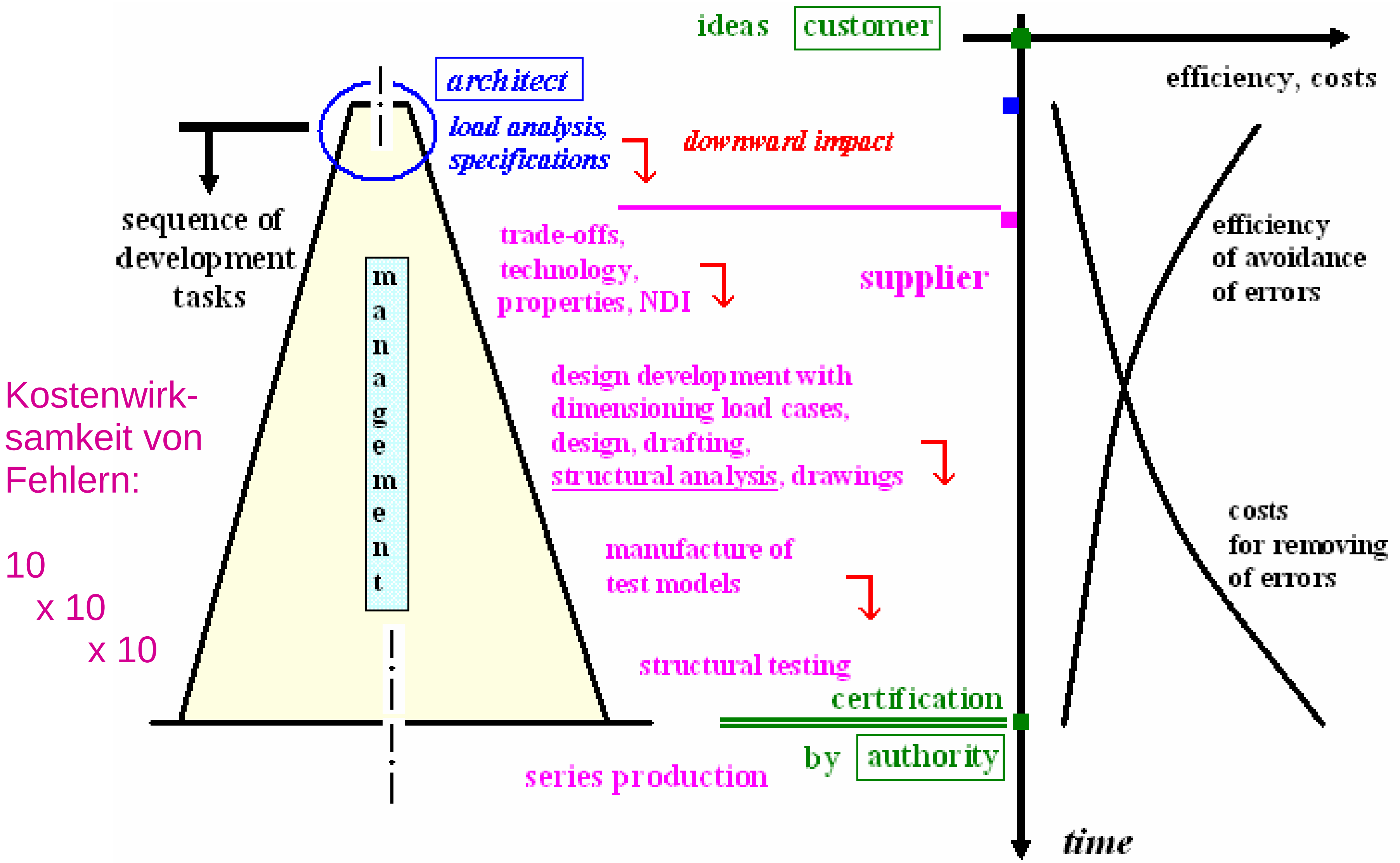
Tools:

Automatisation,

in-house manufacturing skills

Risk = amount of cost incurred in the case of later failure x probability of its occurrence

3.3 Cost penalty by mistakes during design development process



Robust design helps to smooth out not-foreseen errors, to save cost & troubles !

4 Safety Concept and Design Factors of Safety

Safety Concept:

- Implements structural reliability in design (safety is actually a wrong term but used)
- Enlarges the deterministic loads (or stresses, if linear analysis is permitted) and
- Causes a distance to the load resistance (or strength). *This unknown, not really quantified distance is 'represented' by the required positive margin of safety (MS).*

necessary, because **Uncertainties** can be found in the:

Loads are often the most uncertain design parameters !

* *load analysis, testing and test data evaluation,*
* *choice of non-linear stress-strain curve and safety concept,*
* *choice of yield condition and fracture conditions,*
* *support (boundary) conditions,*
* *structural analysis procedure,*
* *determination of the MS-value itself.*

Concerns: *loads, strength properties, geometry, elasticity properties, tolerances,*

Includes: *small inaccuracies as well as any simplifications in the design*

Missing essential accuracy in modelling, computing, or test data determination/evaluation can not be covered by a FoS !!!

Example for a Factors of Safety (FOS) Table

Experience won, shows up higher risk than usual

Structure type / sizing case	FOSY $j_{p0.2}$	FOSU j_{ult}	FOSY *for verification 'by analysis only'*	FOSU *for verification 'by analysis only'*	*Design Factor*	FOSY $j_{p0.2}$	FOSU j_{ult}	j_{proof}	j_{burst}
	external loadings incl. extern press.					internal pressure			
Metallic structures	1.1	1.25	1.25	1.5		1.0	1.0	1.2	1.5
FRP structures (uniform material)	?	1.25	-	1.5		1.0	1.0	1.?	1.5
FRP structures (discontinuities)	-	1.25	-	1.5	1.2				
Sandwich struct.: - Face wrinkling - Intracell buckl. - Honeycomb shear	-	1.25 1.25 1.25	-	1.5 1.5 1.5					
Glass/Ceramic structures	-	2.5	-	5.0					
Buckling	-	1.5	-	?					

(ECSS-E-30-10, spacecraft)

Term $j_{p0.2}$ does not so much fit to actual (relatively brittle) composites!

5. Modelling and Analysis

resistance

5.1 Levels of Design Verification, *here:* static ‘strength‘ demonstration

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Dimensioning and Design Verification may be performed on different levels :

- **Structure level : forces and moments** (resistance of a truss element *strut*)
- **Cross-section level: section forces** (stress resultants) **and section moments** (resistance of a shell wall)
- **Material level : stresses** (strength at a material point, *envisaged most often*).

Structural load-carrying capacity is mainly *locally* determined,

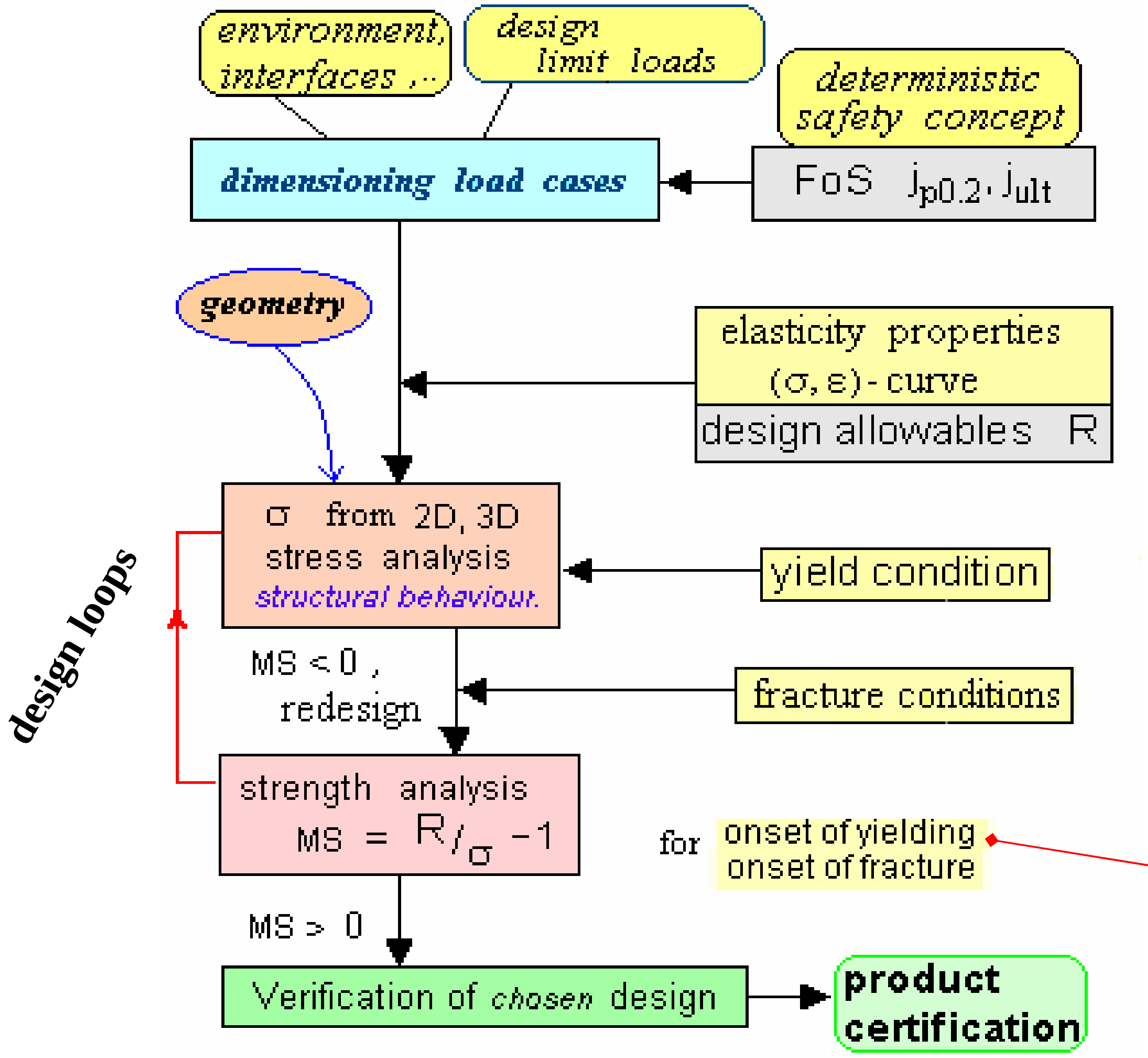
by the stress state in the critical material locations :

* **undisturbed areas** (uniform material areas, membrane areas etc.),
* **disturbed areas** (discontinuities such as joints etc.).

Assessment of stresses at critical locations (material point), such as

* **isotropic material**
* **transversally-isotropic material (UD := uni-directional material, *envisaged here*)**
* **rhombically-isotropic material (fabrics, ‘higher‘ textiles)**

5.2 Structural Analysis *Flow Chart*



DLL:= Design Limit Load (sichere Last)

FoS := (design) Factor of Safety j.

MS := Margin of Safety

Usual strength design Verifications :

Deformation limit

(onset of yielding)

Fracture Limit

(onset of fracture)

situation for composites is different

5.3 Aspects at Model Choice

- Analysis aims to predict and therefore to accurately model the response of a structure or material, subjected to a set of mechanical and environmental constraints.
- The accuracy of the model can only be as good as the input values are. These must be adequately defined, and the scatter expected for each design parameter has to be estimated, at least.
- Modelling is often confirmed by testing to ensure that the predicted response and the actual tested performance are as expected and as required. This adds confidence to the use of the applied software and leads to model *validation*.
- Task + Deadline determine the Model ! Überlegen, was man sich erlauben kann
- Think first, analyse then!

5.4 Treatment of Notches and Cracks (delaminations)

Stress (local material point):	verification by a strength
Stress concentration (stress peak at a joint):	verification by a notch strength (Neuber)
Stress intensity (delamination = crack):	verification by a fracture toughness

6 Input of Appropriate Properties for Linear and Non-linear Analysis

6.1a Self-explaining Notations for Elasticity Properties (homogenised material)

		Elasticity Properties									proposed for ESA/ESTEC standards
	direction or plane	1	2	3	1	2	3	12	23	13	
9	***general orthotropic***	E_1	E_2	E_3	G_{12}	G_{23}	G_{13}	ν_{12}	ν_{23}	ν_{13}	**comments**
5	***UD, ≅ non-crimp fabrics***	$E_{\parallel}$	$E_{\perp}$	$E_{\perp}$	$G_{\parallel\perp}$	$G_{\perp\perp}$	$G_{\parallel\perp}$	$\nu_{\parallel\perp}$	$\nu_{\perp\perp}$	$\nu_{\parallel\perp}$	$G_{\perp\perp} = E_{\perp} /(2 + 2\nu_{\perp\perp})$ $\nu_{\perp\parallel} = \nu_{\parallel\perp} \cdot E_{\perp} / E_{\parallel}$ *3 is perpendicular to quasi-isotropic 2-3-plane*
6	***fabrics***	E_W	E_F	E_3	G_{WF}	G_{W3}	$G_{\vert W3}$	ν_{WF}	ν_{W3}	ν_{W3}	*Warp = Fill*
9	***fabrics general***	E_W	E_F	E_3	G_{WF}	G_{W3}	G_{F3}	ν_{WF}	ν_{F3}	ν_{W3}	*Warp ≠ Fill*
5	***mat***	E_M	E_M	E_3	G_M	G_{M3}	G_{M3}	ν_M	ν_{M3}	ν_{M3}	$G_M = E_M/(2+2\nu_M)$ *1 is perpendicular to quasi-isotropic mat plane*
2	***isotropic*** *for comparison*	*E*	*E*	*E*	*G*	*G*	*G*	*ν*	*ν*	*ν*	$G=E/(2+2\nu)$

Number of independent properties due to material symmetry

It is mandatory that the notations -especially for composites- are unique and self-explaining! Then, expensively generated test data will remain understandable and therefore not get lost [Böhler].

6.1b Self-explaining Notations for hygrothermal Properties (homogenised material)

Hygro-thermal properties							
direction, or **plane**	1	2	3	1	2	3	
general orthotropic	α_{T1}	α_{T2}	α_{T3}	α_{M1}	α_{M2}	α_{M3}	**comments**
UD, ≅ non-crimp fabrics	$\alpha_{T\|\|}$	$\alpha_{T\perp}$	$\alpha_{T\perp}$	$\alpha_{M\|\|}$	$\alpha_{M\perp}$	$\alpha_{M\perp}$	
fabrics	α_{TW}	α_{TW}	α_{T3}	α_{MW}	α_{MW}	α_{M3}	$Warp = Fill$
fabrics general	α_{TW}	α_{TF}	α_{F3}	α_{MW}	α_{MF}	α_{M3}	$Warp \neq Fill$
mat	α_{TM}	α_{TM}	α_{TM3}	α_{MM}	α_{MM}	α_{MM3}	
isotropic **for comparison**	α_T	α_T	α_T	α_M	α_M	α_M	

Minimum number !!

NOTE: 1.) Number of properties is remains the same for strength and physical parameters (VDI 2014)
2.) Despite of annoying people, I propose to rethink the use of α for the CTE and β for the CME.
Utilizing α_T and α_M automatically indicates that the computation procedure will be similar.

6 Input of Appropriate Properties for Linear and Non-linear Analysis

6.1c Self-explaining Notations for Strength Properties (homogenised material)

	Fracture Strength Properties									
	loading	**tension**			**compression**			**shear**		
	direction or **plane**	1	2	3	1	2	3	12	23	13
9	**general orthotropic**	R_1^t	R_2^t	R_3^t	R_1^c	R_2^c	R_3^c	R_{12}	R_{23}	R_{13}
5	**UD, ≅ non-crimp fabrics**	$R_{\parallel}^t$ NF	$R_{\perp}^t$ NF	$R_{\perp}^t$ NF	$R_{\parallel}^c$ SF	$R_{\perp}^c$ SF	$R_{\perp}^c$ SF	$R_{\parallel\perp}$ SF	$R_{\perp\perp}$ NF	$R_{\parallel\perp}$ SF
6	**fabrics**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}
9	**fabrics general**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}
5	**mat**	R_{1M}^t	R_{1M}^t	R_{3M}^t	R_M^c	R_{1M}^c	R_{3M}^c	R_M^τ	R_M^τ	R_M^τ
2	**isotropic**	R_m SF	R_m SF	R_m SF	*deformation-limited*			R_M^τ	R_M^τ	R_M^τ
		R_m NF	R_m NF	R_m NF	R_m^c SF	R_m^c SF	R_m^c SF	R_m^σ NF	R_m^σ NF	R_m^σ NF

NOTE: *As a consequence to isotropic materials (European standardisation) the letter R has to be used for strength. US notations for UD material with letters X (direction 1) and Y (direction 2) confuse with the structure axes' descriptions X and Y . *Effect of curing-based residual stresses and environment dependent on hygro-thermal stresses. *Effect of the difference of stress-strain curves of e.g. the usually isolated UD test specimen and the embedded (redundancy) UD laminae. R_m := 'resistance maximale' (French) = tensile fracture strength (superscript t here usually skipped), R:= basic strength. Composites are most often brittle and dense, not porous! SF = shear fracture

How to achieve *Strength Design Values & Design Allowables* (Airbus Diskussion)

Material Supplier	Customer			
Manufacture *1* raw data, T99 / T90 data **Manufacture *2*** raw data, T99 / T90 data **Manufacture *n*** raw data, T99 / T90 data	**In-house tests** raw data, T99 / T90 data	**Pooling of T data,** **S-value adjustment, Material Procurement** **Determination of *Strength Design Values***	**Determination of *Strength Design Allowables*** *(A-, B-values)* based on statistical rules in MMPDS Hdbk (formerly MIL Hdbk 5)	**approval** by handbook committee , agency etc.
		for **design + analysis**	for **design verification**	

S-value: Procurement value

A-, B-value: Strength *Design Allowables. Statistically defined like T99/T90 –values. Number of different batches is required, on top.*

T99/T90-values: *Material* strength allowables. The determination follows the same statistical procedure as with the Strength Design Allowables. However, the data volume and batch requirements are less stringent.

A > S, only allowed if premium selection of material is applied. Normally ***A < S.***

HSB HANDBUCH STRUKTUR BERECHNUNG	Material properties, CFRP, T300 / Code69, UD-Prepreg	12911-01 Issue D Year Page 1 of

Key Words: Material properties, CFRP, T300, Code69, UD-Prepreg

References

[1] Report QE-630 / 83, WEP, DORNIER, 1978/79

[2] Report DOL73/74, DORNIER, 1973/74

[3] Report SK50-266/85, DORNIER, 1985

1 Material

Material specification	CFRP T300 / Code69 UD-Prepreg
Specification for delivery	DOL 74, Edition January 1978

Characteristic	Unit	Value (remarks)
Fiber type		Toray T300/6K
Fiber density	g/cm^3	1.75
Matrix type		Epoxy-Code69
Matrix density	g/cm^3	1.27
Prepreg ply thickness	mm	0.231
Contents of prepreg resin	mass %	43 ± 2.5
Fiber volume fraction	%	60
Prepreg density	g/cm^3	1.56
Cure process specification		DOL 74, Edition January 1978
Cure temperature	°C	175 (hold time = 75 min.)
Cure vacuum	bar	0.07 (hold time = whole process)
Cure pressure	bar	7 (hold time = whole process)
Post cure temperature	°C	

2 Physical properties

Characteristic	Unit	Value	Statistics	Ref.
c	kJ/(K · kg)			
$\lambda_{\parallel}$	W/(K · m)			
$\lambda_{\perp}$	W/(K · m)			
$\kappa_{\parallel}$	1/(Ω · m)			
$\kappa_{\perp}$	1/(Ω · m)			

HSB HANDBUCH STRUKTUR BERECHNUNG	Material properties, CFRP, T300 / Code69, UD-Prepreg	12911-01 Issue D Year 198 Page 2 of 2

3 Mechanical properties

Test temperature		RT		
Moisture contents		SA[a]		
Property	Unit	Value	Statistics	Ref.
$R_{\parallel t}$	MPa	1280	A	[1]
$R_{\perp t}$	MPa			
$R_{\parallel c}$	MPa			
$R_{\perp c}$	MPa			
$R_{\perp \parallel}$	MPa			
$ILSS$	MPa	65	A	[1]
$E_{\parallel t}$	MPa	133000/116000	$\overline{x}$/A	[1]
$E_{\perp t}$	MPa			
$E_{\parallel c}$	MPa			
$E_{\perp c}$	MPa			
$G_{\parallel \perp}$	MPa			
$\nu_{\parallel \perp}{}^{c}$	-	0.32	$\overline{x}$	[2]
$\nu_{\perp \perp}$	-	0.4^{d}		
$e_{\parallel t}$	%	1.3	S	[2]
$e_{\perp t}$	%			
$e_{\parallel c}$	%			
$e_{\perp c}$	%			
$e_{\parallel \perp}$	%			
$\alpha_{M\parallel}$	mm/(mm · %)			
$\alpha_{M\perp}$	mm/(mm · %)			
$\alpha_{T\parallel}$	mm/(mm · K)	$-(0.8 \pm 0.2) \cdot 10^{-6}$	$\overline{x}$	[2]
$\alpha_{T\perp}$	mm/(mm · K)	$+(27.0 \pm 1.0) \cdot 10^{-6}$	$\overline{x}$	[2]
T_g	°C	200	[b]	[3]

T_g = glass transition temperature

[a] = Standard Atmosphere according to ISO554/DIN50014: $23/50 = 23 \pm 2°C/50 \pm 5\%RH$

[b] = no statistical base

[c] = major value

[d] = assumed

Note: DOL 74 (Edition Jan.78) has been replaced by DOL 74 (Edition Nov.82), strength data have not changed. Determination of the elastic moduli according to LN 29971.

Beispiel: HSB-Werkstoffblätter

6.2 Utilization of which Statistical Properties ?

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1 Input: ***DESIGN*** **Stress & Strain Analysis** **(*Struktur-Analyse)***

** Mean elasticity properties and geometry (thickness, length) to represent mean structural behaviour. Is economic wrt number of analyses as well as a necessity in case of (usual) redundant behaviour of the structure.*

** Choice of code-dependent + problem-dependent stress-strain curve*

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2 Input: Strength Demonstration (verification) **(*Nachweis)***

One-sided (static and fatigue strength), and two-sided tolerance bands (thickness, E-modulus) have to be considered …

3 Input: Stiffness Demonstration

Due to stiffness requirements → upper and/or lower tolerance limits

………………………………………………………………………………………………….

4 A-and B-value *Design Allowables* (Aerospace) (statistics–based, Mil Hdbk)

A-values: In application of the military Safe Life Concept

B-values: In application of Damage Tolerance Concept (multiple load paths).

NOTE: To achieve a reliable design the so-called *Design Allowable has* to be applied.
It is a value, beyond which at least 99% (“A” value) or 90% (“B” value) of the population of values is expected to fall, with a 95% confidence (on test data achievement) level, see MIL-Hdbk 17.

7. Failure Conditions
Example: Strength Failure Conditions

Failure Conditions shall

• ***assess multi-axial stress states in the critical material point***

Mises ??

$$\frac{\sigma_{eq}}{R} = \frac{\sigma_{eq}^{mode}}{R^{mode}}$$

more precisely

by **utilizing the uniaxial strength values R** and an **equivalent stress σ_{eq}, representing a distinct actual multi-axial stress state**

Physically necessary curve parameters on top of the strengths should be assessable on the safe side for pre-dimensioning .

→ Extra-Vortrag

They have to be generated :

for *** dense & porous,**

*** ductile & brittle behaving materials,**

for *** isotropic material**

*** transversally-isotropic material (UD := uni-directional material)**

*** rhombically-anisotropic composite material (woven fabrics, non-crimped fabrics, braided + stitched + z-pin textiles, …)**

8. Material & Structural Testing and NDI

8.1 General

Materials Testing

Structural Testing (most often destructive testing)

Non-Destructive Testing (NDT, NDI, NDE),

NDI should be part of a
"systems solution"

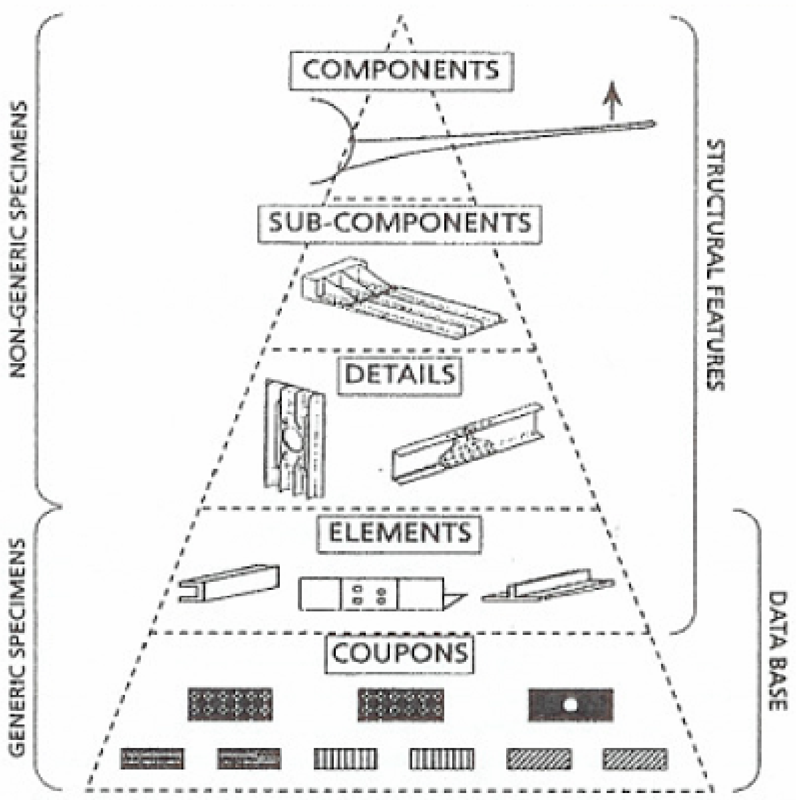
* Failure: Detection, localization, sizing + shaping

* Failure: Assessment (*risk-based)*

8.2 Characterisation of Composite Material and Components

MIL Hdbk 17: *Composites*	**Material**			**Structure**
Structural complexity level	***Screening***	***Qualification***	***Acceptance***	***structural substantiation***
constituent	X			
lamina	X	X	X	
laminate		X	X	X
structural element	X	X	X	X
structural compon.				X

The pyramid of tests MIL-HDBK-17-1E



composite test specimens

Modelling & Discretizing
determines type of test specimen

8.3 Structural Testing (often destructive testing)

8. Testing and NDI

8.4 Structural Testing

(often destructive testing)

ARIANE 5

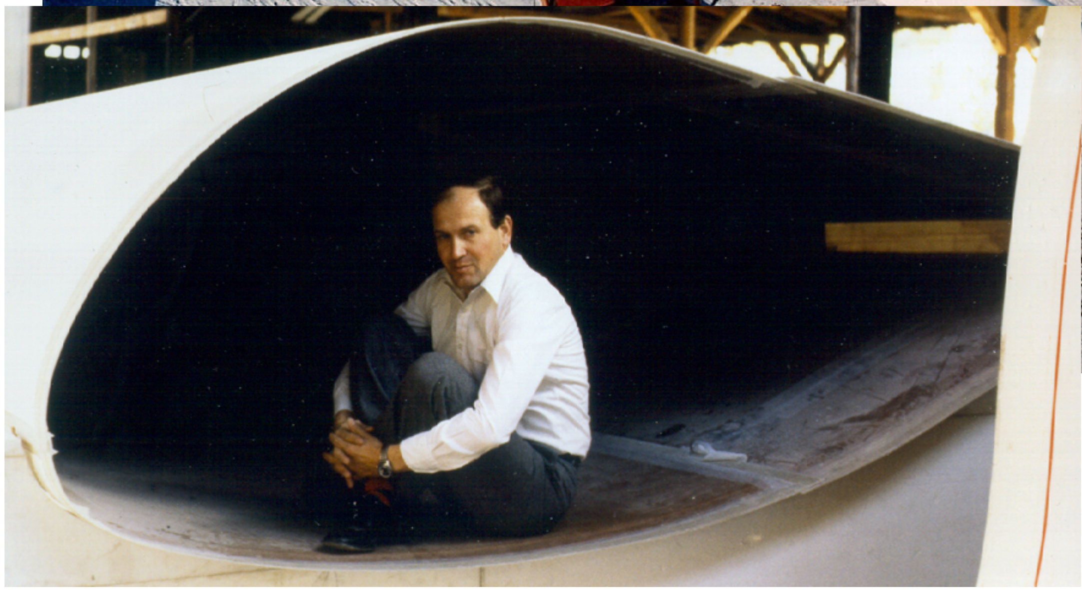
Front Skirt

Lesson Learnt:

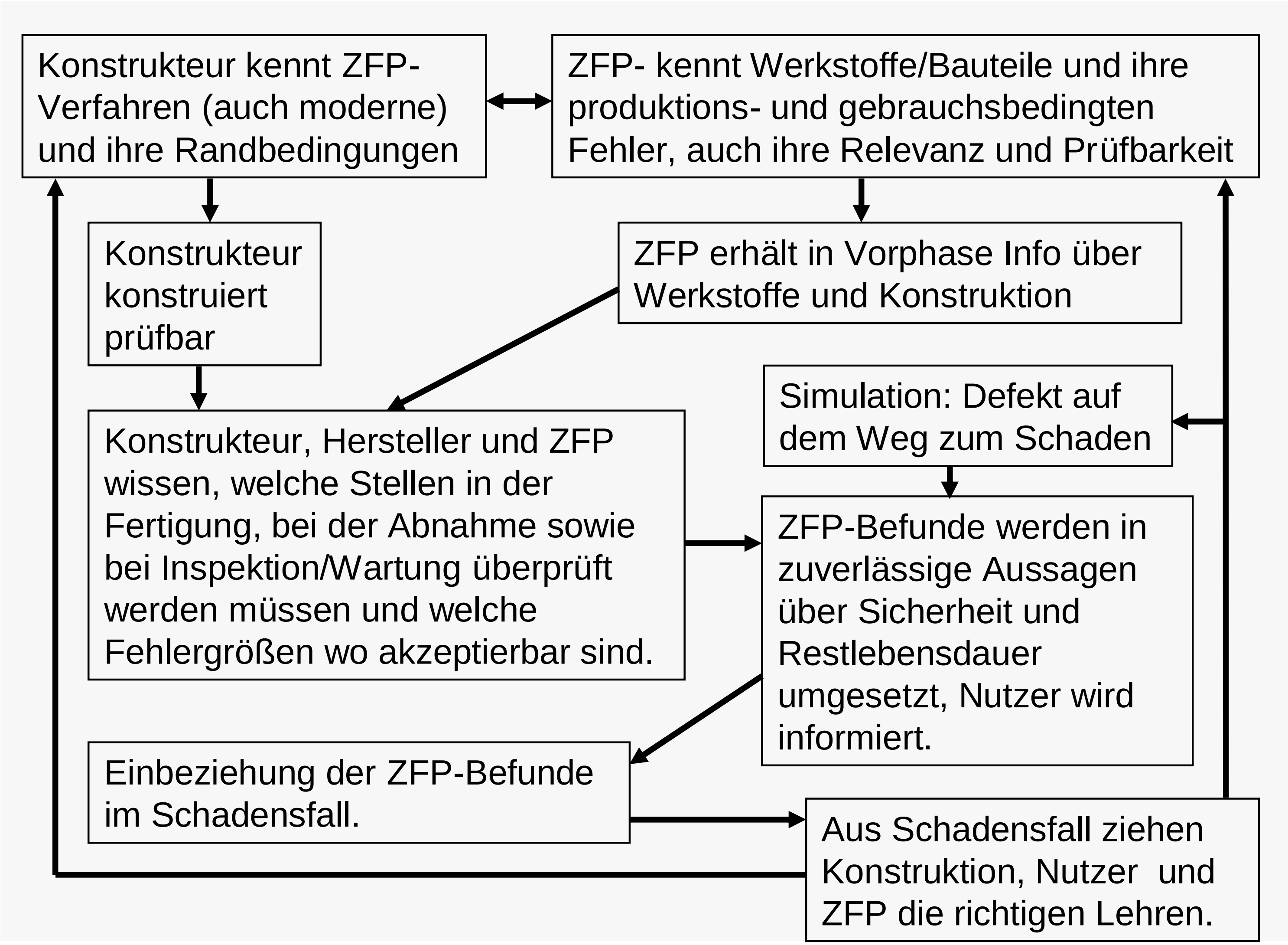
Strain gages in the smooth strain regimes , only !

8. Material & Structural Testing and NDI

8.6 Structural Testing of GROWIAN

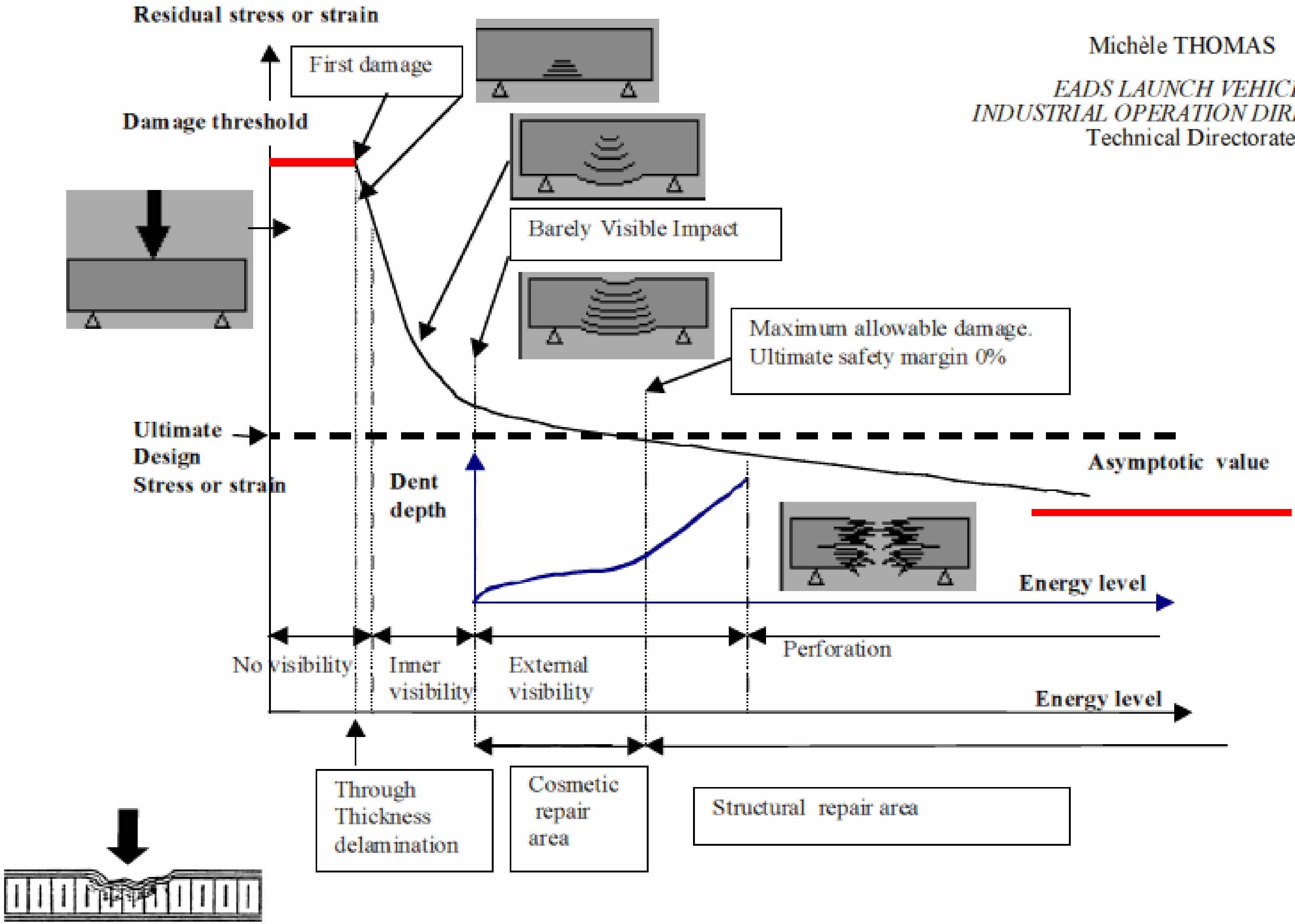


G. Busse: Wunschtraum über Einbindung der ZFP



8. Material & Structural Testing and NDI

8.8 Effects of Defects (better flaws !)



Michèle THOMAS

EADS LAUNCH VEHICLES
INDUSTRIAL OPERATION DIRECTORATE
Technical Directorate

Figure 1 - Impact damage phenomenon

8.9 Damage Assessment

Damage assessment necessary for:

- Damage Tolerance Analysis
- Fixation of Accept-Reject Criteria for Quality Assurance

Was denkt z. B. die US-Luftfahrtbehörde FAA aktuell über ?

Certification Specifications Airplanes:

FAR 25 of Federal Aviation Agency

(CS 25 of European Aviation Safety Agency)

Composite Damage Tolerance and Maintenance Safety Issues

Federal Aviation Administration

LBA Braunschweig analog

Larry Ilcewicz

CS&TA

Federal Aviation Administration

July 19, 2006

- *Background*
- *Damage threat assessment*
  - *Key composite behavior*
  - *Categories of damage*
  - *Structural substantiation*
- *Inspection & repair considerations*
- *Safety management*

2006 FAA Composite Damage Tolerance and Maintenance Workshop

Primary objective: Address safety concerns and technical issues for composite damage tolerance & maintenance

Secondary objectives

1. Discuss factors affecting the substantiation of damage tolerance and maintenance inspection & repair
2. Discuss elements of safety management
3. Discuss structural test protocols and supporting analyses
4. Discuss damage & defect types and inspection technology used for manufacturing, field inspection and repair
5. Identify needs for regulatory requirements and guidance
6. Identify needs for standards (guidelines, databases, and tests)
7. Provide directions for research and training developments

Damage Threat Assessment for Composite Structure

FAR 25.571 Damage Tolerance & Fatigue Evaluation of Structure … must show that catastrophic failure due to fatigue, corrosion, *manufacturing defects, or accidental damage* will be avoided through the operational life of the airplane.

Categories of Damage & Defect Considerations for Primary Composite Aircraft Structures

Category	Substantiation Considerations	Elements of Safety Management*
Category 1: Damage that may go undetected by field inspection methods (detection not required)	Demonstrate reliable service life Retain Ultimate Load capability Used to define retirement	Design-driven (with safety factor) Manufacturing QC Maintenance interface
Category 2: Damage detected by field inspection (repair scenario)	Demonstrate reliable inspection Retain Limit Load capability Used to define maintenance	Design for rare damage Manufacturing QC Maintenance action
Category 3: Obvious damage detected within a few flights by operations (repair scenario)	Demonstrate quick detection Retain Limit Load capability Used to define operation actions	Design for rare large damage Operation action Maintenance action
Category 4: Discrete source damage and pilot limits flight maneuvers (repair scenario)	Defined discrete-source events Retain "Get Home" capability Used to define operation actions	Design for rare known events Operation immediate action Maintenance action
Category 5: Severe damage created by anomalous ground or flight events (repair scenario)	Repair generally beyond design validation *(known to operations)* May require new substantiation	Requires operations awareness for safety (immediate reporting) Maintenance & design action

* All categories include requirements

Recommended Strategies for Composite Maintenance Technology Development

Design for Repair

Early development of maintenance procedures

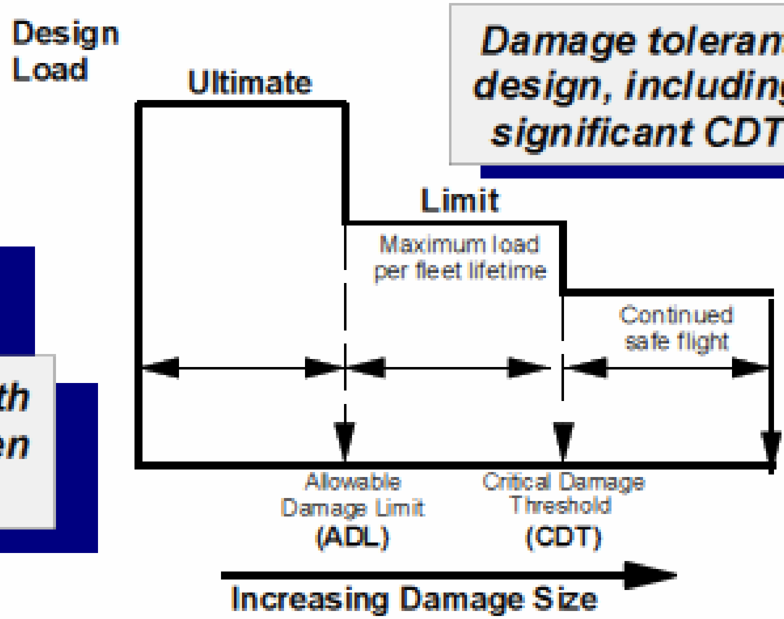
***Efficient, low-cost NDI procedures to locate damage** (that always find CDT)*

Reliable and simple NDE to quantify effects of damage

Cost-effective repair with minimal down time when damage is found

Well-defined ADL

Damage tolerant design, including significant CDT



Taken from: "Composite Technology Development for Commercial Airframe Structures," L.B. Ilcewicz, Chapter 6.08 from *Comprehensive Composites* Volume 6,, published by Elsevier Science LTD, 2000.

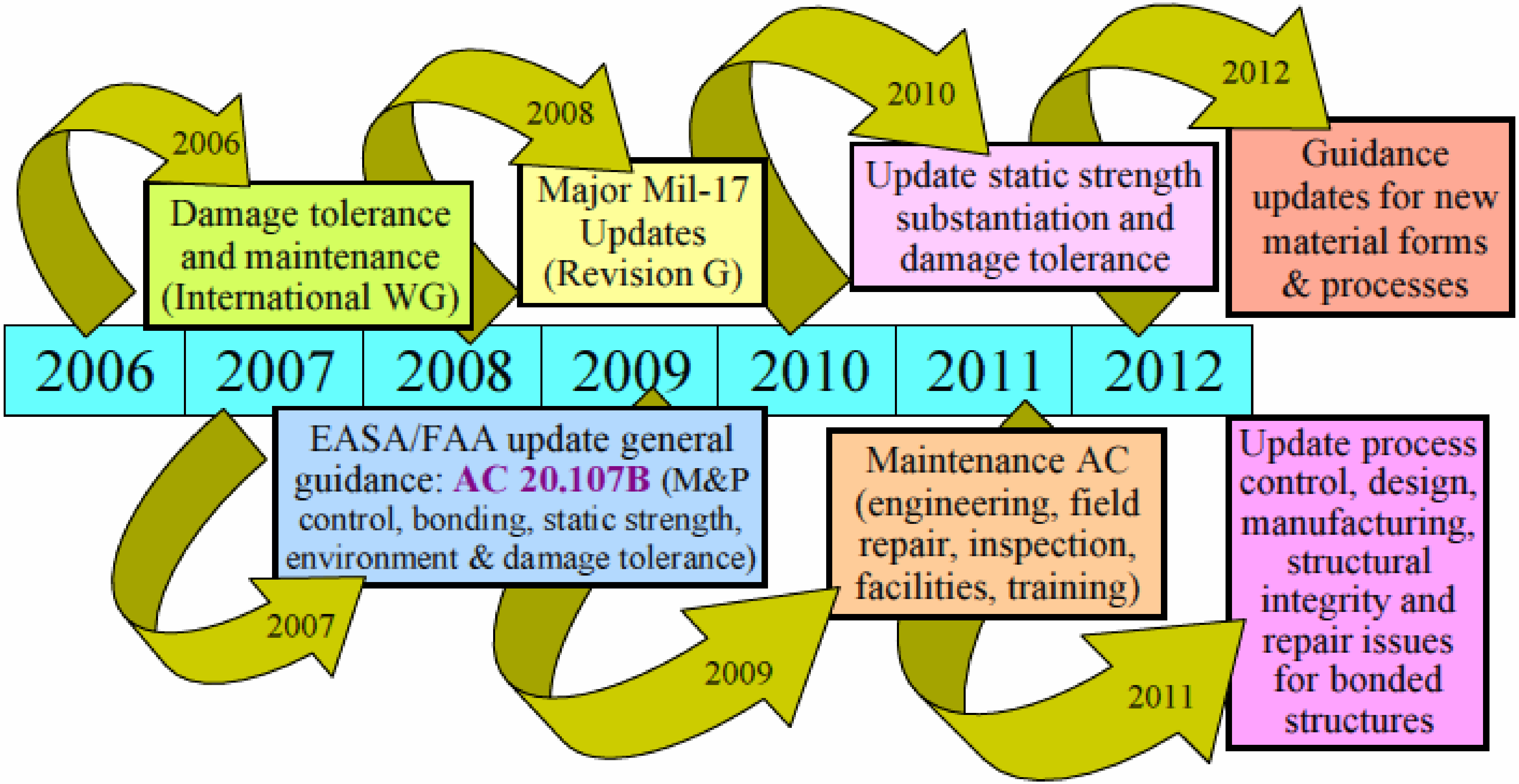
Inspection & Disposition Considerations

- Questions to drive damage detection
  - Advantages possible with more sophisticated NDI?
  - Inspection technologies needed for the least detectable Category 2 and 3 damages?
  - Are there Category 5 damages that are not visibly detectable from the exterior?
- Questions to ask after damage is detected
  - What is the full extent of damage?
  - Is a special inspection needed for non-obvious damage?
  - Does the damage require repair?
  - Is there a substantiated repair for the specific damage?
  - What engineering steps are needed for repair substantiation? (primary vs. secondary, design, analysis, test data)

Safety Concerns for Composite Airframe Structures

- Unanticipated accidental damage threats that are not covered by design criteria
  - Damage that can't be found with maintenance inspection procedures and lowering structural capability below URS
  - Damage that is not obvious and lowering structural capability to near LRS
- Environmental damage developing/growing with time
- Systematic structural bonding process problems that are not localized or contained to limited aircraft
- Severe damage occurring in flight, incl. take-off & landing, without knowledge of flight crew (overloads)

Future milestones for Composite Safety & Certification Policy, Guidance & Training



*FAA hat sich eine **langjährige** Arbeit zusammen mit der Industrie vorgenommen* !

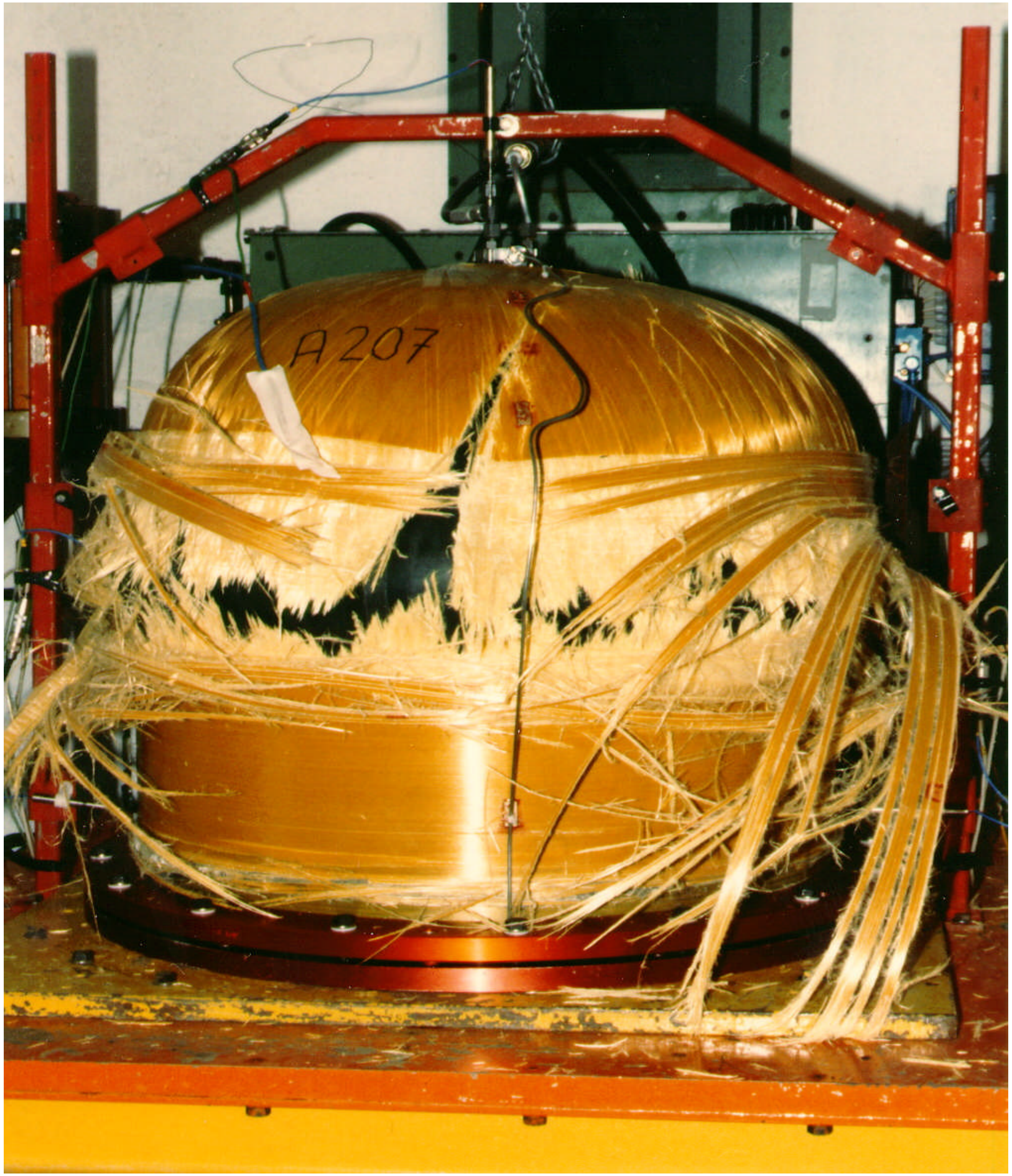
Ersatz-Bibel für Compositler !

Links with Mil-Handbook-17 (CMH-17), SAE CACRC and Safety Management

- Mil-Handbook-17 (Composite Materials Handbooks, CMH-17)
  - ~ 100 industry engineers meet every 8 months
  - Airbus/Boeing/EASA/FAA WG deliverables to update CMH-17, Vol. 3 Chapters on Damage Tolerance & Supportability for Rev. G
  - New CMH-17 Safety Management WG has been initiated
  - *FAA strategy: use CMH-17 for educational purposes to generate revenue that helps develop more standards*
- SAE CACRC (Commercial Aircraft Composite Repair Committee)
  - ~ 50 industry engineers meet every 6 months (~7 WG)
  - Airlines have dropped out of CACRC over time, requiring more OEM and MRO leadership for organization to survive
  - *FAA strategy: continue to support CACRC with resources and research funding of standards & repair process trials*

einige Besonderheiten + Achillesfersen der Composites

- \- NDI: Impact, ‘kissing bonding‘
- \- Stress peak sensitivity
- \+ Relatively flat S-N curves, in consequence large scatter for repeated loading
- \- Environmental effects require careful consideration (moisture)
- \- Relatively large manufacturing defects and impact damage to be considered in design criteria
- \- Compression & shear residual strength are affected by damage
- \+ Similar tensile residual strength behavior to metals
- \+ Gute Integrierbarkeit mit weiteren (z.B. smarten) Werkstoffen
- \- Still limited service and repair experiences.



MAGE

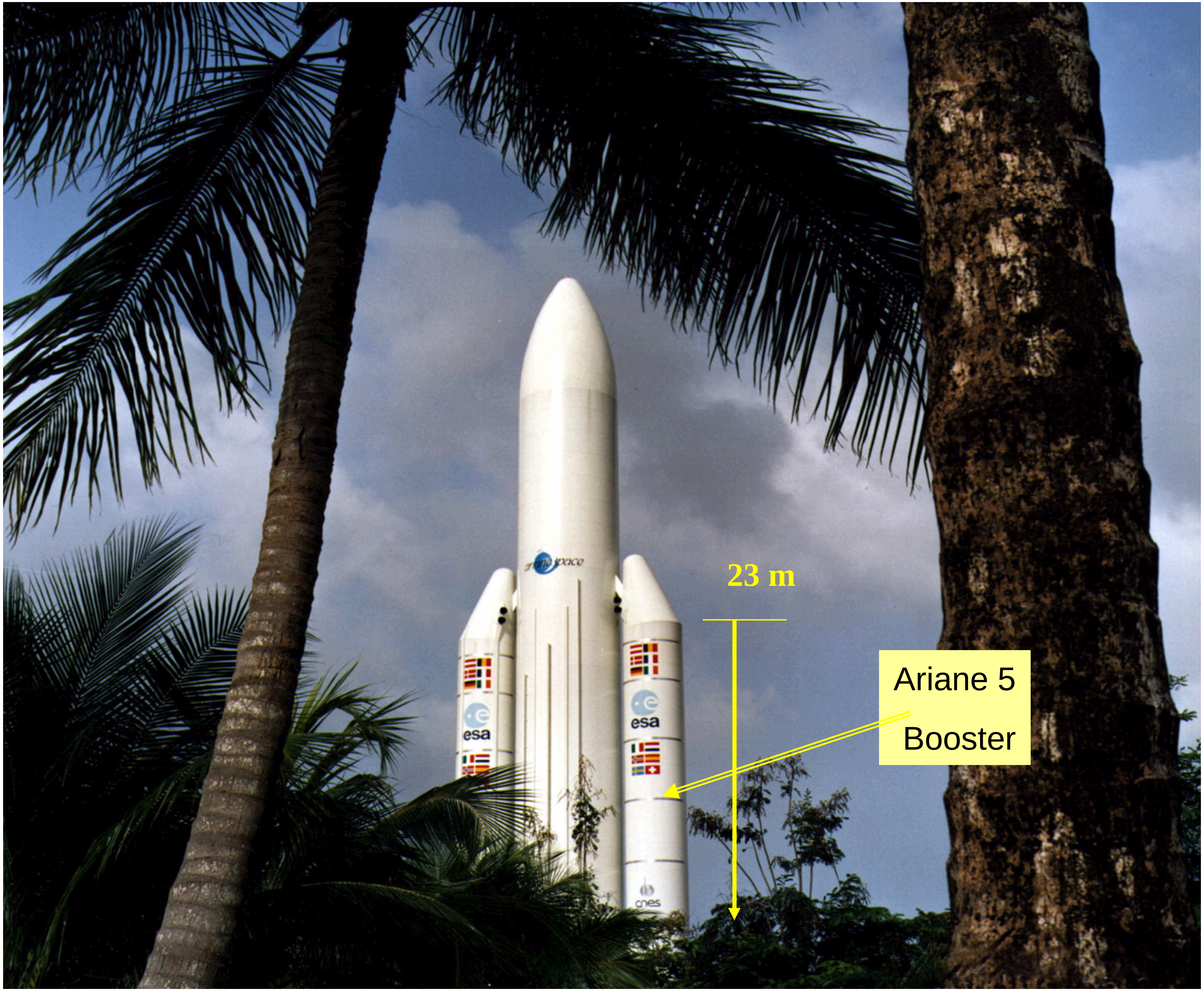
motor case

after

Qual. Test

Vorhersage des Abstandes der Polkappen

Eigenspannungen aus Aushärtung


23 m
Ariane 5
Booster

Influence of Manufacturing Tolerance

Booster Wall Thickness tolerance:

Former : t = 8.2 +- 0.20 mm

Improved manufacturing : t = 8.2 +- 0.05 mm .

Reduction in scatter permits, if

keeping the same theoretical reliability value $\Re = 1 - p_f = 1 - 5 \cdot 10^{-6}$

-

New nominal thickness : t = 8.1 +- 0.05 mm.

How much mass did we save keeping to the same reliability level ? And, fuel savings ???

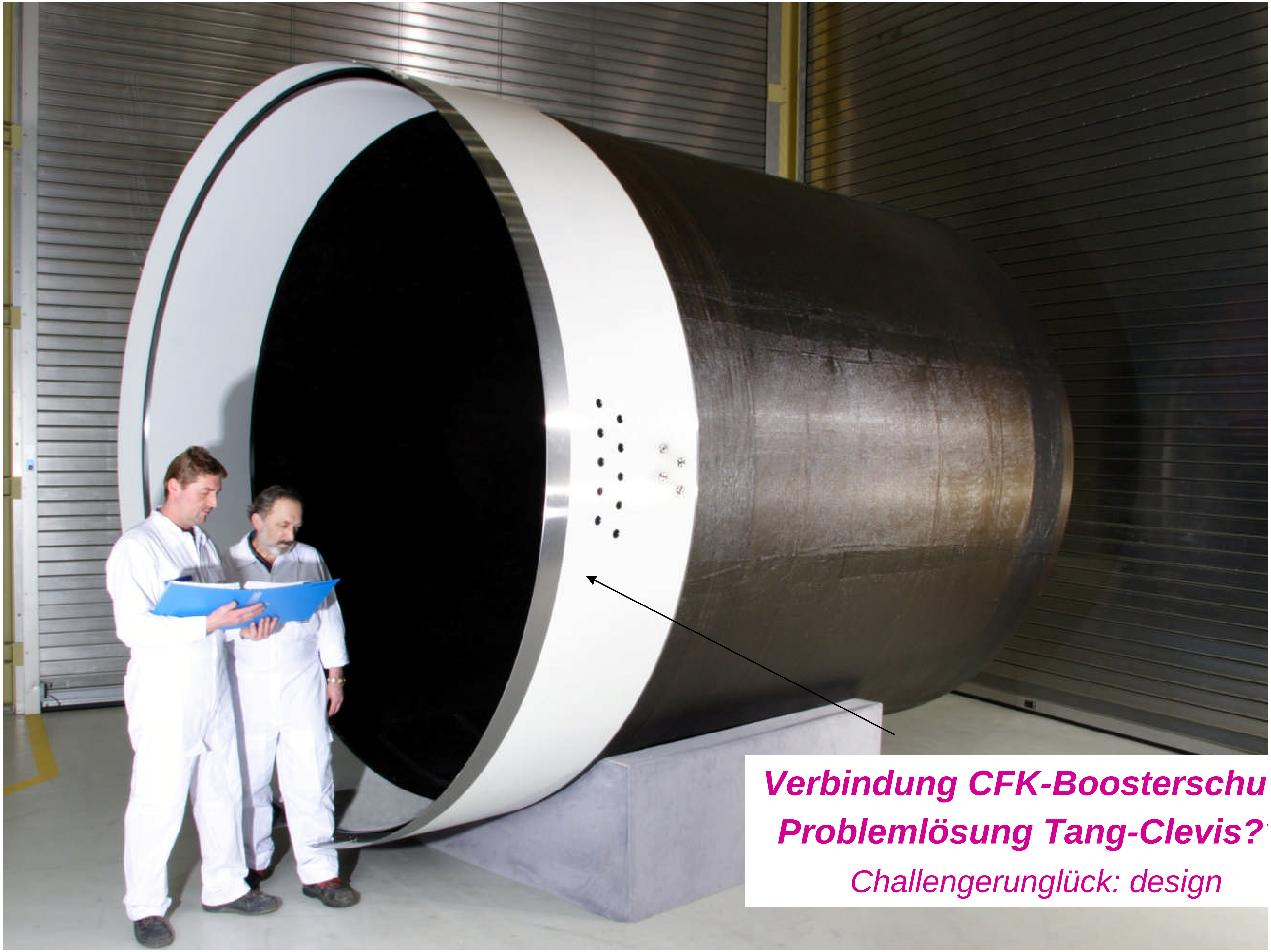
Connecting pins of the Booster sections, termed Tang-Clevis connection:180 pieces

Probabilistic modelling of the geometrical tolerances of:

bore hole, pin, position (pitch), strength

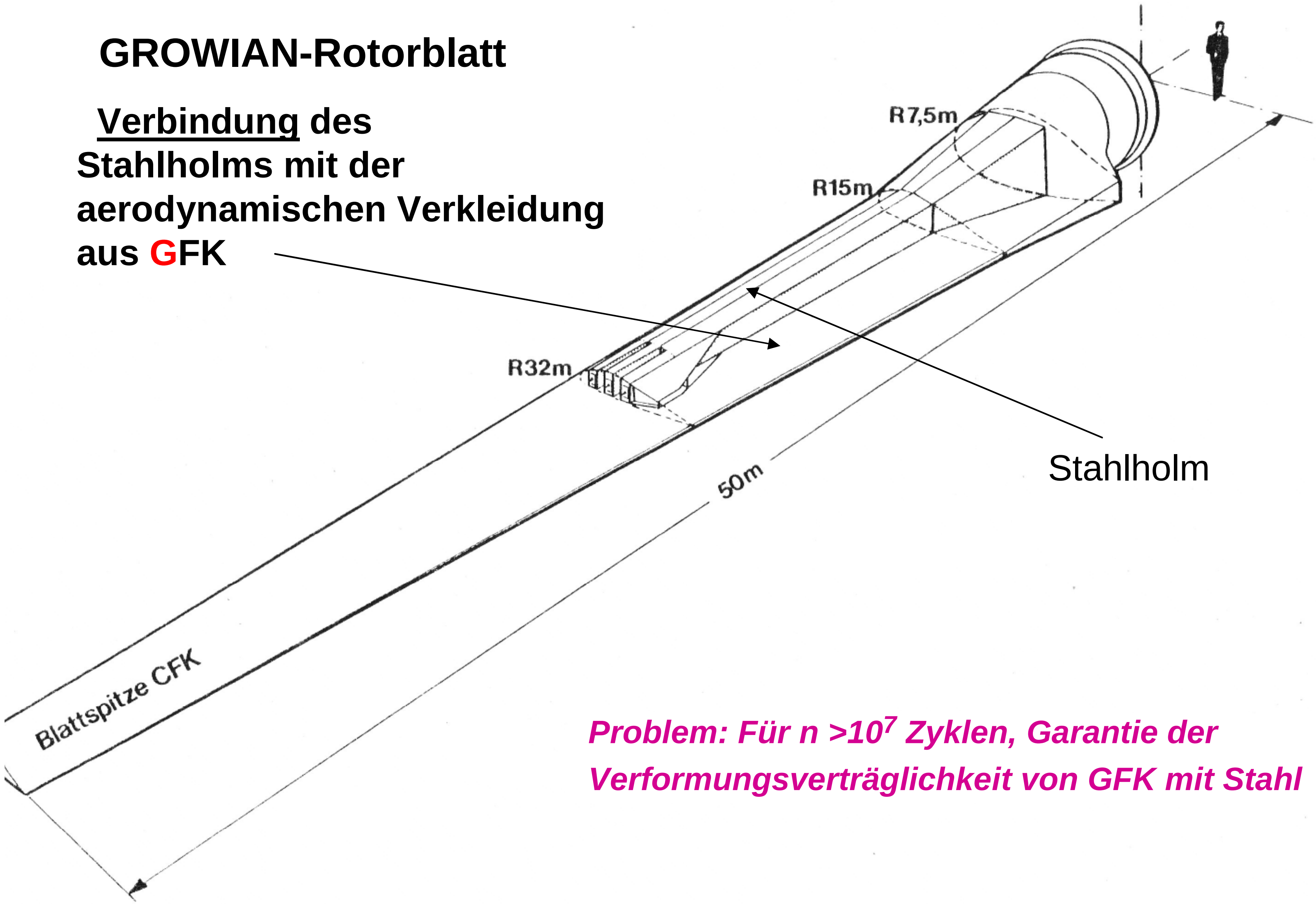
in order to support a design decision on *asssembly + fixation of tolerance values.*

The pitch (Teilung) was the driving design parameter.


Verbindung CFK-Boosterschu
Problemlösung Tang-Clevis?
Challengerunglück: design

GROWIAN-Rotorblatt

<u>Verbindung</u> des Stahlholms mit der aerodynamischen Verkleidung aus GFK



Problem: Für n >10^7 Zyklen, Garantie der Verformungsverträglichkeit von GFK mit Stahl

9 Margin of Safety (MOS) and Reserve Factor

9.1 Determination of Load-based Reserve Factor for *example strength*

Testauswertung

$$f_{Res} = \frac{Final\ \ Failure\ \ Load}{j \cdot Design\ \ Limit\ \ Load} = MS + 1$$

$$= \frac{design\ \ allowable\ \ 'load\ \ resistance'}{j \cdot Design\ \ Limit\ \ Load}$$

If linear analysis permitted:

$$f_{Res} = \frac{design\ \ allowable\ \ "strength"}{j \cdot \sigma(DLL)}$$

9 Margin of Safety (MOS) and Reserve Factor

9.2 Lessons Learnt

1. ***Robust*** (tolerant) ***design*** or robustness to later changes of the design parameters with identification of the most sensitive design parameters is a NEED

2. ***Physics have to be modelled accurately* !**

   The choice of the task-corresponding stress-strain curve has to be carefully performed (min or mean or max).

3. ***Increasing mean value*** and **decreasing *standard deviation*** lower failure probability

4. ***Failure probability*** p_f does not dramatically increase if *MS* turns slightly negative

   A local **safety measure** ***MS*** = *-1 %* is no problem in *design development* .
   The MS value does not outline the risk or the failure probability!

MS=-0.3

- Do not overreact by re-design

- Apply a ' Think (about) Uncertainties ' attitude by

*** recognizing the main *driving design parameters*** and

*** reducing the scatter (uncertainty) of them.**

This highly pays off !

Essential question wrt all uncertainties:

Do they increase the risk to an unacceptable level or not !

Final Comments

Prof. Klöppel: In den 50er und 60er Jahren ‚Stahlbaupapst‘ in Deutschland

„Mir ist angst vor 2 Typen von Ingenieuren:

- Der eine kann <u>alles</u> rechnen!

- Der andere hat <u>alles</u> im Gefühl!“

Finde einen Kompromiß !

- Experimental results can be far away from the reality like an inaccurate theoretical model !

- <u>Theory</u> ‘only’ creates a model of the reality, and <u>experiment</u> is ‘just’ one realisation of the reality !

Mach beides,analysiere und teste !

Aristoteles/Heriot: “The Whole is more than the sum of its parts”:

“Think the WHOLE of functional requirements” ,

not -for instance- strength only, <u>and</u> look over the fence !

Agenda (Dr. Schroeder)

Kick-off Meeting der CCeV Arbeitsgruppe „Engineering" am 03.04.2009
Beginn 13:00 Uhr, IHK Schwaben, Stettenstrasse 1 + 3, Augsburg

- **Vorstellung der Teilnehmer**
- **Vorstellung CCeV** *H.-W. Schroeder*
- **Impulsvortrag „Auslegung und Nachweis"** *R. Cuntze*
- **Diskussion der Themen:**
  - Was sollte in den Engineering-Unterarbeitsgruppen bearbeitet werden?
  - Festlegung von Arbeitschwerpunkten (nach augenblicklicher Wichtigkeit)
  - Werkstoffdaten für die Analyse? (Prüfstandards seitens der Konstruktion)
  - Fachwissenschaftliche Vortragsthemen gewünscht ? (s. Impulsvortrag)
  - Zusammenarbeit mit anderen Gremien, Instituten, …
- **Festlegung von Unterarbeitsgruppen**
- **Workshops ?**

Themenblock-Vorschläge

- Theorie (Modell-Bildung, Analyse, Bruchmechanik, Parameteridentifikation, Optimierung, Sensitivitätsanalyse + Fertigungstoleranzanalyse mit Einsatz prob. Mittel, Nachweise
- Werkstoffkennwerte-Ermittlung (Standards, Auswertung, Probekörper, statisch/zyklisch/impact, ungekerbt(gekerbt, ..)
- Bauweisen/ Lasteintragung/ Verbindungen, Repair
- Herstell-Imperfektionen (manufacturing signatures = Fehler, Faserablage, …)
- Konstruktionshinweise zwecks Minimierung von Composites-Nachteilen (Baier)
- Ermüdung, Impakt, Schadensakkumulation, Delaminationsfortschritt