Integrating Materials Modeling Aspects into the Industrial Analysis of Composite Structures

Composites Testing & Model Identification 2008
1. Context for the Industrial Analysis of Composite Structures

2. Integrating Materials Modeling Aspects

3. Case Study: Plain Strength Criteria

4. Conclusions and Perspectives
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Context for the Industrial Analysis of Composite Structures

- Constant innovation is necessary in order to reach the objectives (Weight, Cost and Time) set by new aircraft programmes.
- The introduction of new materials and technologies shall not degrade the current already agreed safety level (i.e., metallic structures).
- The developments must fit the industrial context, taking into account:

  **CERTIFICATION**

  FAR25/CS25; AC20-107A/AMC25.603; etc.

  **IN-SERVICE EXPERIENCE**

  f.y.i. : “How, over the past 30 years, ‘Part 25’ Composite Structures have been coping with metal minded F&DT requirements, J. Rouchon, 24th ICAF Symposium, Naples, Italy, 16 May 2007.

  **VERIFICATION & VALIDATION**

  Improvement often refers to Virtual testing: This requires the development of physical and robust approaches to predict the deformation and failure of composite structures.

  **STATIC-F&DT ANALYSES**
Context – Airworthiness requirements for Loads

- (FAR/CS25.301/.305/.307) Proof of structure:
  - *Limit load* without detrimental permanent deformation,
  - *Ultimate load* (1.5*LL) during 3s without failure,
  - *Maintain in the time* this ability.

- *Load Cases are combined Mechanical & Thermal,*
  - *Example (Rudder):*
    - 400 load cases such as mechanical (gusts, manoeuvres, ground), fail-safe, system failures, etc.
    - Combined with relevant hot/cold cases
  → around **800 load cases**, multi-axials.
AMC25.307: … Compliance can be shown by:

- analysis supported by previous test evidence (best),
- analysis supported by new test evidence (most likely) or,
- by test only (impractical in most cases).

… The application of methods … to complex structures … is considered reliable only when validated by full scale tests …
Context – Structure Analysis

- **Product requirements**
- **Structural criteria and requirements**
- **Stressing process**
- **Sizing and Stress Methods**
  - Structure Idealisation
  - Internal Load Distribution
- **Strength Methods**
  - Global-Local Models
  - Deformation and Failure Models and Criteria
- **Evaluations**
  - Requirements
  - **Validation**
  - Design Values
  - Structure Allowable Tools
  - Validation
- **Material/Processes**
  - Load cases
  - Design principles
- **Design principles**
- **Reserve factor**
Context – Building-Block approach

1. Full scale

- Demonstrate / Validate accuracy against predicted failure mode up to specific features
- Establish process capabilities (assembly/parts vs inspection methods)

25.307
- Validate design & assembly concepts
- Verify global FEM predicted stress/strain distribution & analysis methods

- Demonstrate / Validate accuracy against predicted failure mode up to specific features
- Establish process capabilities (assembly/parts vs inspection methods)

25.603-605-613
- Establish standards specification (materials / manufacturing)

(x 1000) Coupon
- Material statistical basis (five batches & 6 specimens)
- Generic characteristics (Strain, Failure Modes, EKDF)

(x 100) Element
- Generic characteristics
- Manufacturing technology
- Intrinsic properties

(x 10) Detail

(x 1) Component

AMC 25.603 for definitions

Test with environment effect

Without ageing & RT

thermal
ToC

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Stress Process

Several Design/Calculation loops taking into account all load configurations.

GFEM: Generation of internal loads
Component loads
Refined GFEM, Refined DFEM

Optimisation
Databank: Interface loads, 2D flows, Beam forces, Rod forces, Grid point forces

Iteration
FE, Analytical studies, Deformation and Failure Criteria

Geo. data
Sizes
Thicknesses
Lay-ups
Fasteners
...

RF status
Analysis and refined FEM solutions
Geometrical update

A Stress Process is required defining different level of analyses, e.g:

- Pre-sizing: fast evaluation (max. simplifications, gross accuracy),
- Quick Sizing with accuracy in line with simplifications,
- Advanced Sizing for state-of-the-art calculations.
Sizing and Stress methods

- Multi-criteria analyses are performed on details, components, elements:
  - Stiffened panels, Lugs, Joints, etc.

- These can be analytical/numerical with assumption in-line with the levels of analysis (Pre-sizing, Quick Sizing or Advanced Sizing).

Ex: Advanced Stiffened Panel sizing

Global-Local Analyses (Strength Methods after critical area selection)
- Disbonding analysis
- Classical Laminate Analysis,
  - Degradation law,
  - Fibre & Matrix Failure Criteria

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Integrating Materials Modeling Aspects - Strength Methods

- Stress Process and Sizing Methods secure Internal Load Distributions.

Integration of material modelling aspects and strength calculation is done in Strength Methods.

Consequences for Methods and Tools

Methods and Tools are validated inside a specific perimeter that include: technologies, design features, loading, ...

This means we cannot just use any calculation methods combined with any material data.
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Development of Plain Strength Criteria

**Determination of Design Values** (CS25.603/.605/.601, see AC20-107A / AMC25.603): assessment of environmental effects on the design properties through tests and established on a statistical basis.

Certification test pyramid

Example of definition of DV

For Plain Strength

- UD values from test
- Plain Strength Method
- Laminate Strength from test
- Laminate predicted Strength
- UD values Modification
- Specific specimens
- Generic specimens
- Design Values
- Elements/coupons
- Design values test program
- Details
- Sub-components
- Components Full-scale
- Qualification
Development of Plain Strength Criteria
Early developments

**Early method based on Tsai-Hill criteria & first ply failure:**

- Direct use of UD properties values lead to underestimation
  ⇒ UD properties tuned (resin moduli knocked down) to cover the structural space.

**Design Values are defined and validated for a particular design/structural space (technology, design features, loading, etc.) and are always linked to a calculation method.**
Development of Plain Strength Criteria
State-of-the-Art

Later approach: Progressive matrix degradation + fibre failure
- Matrix failure analysed with Matrix criteria & stiffness degradation
- Load redistribution until Fibre failure analysed with Fibre criteria

Current development – Physically-based Multi-scale analyses

Choice of the modelling scale
- Macroscopic scale
- Mesoscopic scale
- Microscopic scale

Mesoscopic behaviour
- Linear elastic behaviour
- Non linear elastic behaviour
- (Visco)-plastic behaviour
- Visco-elasticity

Degradation model
- Instantaneous degradation
- Micromechanical model
- Damage model

Mesoscopic failure criterion
- Maximum stress criterion
- Quadratic criterion
- Puck criterion
- LARC failure criterion
- Etc.

Angle of failure in trans. compression

Kinking fibre
Development of Plain Strength Criteria
State-of-the-Art

- Multi-Scale analyses aims at predicting deformation and final fracture of composites. Difference with semi-empirical approaches:
  - Physically-based, allowing for greater predictive capability,
  - But more complex in terms of testing (model identification) and analyses.

E.g., Multi-scale Approach of Laurin, Maire & Carrere (ONERA):

1/ Onset of micro-damage
2/ Onset of meso-damage
3/ Increase of the damage rate.
4/ Final failure of laminate

Complex damage mechanisms:
- Different scales (micro and meso)
- Coupling between mechanisms

Multi-axial damage mechanism more complicated to define
Challenges still ahead of us for wide-scale industrialisation:

- High strain gradient areas (notches and holes)
- Out-of-plane failure modes
- Effect of Defects, Damage Tolerance, Durability.
- Guidance and Standardisation on Tests / D&F parameters.

There remains still Experimental vs. Theoretical views…

Validate approach against:

- Multi-axial loading,
- Different stacking sequences and realistic design features,
- Manufacturing – NDI capabilities,
- Consider scale effect, Natural variability in results, Etc.
ToC

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Conclusions and Perspectives

**The industrial context:**
- Constant innovation is required.
- Safety is secured through means of compliance.
- Analyses must be accurate, robust & adapted to the need.

**The perception from research:**
- Precise, but often limited (UD, non industrial lay-ups),
- Accuracy / Volume of analyses not considered,
- Experimental / Theoretical could be better bridged:
  - Interaction between Model and Identification could be clarified, Standardisation of tests is crucial.
  - Investigation of Effect of Constituents and manufacturing deviations on performance is rarely addressed.
Conclusions and Perspectives
Drivers for new developments

- **INCREASED PERFORMANCE**
  - Understanding of D&F properties of materials
  - Physical understanding (failure modes, fibre/resin functions)
- **REDUCED DEVELOPMENT CYCLE**
  - Calculation methods adapted to the need: from Pre-Design to Advanced Calculations.
  - Trade off between Complexity ↔ Accuracy
- **CONTROLLED STRUCTURAL INTEGRITY**
  - Robust Validation by testing and analysis at all levels of the test pyramid
  - Predictive ↔ cost savings
  - Accurate ↔ weight savings
- **CONTROLED MATURITY FOR NEW MATERIALS AND TECHNOLOGIES**
  - Tool development and deployment to extended enterprise
  - Control of design/stress space
- **REDUCTION OF DIRECT AND INDERECT (repair, maintainability) COSTS**

**Aircraft Development**

Enable Virtual Testing

- Test
- Analysis

INCREASED PERFORMANCE
REDUCED DEVELOPMENT CYCLE
CONTROLLED STRUCTURAL INTEGRITY
CONTROLED MATURITY FOR NEW MATERIALS AND TECHNOLOGIES
REDUCTION OF DIRECT AND INDERECT (repair, maintainability) COSTS
Conclusions & Perspectives
The not so distant future

*Implementation of industrial and validated multi-scale, multi-level, robust, analyses into large NL simulations*
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