Virtual Testing of Aircraft Structures, considering Postcritical & Thermal Behavior

(DLR – Institute of Structural Mechanics, Braunschweig, Germany),

COMPOSIT Thematic Network,
Workshop on Modeling and Prediction of Composite Transport Structures
in Zaragoza, Spain, 30.06.2003
Model Verification: „Solve the equations right“

Model Validation: „Solve the right equations“
Postcritical behavior of stiffened panels

Panel in Buckling Test Facility

- Top plate
- Clamping box
- Specimen
- Clamping Box
- Displacement pickup
- Load distributor
- Load cells
- Drive plate

Deformation pattern (ARAMIS)
Non linear FEM using ABAQUS/Standard

Real Structure CFRP-Panel

FE-Model

Linear Eigenvalue Analysis
- Buckling Modes
- Buckling Load

Nonlinear Analysis
- Newton-Raphson-Method + automatic / adaptive damping to stabilize the analysis (*STATIC, STABILIZE)

Postprocessing
- (Load-Shortening-Curve, deformation of the structure, ...)

Measured Imperfections

Scaled imperfections

Rough estimate
Numerical Pre-Test Analysis

„Experimental Validation of computational Analysis is expensive & time consuming“

„Pre-Test Analysis and Pre-Test Planning“

„Validation Experiments“ versus „Phenomenological Experiments“

Goal: Load – Deformation curve showing:
- characteristic skin buckling, coupled with axial stiffness reduction
- large load bearing capacity during postbuckling without structural failure

FEA investigation w.r.t.: panel geometrie
discretisation
experimental boundary conditions
initial imperfections
...
Pre-Test Analysis

1. Influence of different STABILIZE parameters
2. Investigation of different failure criteria

![Graph showing the influence of different STABILIZE parameters and the investigation of different failure criteria with various load-shortening curves for Tsai Hill, Azzi Tsai Hill, and Tsai Wu, along with nominal data for ABAQUS/Standard Mesh I (3024 elements).]
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Pre-Test Analysis

Convergence study

Mesh I: 3024 elements
Mesh II: 2*3024 elements
Mesh III: 16*3024 elements

Nominal data
ABAQUS/Standard
STABILIZE = 2.e-6

Load [kN] vs. Shortening [mm] graph
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Pre-Test Analysis

Influence of lateral boundary conditions

- Covered width = 25.0 mm
- Covered width = 12.5 mm
- Only lateral nodes fixed

Nominal data
ABAQUS/Standard
STABILIZE = 2.e-6
Mesh I (3024 elements)
Pre-Test Analysis

Influence of imperfections

Load [kN] vs. Shortening [mm]

- No imperfections
- Mode 1, 2% skin thickness
- Mode 1, 10% skin thickness
- Mode 1, 100% skin thickness

Nominal data
STABILIZE = 2.e-6
Mesh I (3024 elements)
Pre-Test Analysis

ABAQUS/Standard vs. ABAQUS/Explicit

Nominal data
Mesh I (3024 elements)

- ABAQUS/Standard, STABILIZE = 2e-6
- ABAQUS/Explicit, v=10mm/s, no damping
- ABAQUS/Explicit, v=10mm/s, with damping

Load [kN] vs. Shortening [mm]
Measurement of geometrical Imperfections (1)

Optical 3D - digitalization

- Measurement of real radius vs. nominal radius (ca. 6% deviation)
- Measurement of initial imperfection

ATOS – Sensor

strip sequenz
Measurement of geometrical Imperfections

Data points (ASCII-Format):

<table>
<thead>
<tr>
<th>X Value</th>
<th>Y Value</th>
<th>Z Value</th>
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<td>1093.6441</td>
<td>211.5491</td>
<td>1.6805</td>
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<td>1093.0879</td>
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</tr>
</tbody>
</table>

... 

Modification of „perfect“

FE – geometry

Application of initial imperfection

Fringe – plot w.r.t. perfect shell
Results of FEA using ABAQUS/Standard

- Lokal skin buckling
- Global "unsymmetric" Buckle
- Global "symmetric" Buckle

Skalierte Verschiebung vs. Skalierte Last
Validation of FEA (Animation)
Validation of computational results

"Globale" Ebene

![Graph showing skalierte Verschiebung and skalierte Last for different experiments and ABAQUS/Standard with Imperfektionen.](image)
Validation of computational results

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Skalierte Verschiebung [mm]

Radialverschiebung [mm]

„Lokale“ Ebene

Wegaufnehmer W88
Knoten 40696; entspricht W88 Position
Wegaufnehmer W89
Knoten 46666; entspricht W89 Position
Wegaufnehmer W90
Knoten 52636; entspricht W90 Position
Wegaufnehmer W91
Knoten 58606; entspricht W91 Position
Thermal Problem

FML's in future aircraft structures
Modeling (on panel level)
Model Verification

- Convergence study with 6 different discretisations
  (1 to 36 elements in thickness direction)
- Homogenisation of smeared layers with:
  
  \[
  k_{\text{out\_plane}} = \frac{\sum_i t_i}{\sum_i \left( t_i / k_{i,\text{normal}} \right)} ,
  \]
  
  \[
  k_{\text{in\_plane}} = \sum_i \left( k_{i,\text{plane}} \cdot t_i \right) / \sum_i t_i .
  \]
Experimental Test in THERMEX – B test site

Infrared Radiator
Isolation (optional)
Skin
Water
Frame
Stringer
Validation

Experiment vs. Computation

- MP43/TE43
- MP43_RF1
- MP34/TE04
- MP34_RF1
- MP24/TE09
- MP24_RF1
Modeling of large fuselage structure
2D Finite Elements for Thermal Analysis of FML‘s

Motivation

- Reduction of modeling effort by using 2D geometrical models
- Reduction of CPU-time
- Compatible temperature field for thermo-mechanical calculations

Scientific Challenge

- 3D temperature field description based on 2D geometry
- Shape functions in z-direction
- 2D-3D-Coupling (Connection to local 3D meshes)
Layerwise Thermal Lamination Theories

Composite structures
- Idealisation as layered structure
- Homogenisation of layers including heat conduction, radiation, convection

Hybrid composite structures

Sandwich structures
- Linear Layered Theory (LLT)
- Quadratic Layered Theory (QLT)

3D temperature distribution by 2D finite elements
Assumptions and Prerequisites

- perfect thermal contact at interfaces
- monolithic conduction within layers
- no internal heat sources
- temperature independent material properties

### Approximation by Layered Construction

\[
\begin{align*}
&\text{radiation} \\
&\text{convection} \\
&\text{conduction} \\
\end{align*}
\]

\[
\begin{align*}
&\text{homogenisation} \\
&\text{equivalent thermal conductivity}
\end{align*}
\]
FE-Formulation

Weak form for heat conduction

\[ \int_{\Omega} (\nabla v)^{T} K \nabla T \, d\Omega + \int_{\Gamma} q^{T} n \, v \, d\Gamma + c \rho \int_{\Omega} \dot{T} v \, d\Omega = 0 \]

Boundary conditions

\[ q^{T} n = q_{c} + \bar{q} \]

- Convection (Robin)
  \[ q_{c} = \alpha_{c} (T_{\text{Wand}} - T_{\infty}) \]

- Heat flux density (Neumann)
  \[ \bar{q} \]
FE-Formulation

Weak form for heat conduction

\[
\int_{\Omega} \eta^T \int_{\partial \Omega} S^T K S \, d\Omega \, \rho \, d\Omega \, + \, \alpha_c \int_{\Gamma} \eta^T R^T R \rho \, d\Gamma \, + \, \int_{\Omega} \eta^T \int_{\partial \Omega} c R^T R \, d\Omega \, \rho \, d\Omega \, = \, (\alpha_c T_{\infty} - \bar{q}) \int_{\Gamma} \eta^T R^T \, d\Gamma
\]

Composite-heat-conduction-matrix

\[
\hat{K} = \int_{\Omega} S^T K S \, d\Omega
\]

\[
= \sum_{k=1}^{N} \int_{z_k}^{z_{k+1}} \left( S^{(k)} \right)^T K^{(k)} S^{(k)} \, dz
\]

Composite-heat-capacity-matrix

\[
\hat{C} = \int_{\Omega} \bar{c} R^T R \, d\Omega
\]

\[
= \sum_{k=1}^{N} \int_{z_k}^{z_{k+1}} c_k \rho_k \left( R^{(k)} \right)^T R^{(k)} \, dz
\]
Example: 3D vs. 2D FEA

GLARE skin with 3D finite elements (Nastran)

Number of 3D-elements: 36
Number of 3D-elements: 2
Number of 2D-elements: 1
Summary

- Experimental data basis for validation of non linear FEA w.r.t. postbuckling of stiffened shells under axial loading
- Investigation of sensitivity w.r.t. to different modeling parameters
- Excellent agreement between experimental and computational results deep into elastic postcritical regime (global & local)

- Reliable thermal analysis of FML structures by verification of discretisation through fine 3D model on panel level
- Validation of thermal panel model by experiments in THERMEX – B test site
- Application of thermal model to large fuselage structures
- Description of fast 2D Finite-Element-Formulation

Question: How many experiments are needed for validation of a specified parameter space?