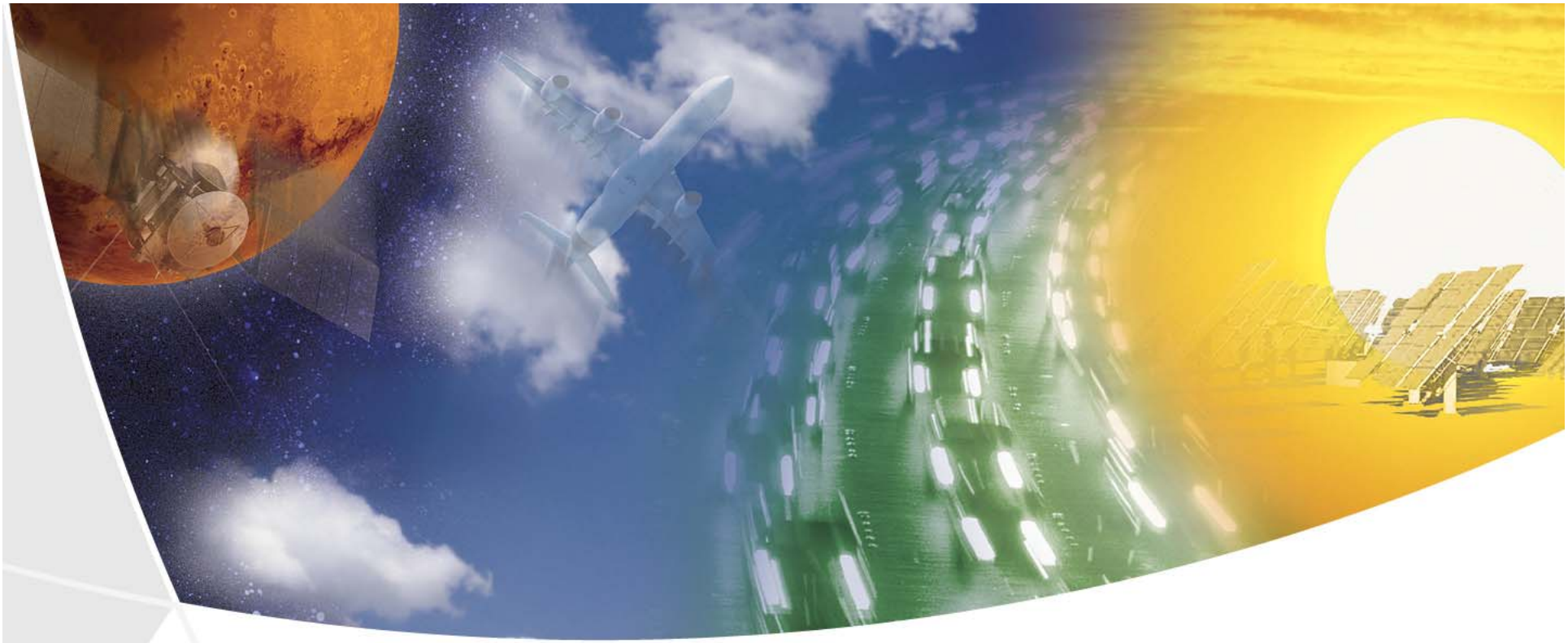


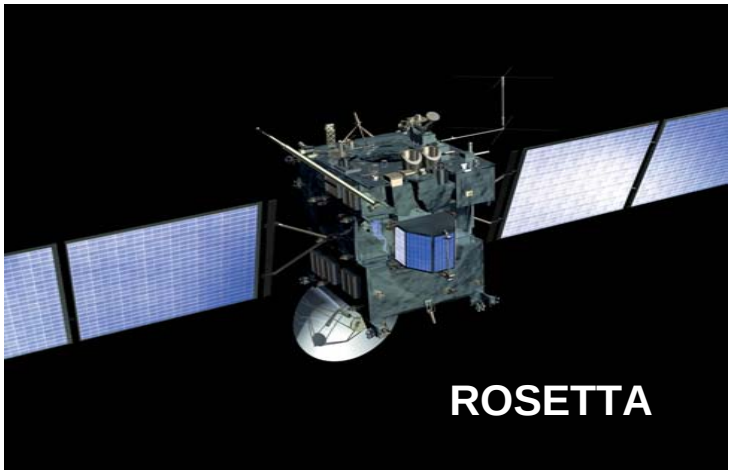
# Damage Tolerance of Sandwich Structures - Modelling, Analysis and Testing -

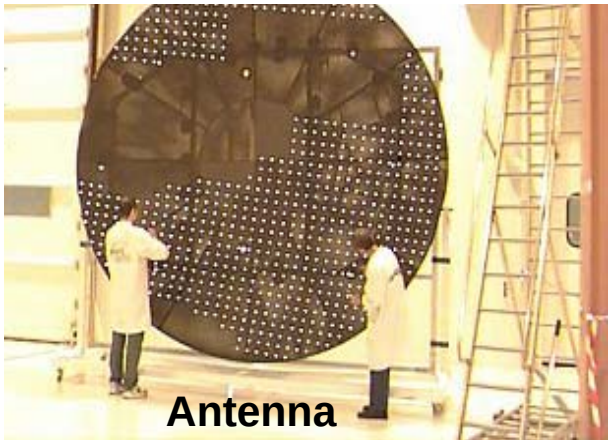
Jan Teßmer, Luise Kärger, Uwe Pfeiffer, Anja Wetzel

Conference on Damage in Composite Materials, Stuttgart, 18.-19.09.2006

Deutsches Zentrum
DLR für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

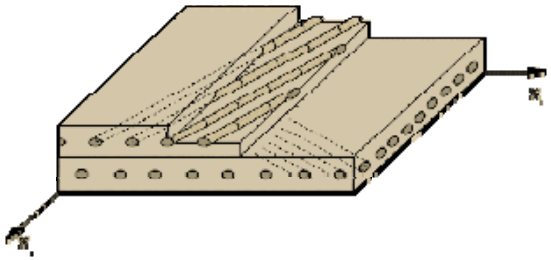
# High Performance Composites in Aerospace Structures

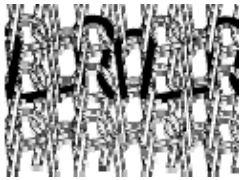



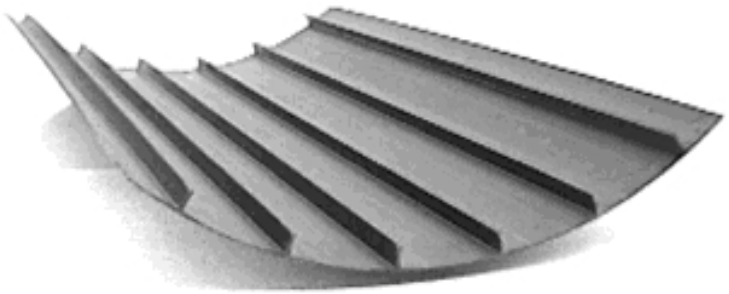




# High Performance Composites in Aerospace Structures

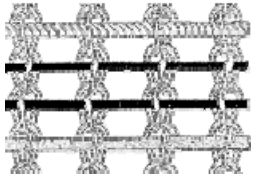
**Monolithic Composites**

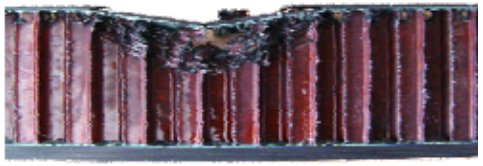






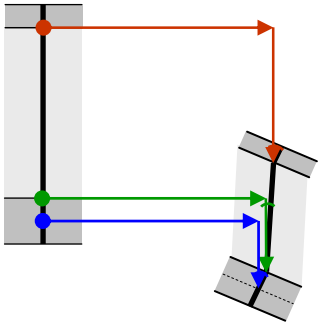
**Textile Composites**





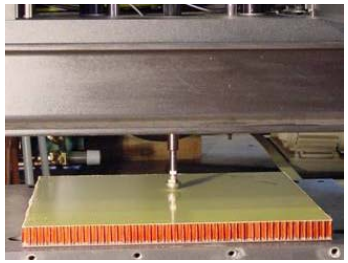
**Sandwich Structures with Composite Face sheets**

## 1 Double shell structures (Sandwiches)



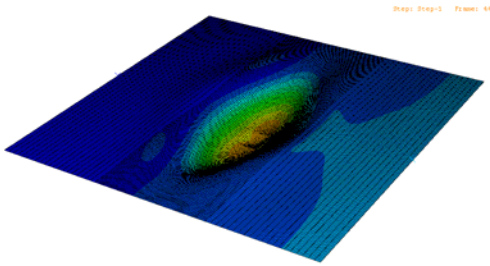
## 2 Impact analysis

Experiments
Simulation tool CODAC
Damage Modelling
Simulation results



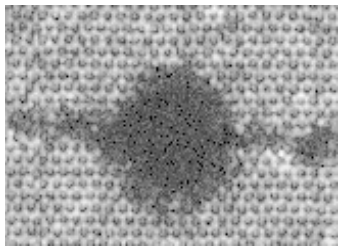
## 3 Residual strength analysis

CAI-Tests
Geometrical non-linear simulation using ABAQUS
Simulation results

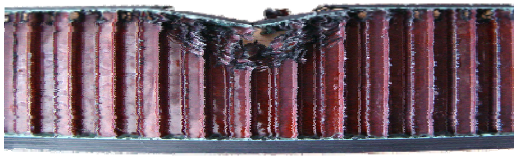


## 4 Non-destructive Testing

Air-coupled Ultrasonic Testing for Sandwiches
Signal Processing for monolithic CFRP (skins)



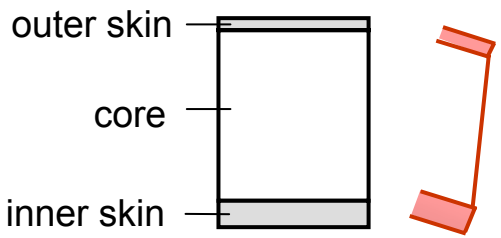
# 1 Double shell structures



## Modelling requirements

by accounting for the specific deformation behaviour:

- fast for being used in the design process
- sufficiently accurate




## Development of two new shell elements

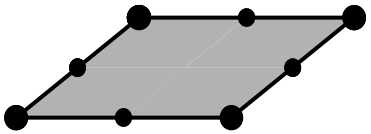
Ref.:

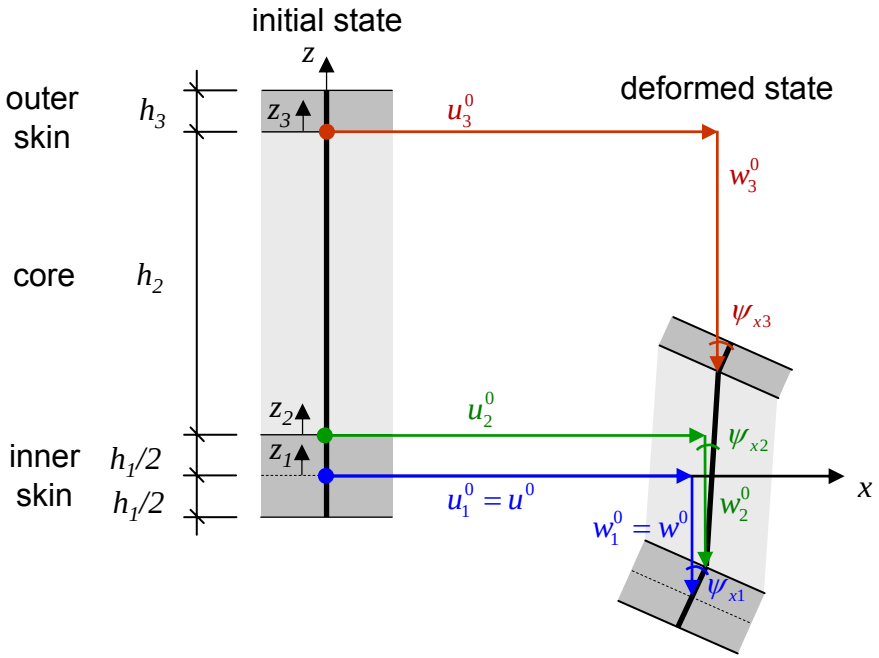
Element S89: *Kärger, Wetzel, Rolfes, Rohwer. Computers & Structures 84. 2006.*

Element S815: *Wetzel, Kärger, Rolfes, Rohwer. Computers & Structures 83. 2005.*

# 1 Double shell structures

**Element S815:** 3-layered shell element with 3-D stress analysis
(**S**andwich element with **8** nodes and **15** dof per node)






Kinematics of layer $L$ :

$$\begin{bmatrix} u_L \\ v_L \\ w_L \end{bmatrix} = \begin{bmatrix} u_L^0 \\ v_L^0 \\ w_L^0 \end{bmatrix} + z_L \begin{bmatrix} \psi_{xL} \\ \psi_{yL} \\ \psi_{zL} \end{bmatrix} + z_L^2 \begin{bmatrix} 0 \\ 0 \\ \varphi_{zL} \end{bmatrix}$$

→ **15 dof per node**

Layer-wise full 3D-material law:

$$\boldsymbol{\sigma}_L = \mathbf{C}_L \boldsymbol{\varepsilon}_L$$

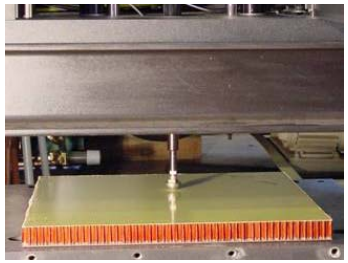
**Stress computation:**

- in-plane stresses: material law
- transv. shear stresses: equilibrium approach by Rolfes & Rohwer
- transv. normal stress: material law and equilibrium approach

## 1 Double shell structures

## 2 Impact analysis

Experiments
Simulation tool CODAC
Damage Modelling
Simulation results



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## 4 Non-destructive Testing

Air-coupled Ultrasonic Testing for Sandwiches
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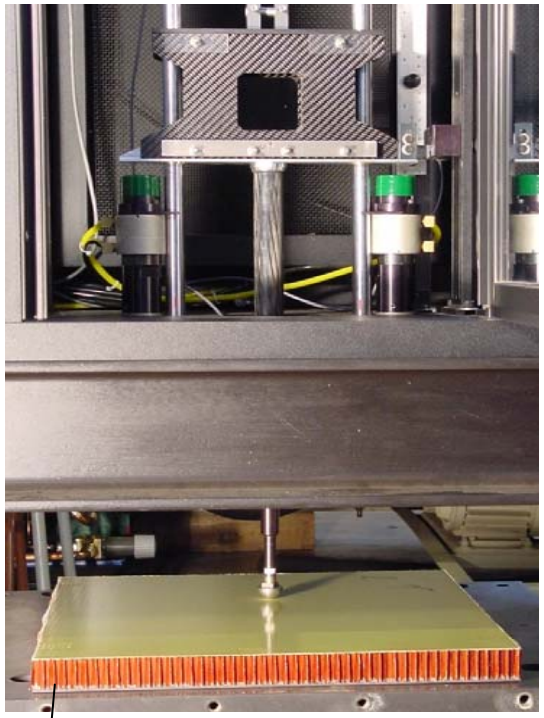
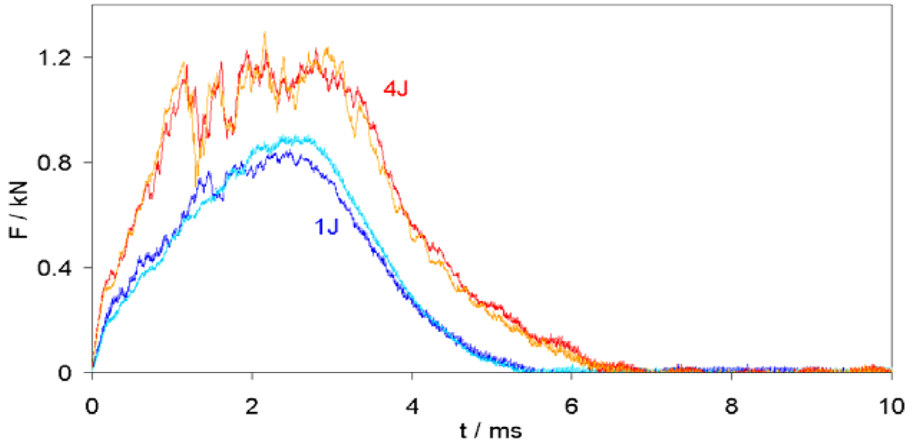
# 2 Impact analysis: Experiments

**Tests conducted at ILR, TU Dresden**

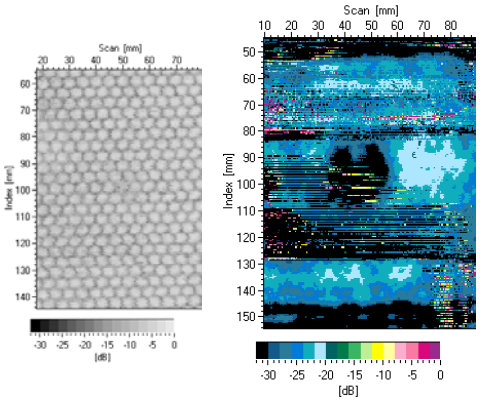


completely supported panel

**Force-time histories:**

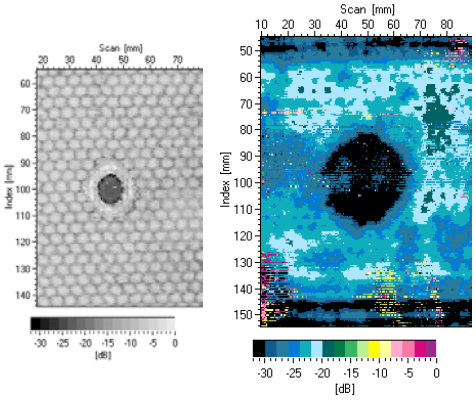



**1 Joule damage:**




top skin core

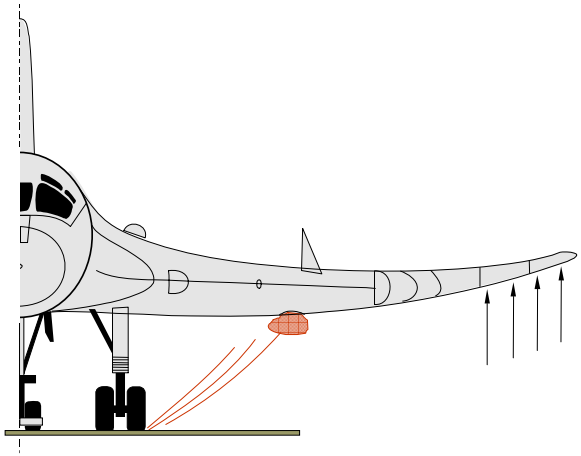
**4 Joule damage:**



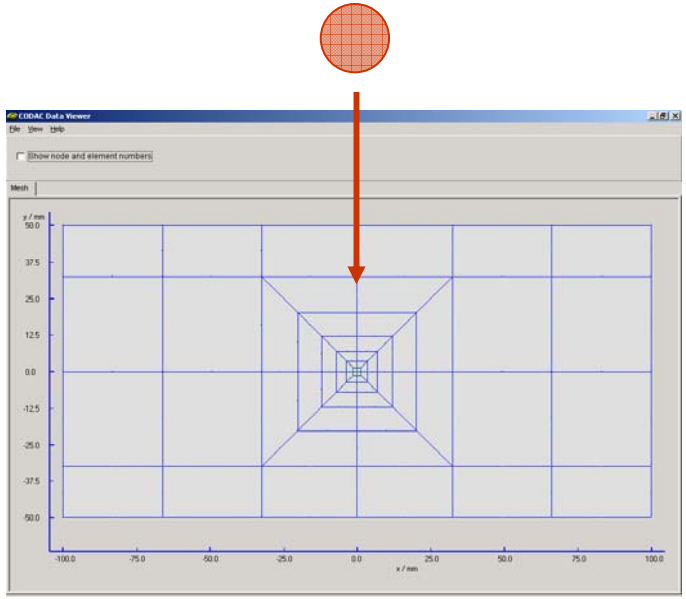

top skin core

# 2 Impact analysis: Simulation tool CODAC

- **CODAC =** **Co**mposite **D**amage Tolerance **A**nalysis **C**ode
- fast evaluation of impact damage and residual strength of composite structures
- Finite Element Method



**Impactor** (Ø25.4 mm):
- point mass
- parabolically distributed surface load




**Transient impact analysis:**
- dynamic FEA with Newmark time integration
- application of Hertzian contact law

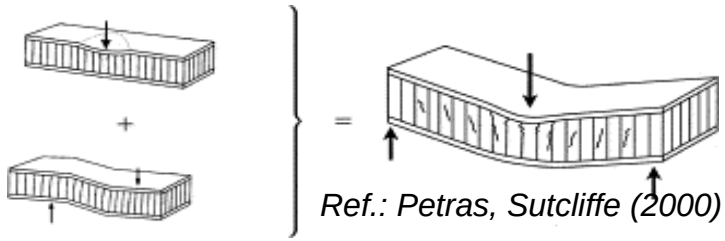
# 2 Impact analysis: Modelling of core damage

Ref.: *Kärger, Baaran, Teßmer. Composite Structures. 2006*

## Failure criterion:

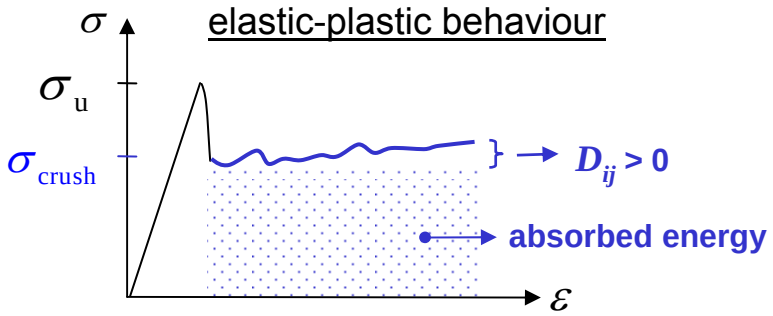
- transverse shear and compression failure of honeycomb core
- criterion by Besant et al.:

$$\left(\frac{\sigma_{zz}}{\sigma_{cc}}\right)^n + \left(\frac{\tau_{xz}}{\tau_{cls}}\right)^n + \left(\frac{\tau_{yz}}{\tau_{cts}}\right)^n \geq 1$$



*Ref.: Petras, Sutcliffe (2000)*

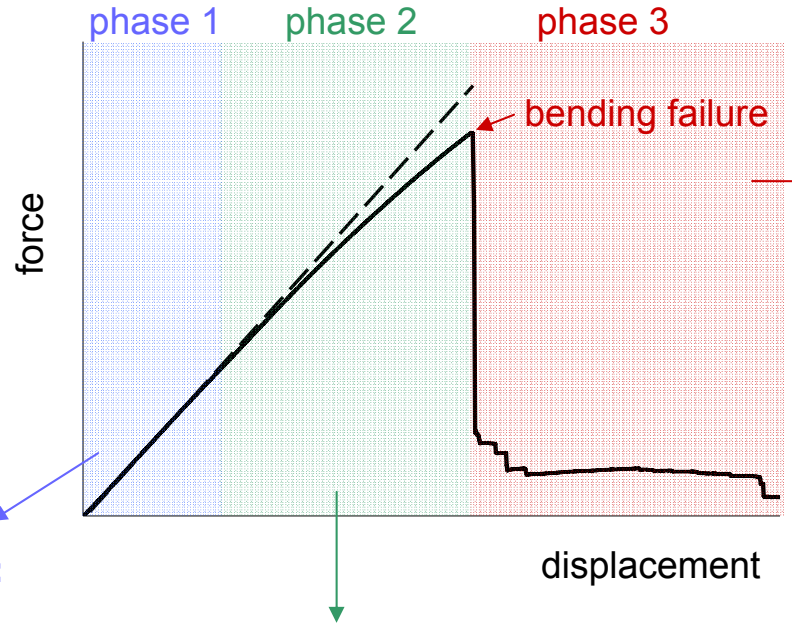
## Degradation:




$$\begin{bmatrix} \sigma_{xx}^* \\ \sigma_{yy}^* \\ \sigma_{zz}^* \\ \tau_{yz}^* \\ \tau_{xz}^* \\ \tau_{xy}^* \end{bmatrix} = \begin{bmatrix} D_{11}C_{11} & D_{12}C_{12} & D_{13}C_{13} & & & \\ & D_{22}C_{22} & D_{23}C_{23} & & & \\ & & D_{33}C_{33} & & & \\ & & & D_{44}C_{44} & & \\ & \text{sym.} & & & D_{55}C_{55} & \\ & & & & & D_{66}C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix}$$

# 2 Impact analysis: Modelling of skin damage

## 3-point bending test:




**fibre breakage in all laminas:**
- skin tears
- simulation stops
  (fracture mechanical models or energy based damage mechanical models with continuous degradation are needed)

**all laminas intact:**
linear-elastic material behaviour

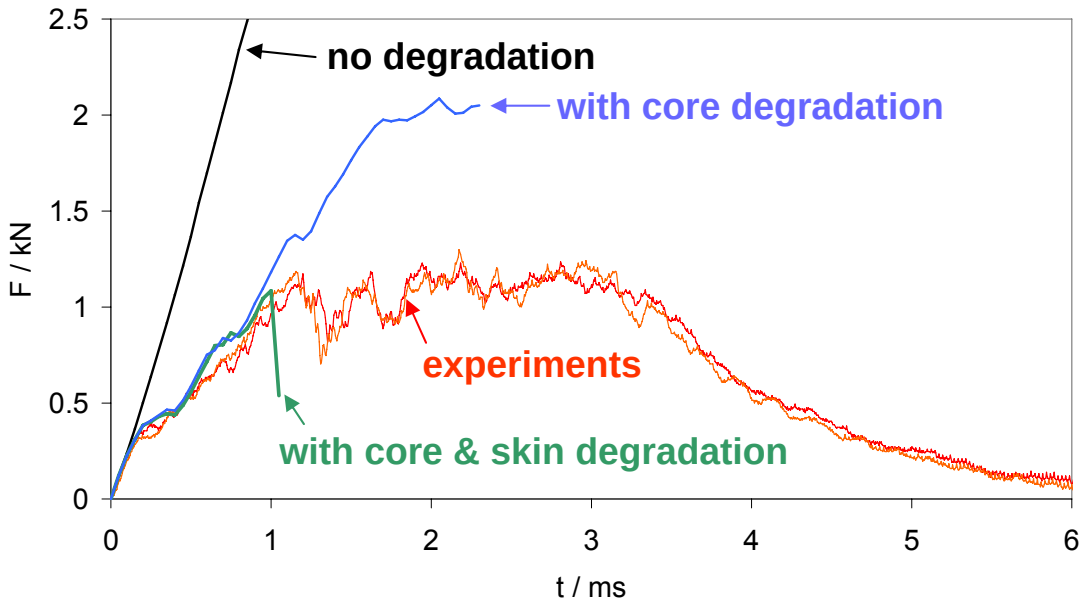
**fibre breakage in a few laminas:**
- degradation of membran stiffness by degradation factor $D_{11}$
- further stiffness components without considerable influence on impact response

$$\begin{bmatrix} D_{11} & (0) & (0) & & & \\ (0) & (0) & (0) & & & \\ (0) & (0) & (0) & & & \\ & & & (0) & & \\ & & & & (0) & \\ & & & & & (0) \end{bmatrix}$$

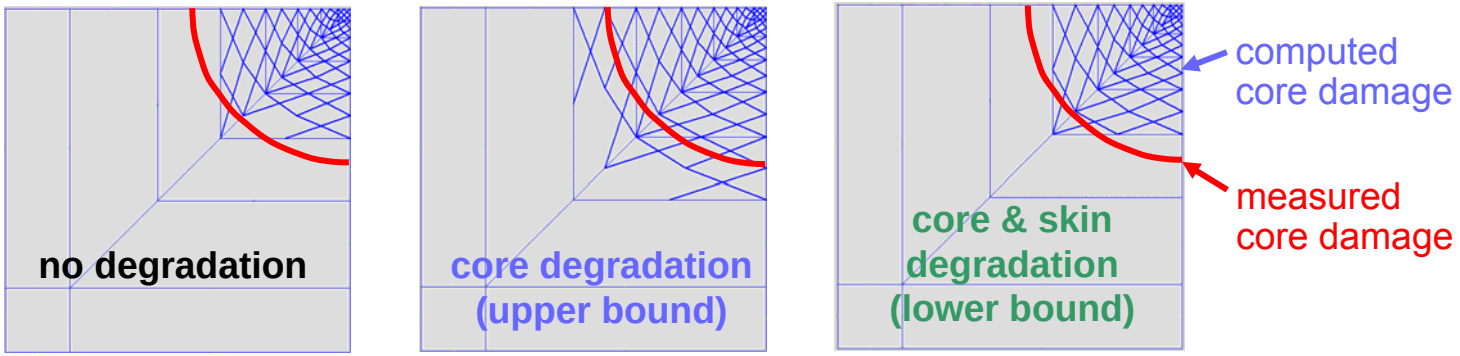
# 2 Impact analysis: Simulation results

## 4J Impact

**Force time history:**




**Core damage:**



## 1 Double shell structures

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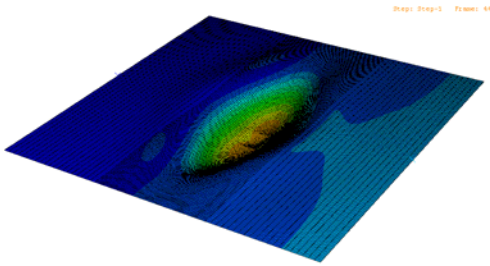
CAI-Tests
Geometrical non-linear simulation using ABAQUS
Simulation results

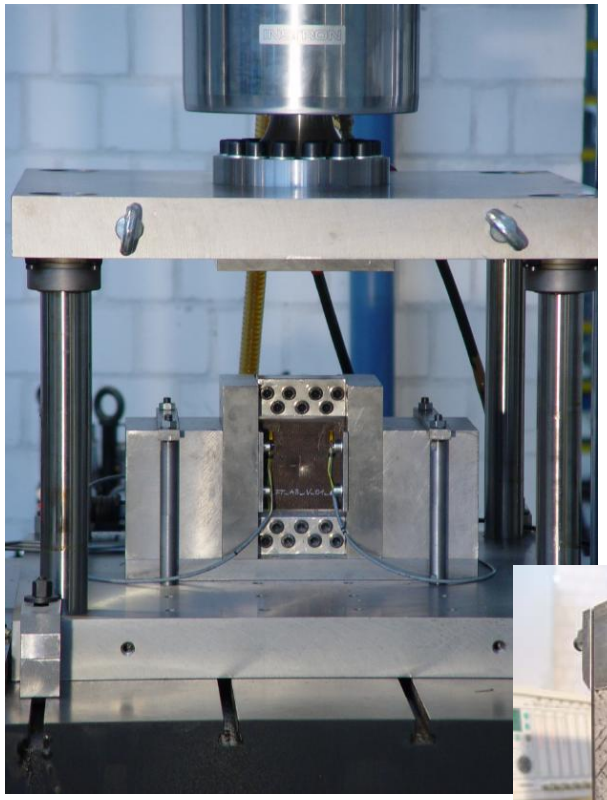


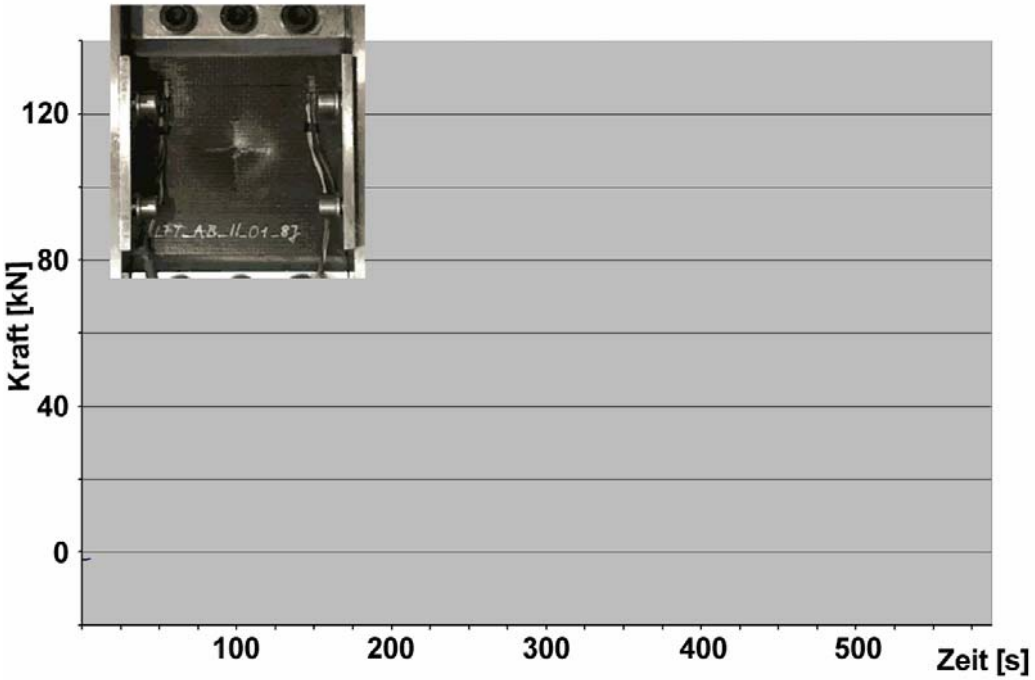
## 4 Non-destructive Testing

Air-coupled Ultrasonic Testing for Sandwiches
Signal Processing for monolithic CFRP (skins)

# 3 Residual strength analysis: CAI-Tests

CAI-Test-Equipment:



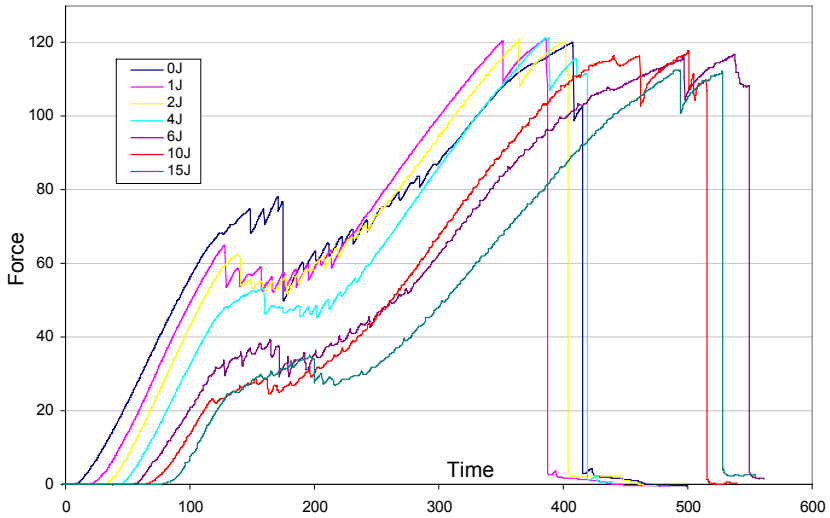



***Source: ILR TU Dresden***

**Failure phenomenon:**

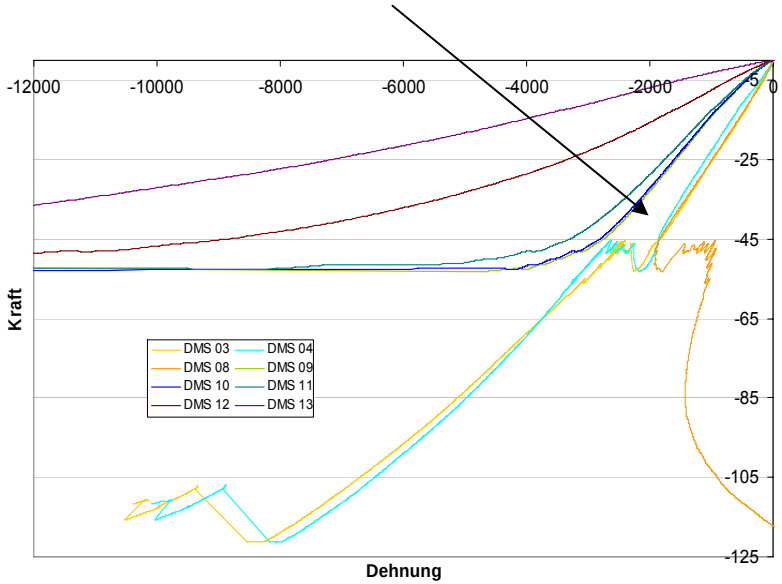
- impacted face sheet: dent propagation transverse to the loading direction
- failure of the impacted face sheet: buckling across the whole specimen width → sudden load decrease
- further load increase
- failure of second face sheet

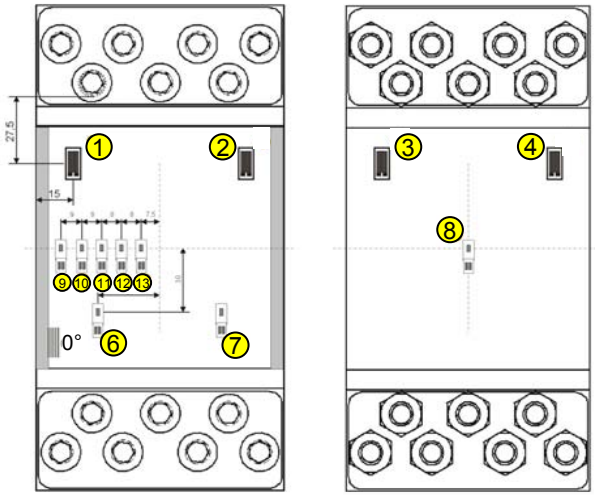
# 3 Residual strength analysis: CAI-Tests




**Test data:**
- Force vs. time
- Strain vs. time at specified location

Force vs. strain for 4 Joule specimen: higher compression on the front side compared to the back side (bending)



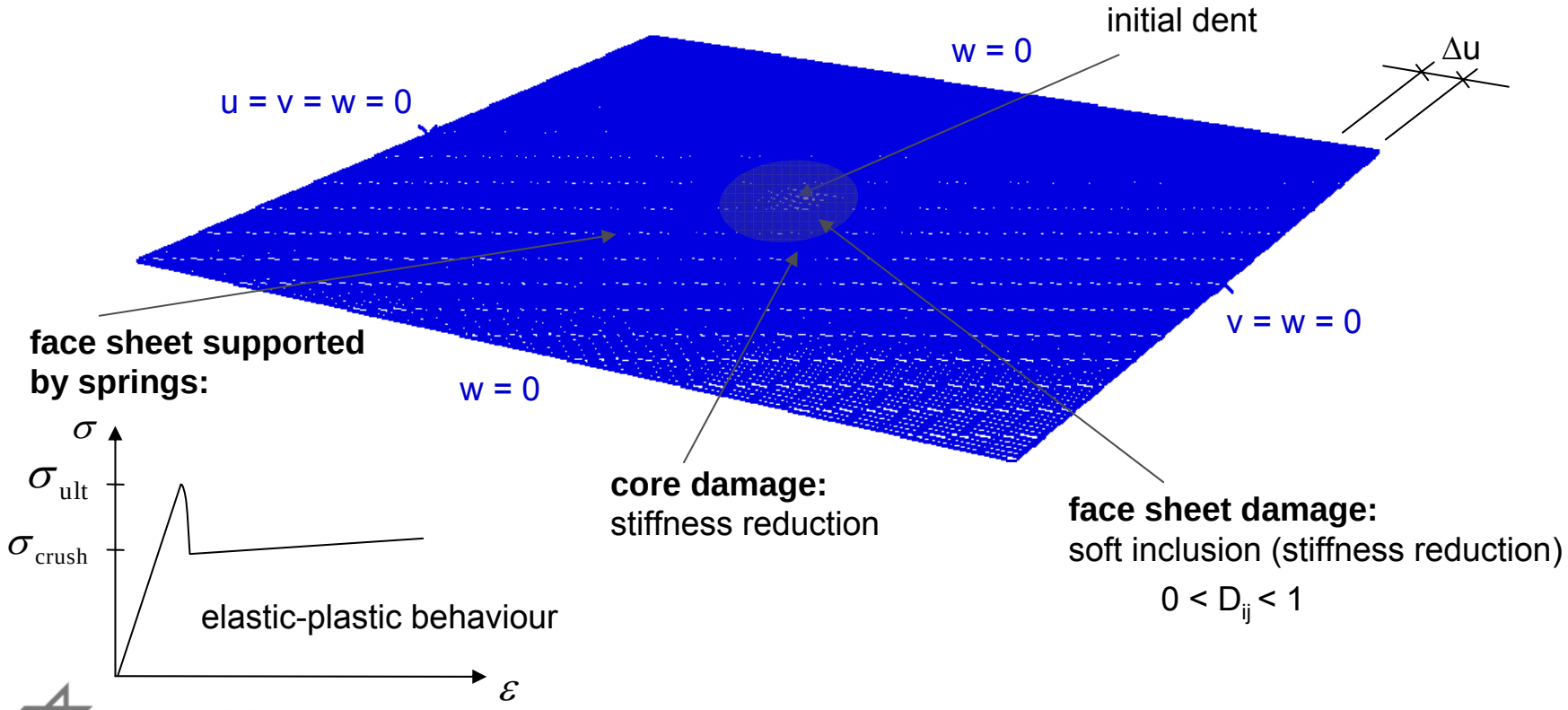




Strain gage positions on front and back side

# 3 Residual strength analysis: Non-linear simulation using ABAQUS

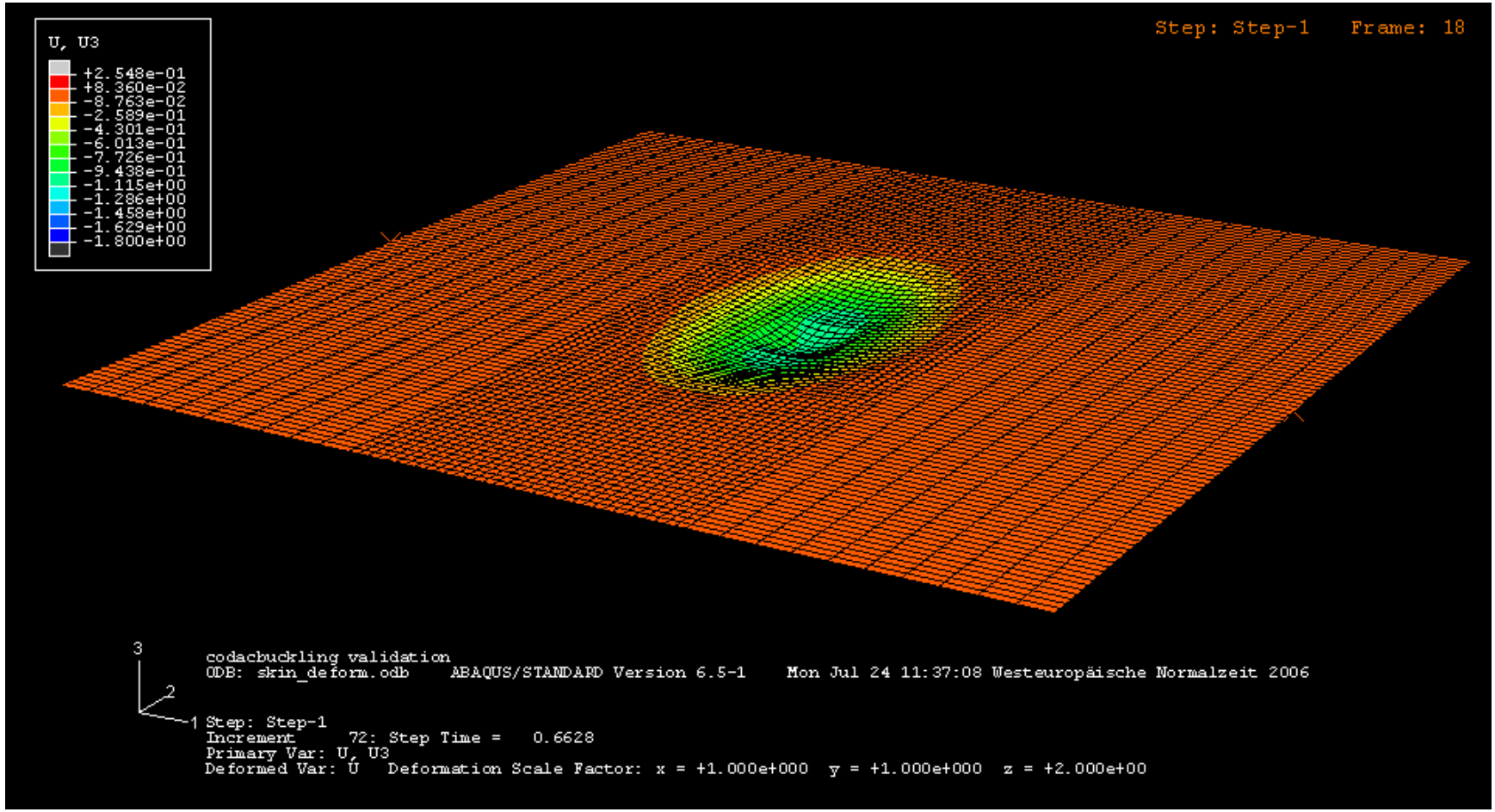
## Non-linear FE analysis of impacted face sheet:

- uniaxial in-plane loading (displacement-driven, $\Delta u$)
- face sheet supported by springs representing the core
- including initial dent, face sheet and core damage due to impact
- including core damage growth
- using automatic stabilization because of local instabilities



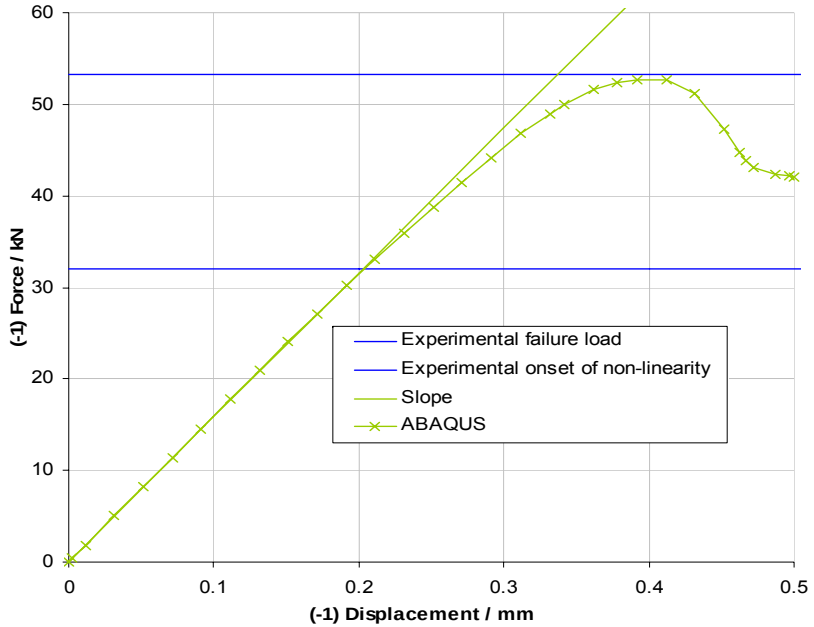
# 3 Residual strength analysis: Simulation results

Dent growth with increasing in-plane loading:

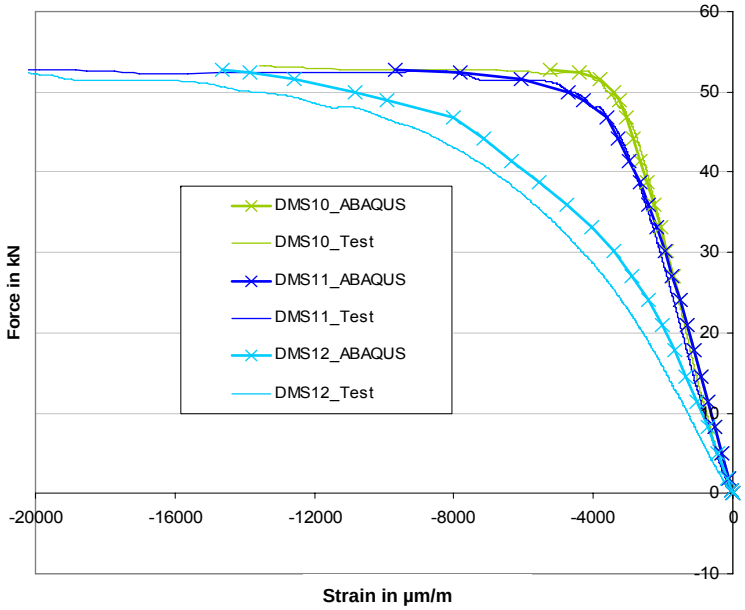


# 3 Residual strength analysis: Simulation results

4 Joule specimen: force vs. displacement Δu




4 Joule specimen: force vs. strain




For 4 Joule damage, $D_{ij}$=0.7, $k_{core}=E_{zz}/h$, $E_{zz}$ and $\sigma_{ult}$ according to data sheet, $\sigma_{plat}/\sigma_{ult}$ = 0.3:

- very good correlation between experimental failure load and maximum load of ABAQUS simulation
- good correlation between experiment and ABAQUS simulation for strains at strain gage locations

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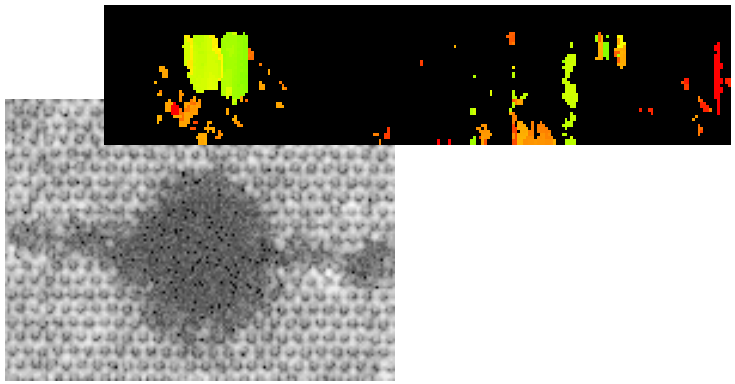
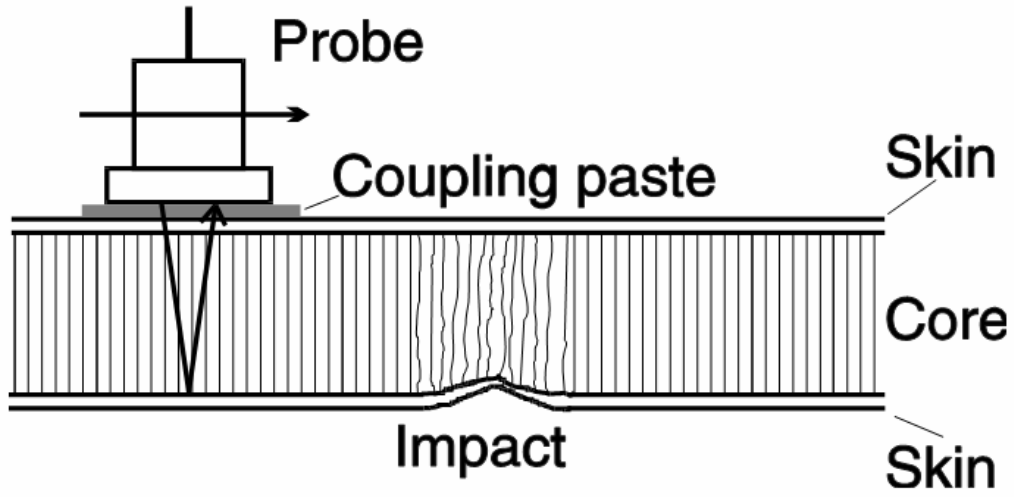
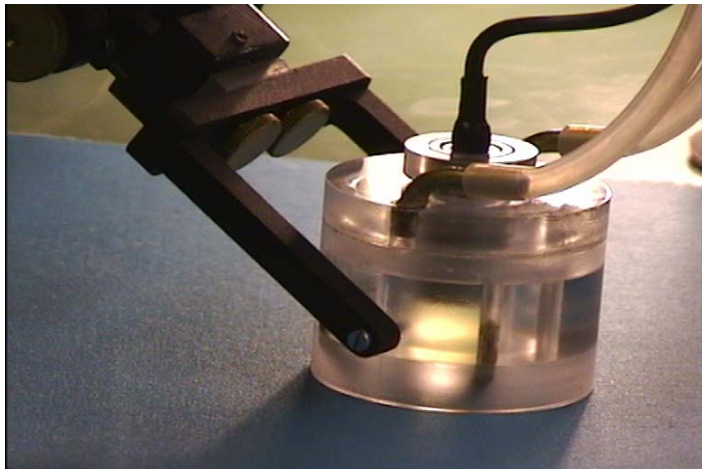
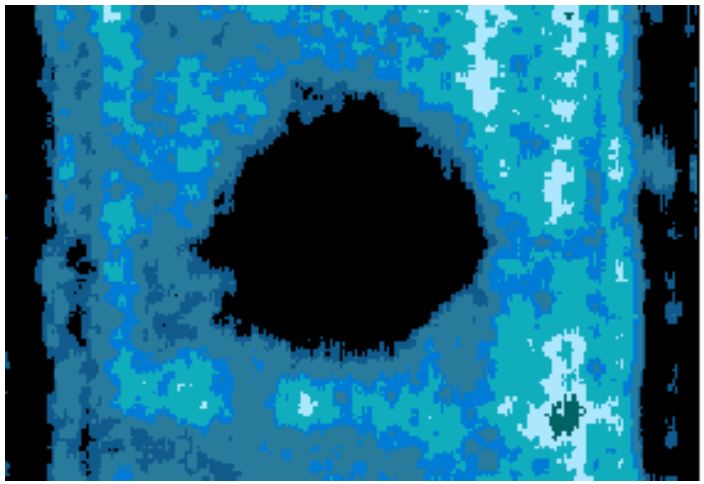


# Sandwich inspection with water coupling





Optimal frequency for
Sandwiches: <500kHz
=> Bad Focussing,
low spatial resolution

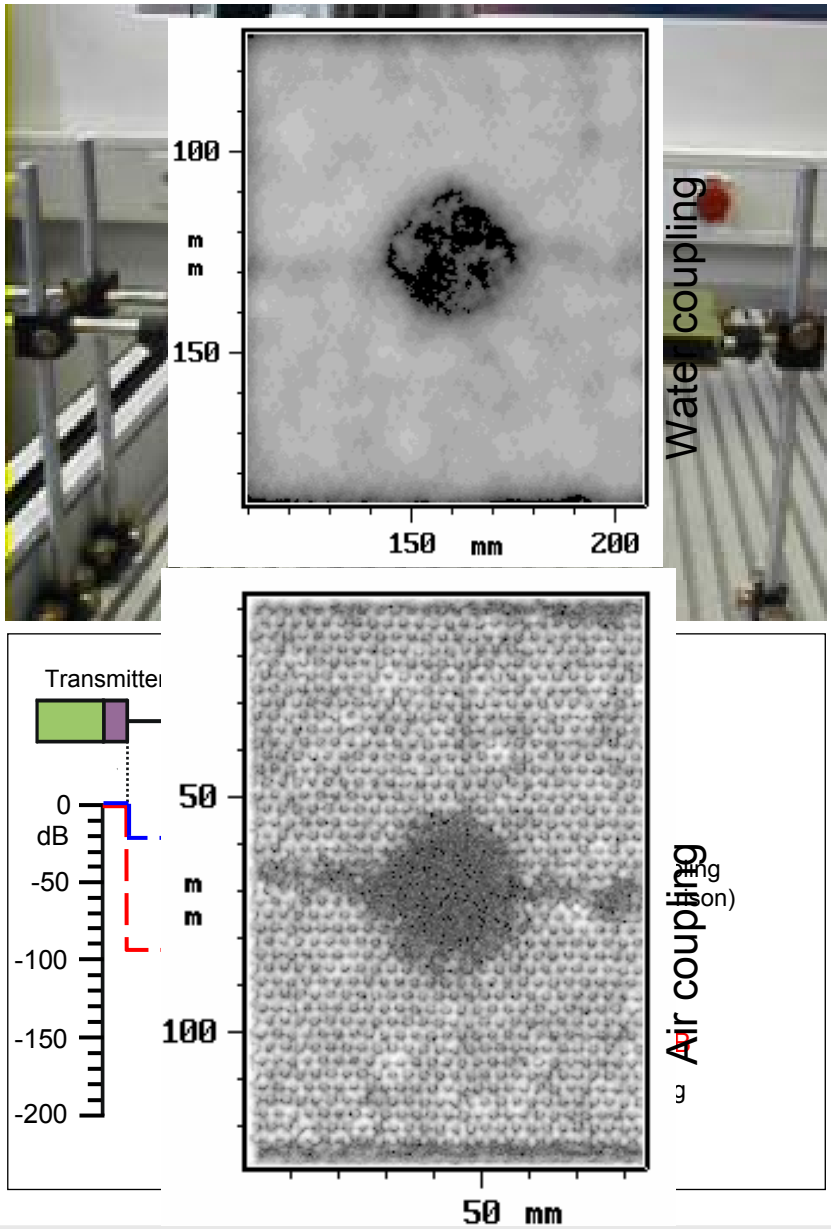
# Air-coupled Ultrasonics

**Benefits:**
- Contact free, without coupling media
- Constant and reproducible coupling
- No incoming water
- <500kHz *and* focussed

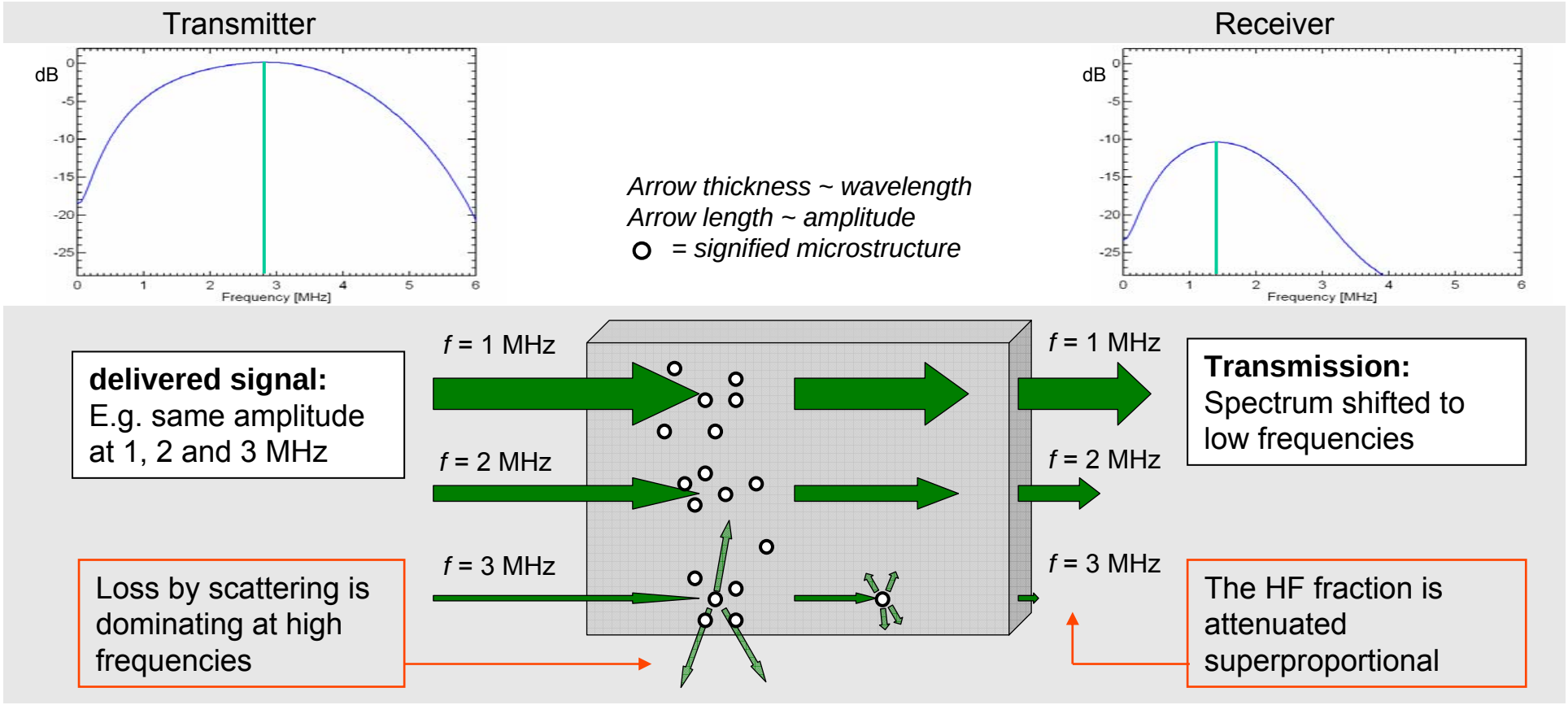
**Challenges:**
- Bad acoustic matching
- More than 160 dB amplitude loss

**Approach**
- Transducers with optimised matching layers
- Optimised transmitter and receiver electronics

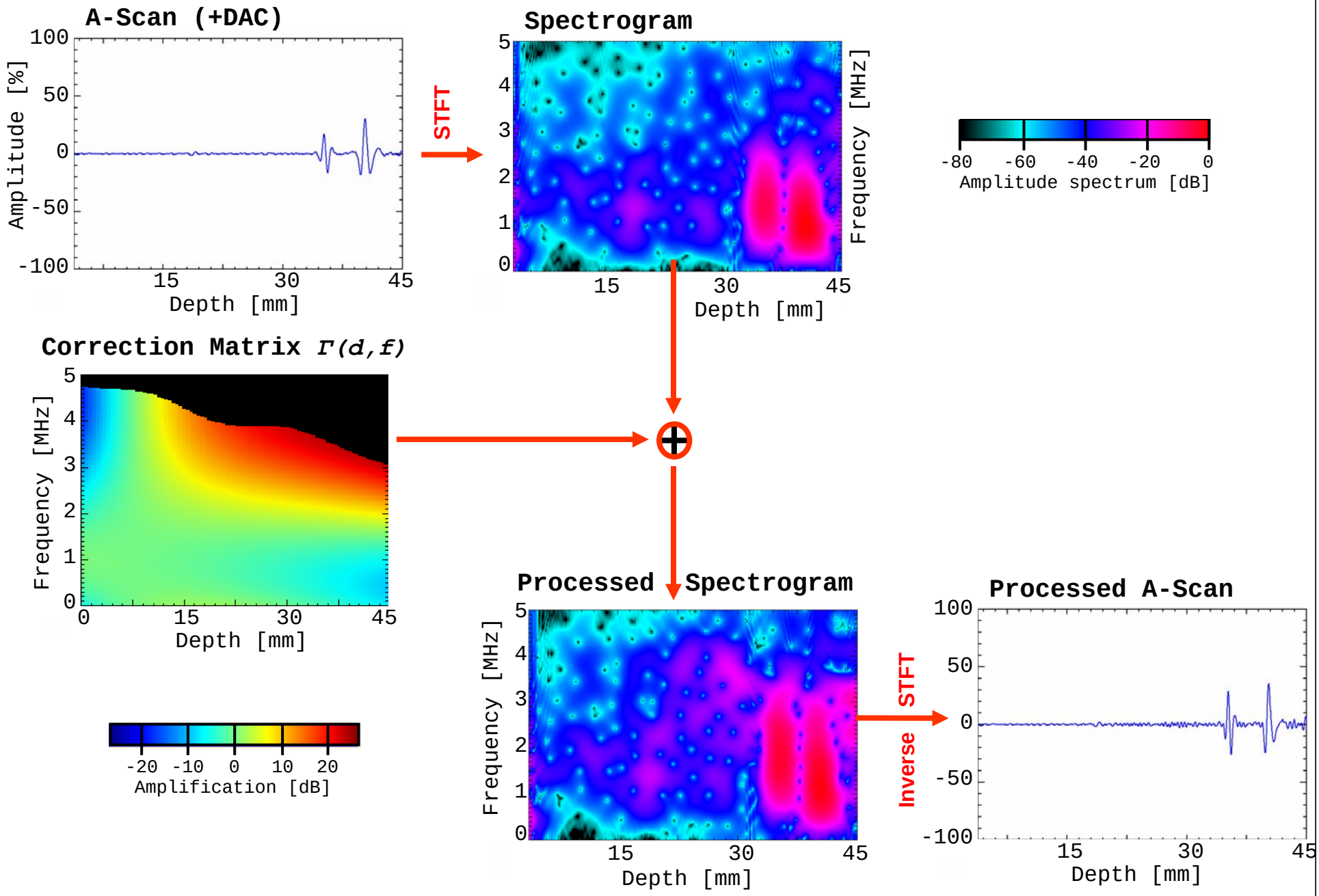
**Our results**
- Signal-to-noise ratio in transmission: 30 dB
- Narrow band, strongly focussing transducers
- Best choice for sandwich testing



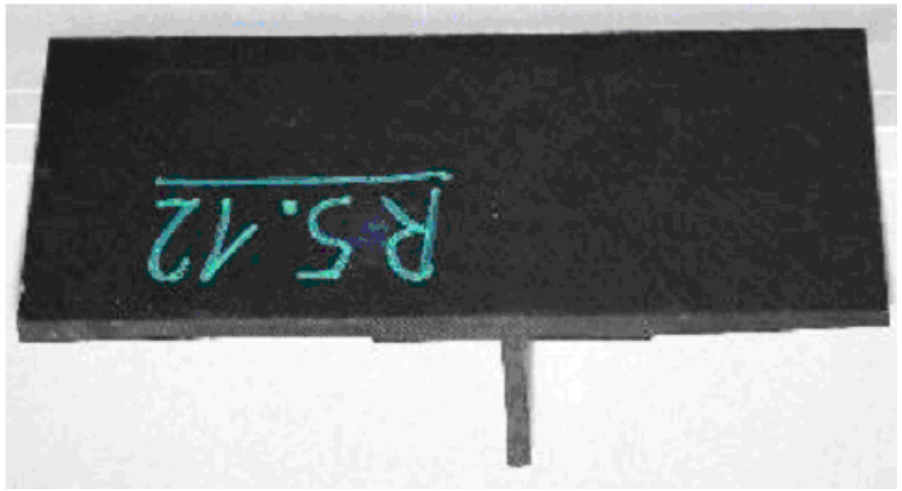
# CFRP: High and frequency-specific sound attenuation

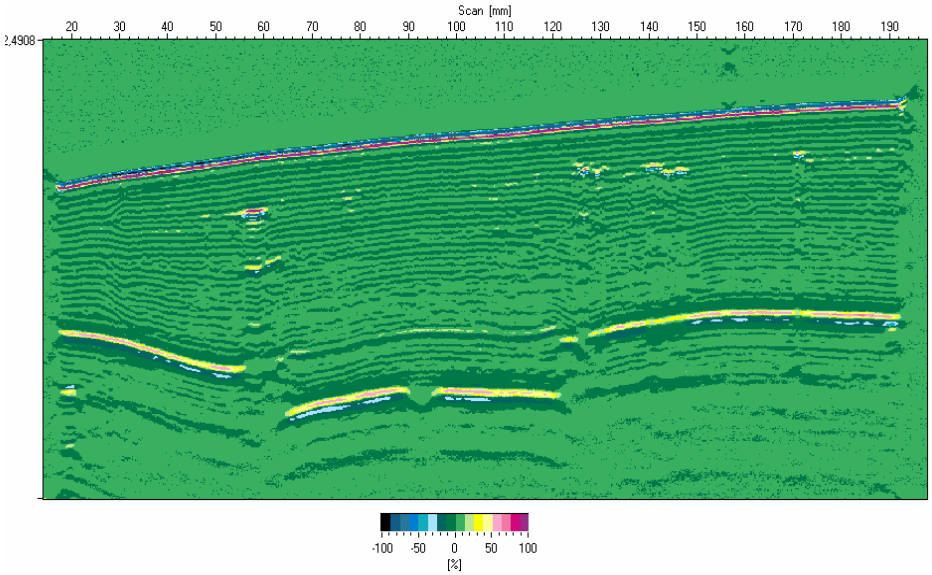


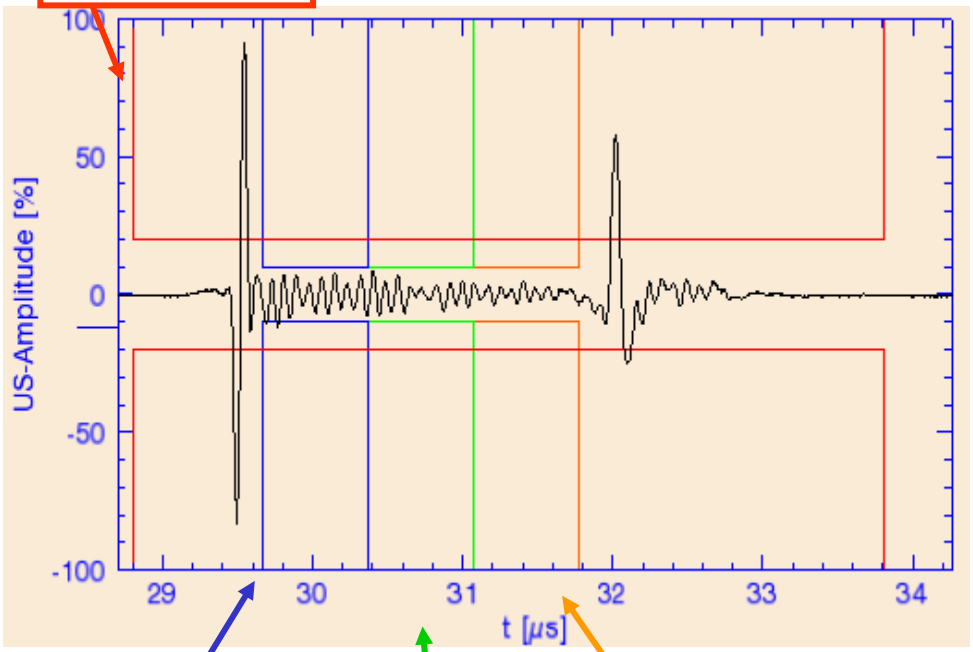
# Spectral Distance Amplitude Correction „SDAC“



# Stringer Specimen: Analysis of Layer Echoes




Gate 1:
0.2 – 0.8µs
„shallow“

Gate 2:
0.8 – 1.4µs
„middle“

Gate 3:
1.4 – 2.0µs
„deep“

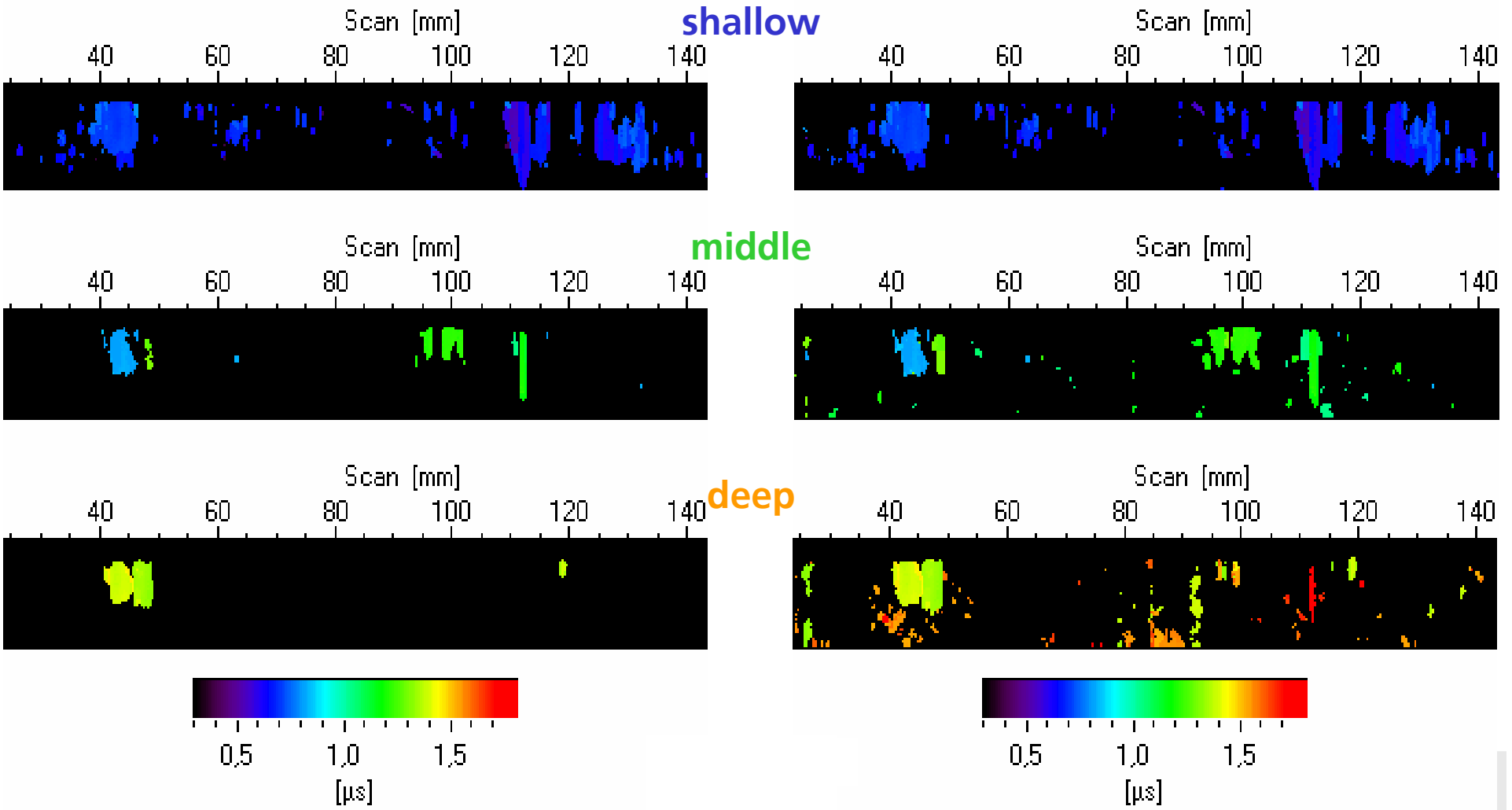
# Flaw Detection in various depths

## (Time-of-Flight D-Scans)

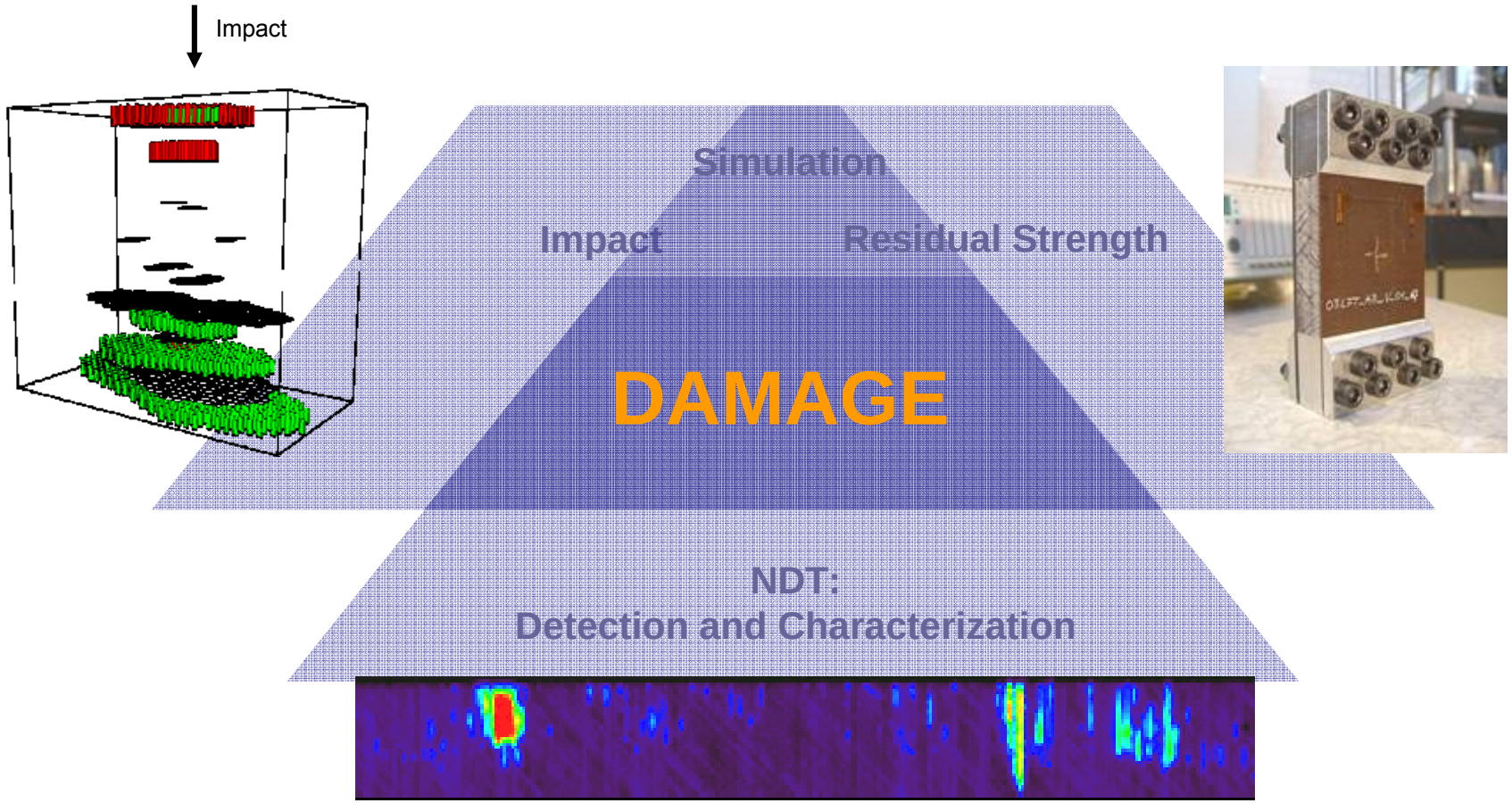
**SDAC: Spectral Distance Amplitude Correction**

*unprocessed*

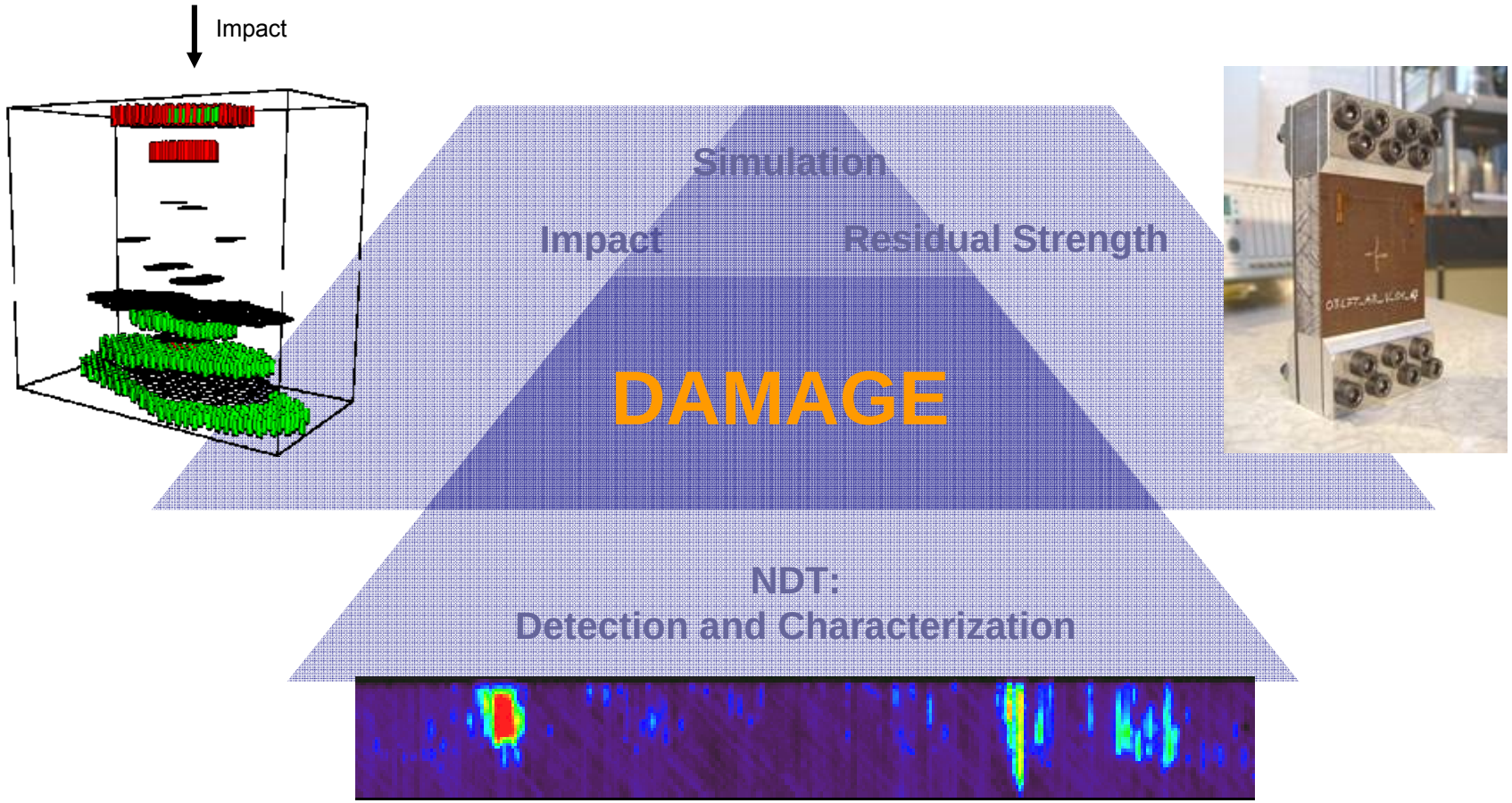
*SDAC processed*



# High Performance Composites in Aerospace Structures



# High Performance Composites in Aerospace Structures




Thank you for your Attention!
Contact: jan.tessmer@dlr.de