CleanSky2

LPA - Platform 1

Efficient simulation of the through-the-thickness damage composition in composite aircraft structures for use with integrated SHM systems

presented by
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DLR

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Clean Sky 2

I. Acknowledgements

Damage localization & size estimation (using an integrated SHM system)

- Dr. Daniel Schmidt
- Maria Moix-Bonet
- Lars Trampe

Damage segmentation & abstraction

- Christoph Dienel

Damage severity assessment

- Marc Garbade

DLR-FA SHM demonstrator @ILA 2018

I. Acknowledgements

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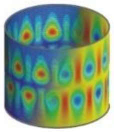


adapted from [1]

Composite aircraft structures are vulnerable to impacts by foreign objects, e.g.

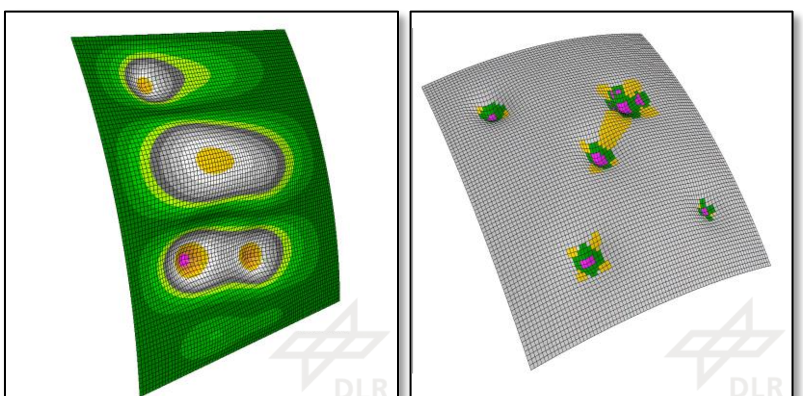
- in-flight & ground hail
- ice-shedding
- tool-drop (production & maintenance)

… leading to barely visible impact damage (BVID), potentially

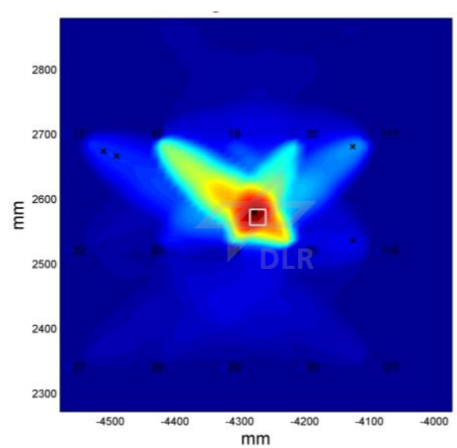
- remaining undetected in the structure
- accumulating up to the next maintenance date

Integrated SHM systems can identify the damage location, but

- the damage size depends strongly on the resolution of the sensor network
- There is no information about the through-the-thickness damage composition



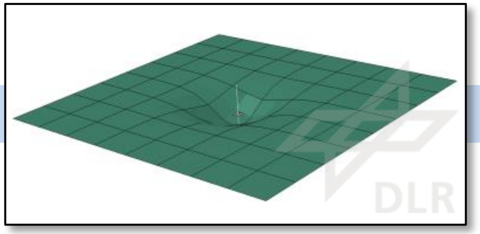
Low-fidelity multiple impact simulation



SHM measurement

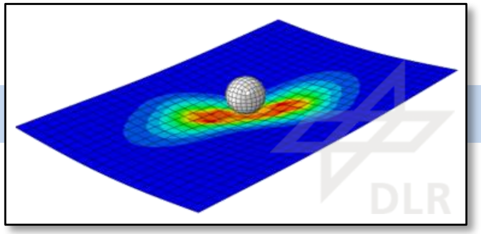
III. A quick recap on fidelity levels

Low-fidelity models



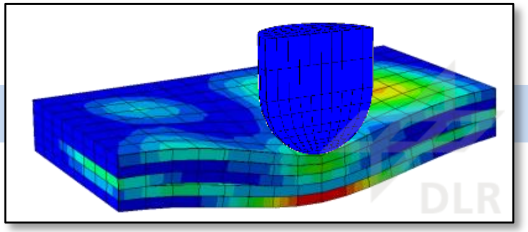
- Limited insight in material and geometrical nonlinearities
- Low modeling effort
- Low computation cost
- High level of abstraction
- Low number of input parameters
- Highly scalable (from coupon to structure level)
- Well suited for parametric & uncertainty studies

Balanced models



- Good balance between physical accuracy & effort
- Medium computation cost
- Suited for development of meta models

High-fidelity models



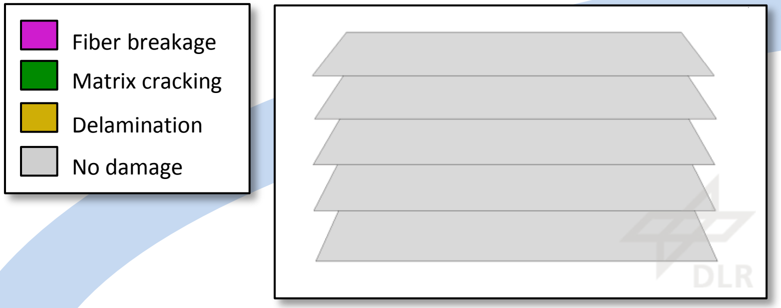
- Full insight in material and geometrical nonlinearities
- High modeling effort
- High computation cost
- Exact physical representation of boundary conditions
- High number of input parameters
- High physical accuracy

Level of Effort

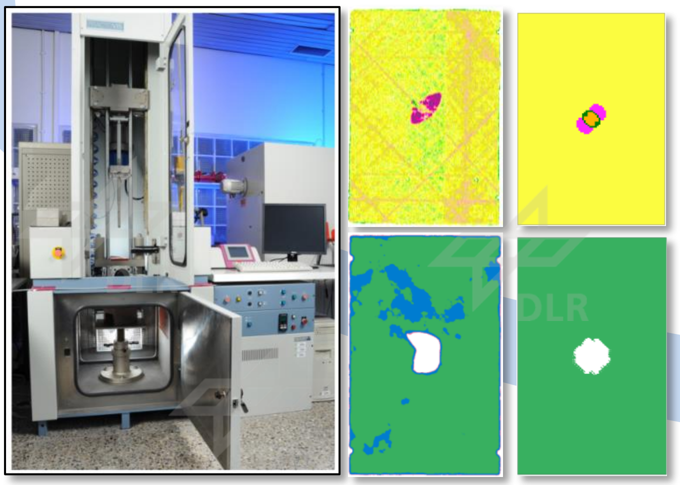
IV. Low-fidelity simulation methodology…

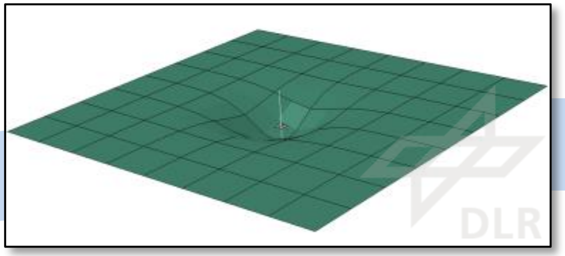
Material modeling

- Three-dimensional stress state recovery
- Use of modern three-dimensional failure criteria
- Material degradation with a lookup table



Experimental vs. virtual testing



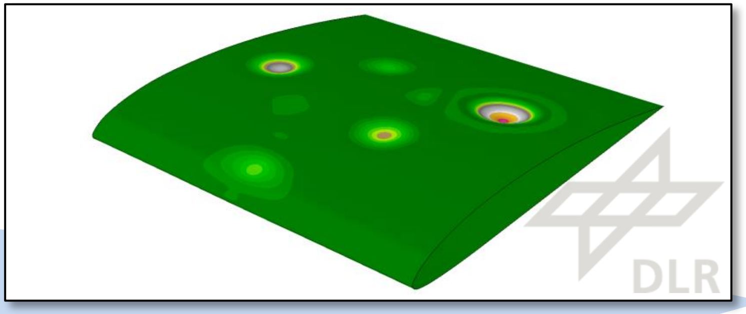


Structural modeling

- Contact modeling by using contact laws
- Discretization with a single layer of shell elements

… in a nutshell

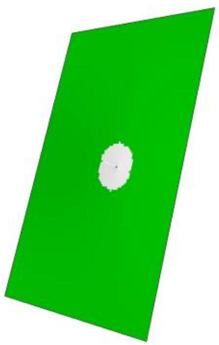
Application in a multiple impact simulation

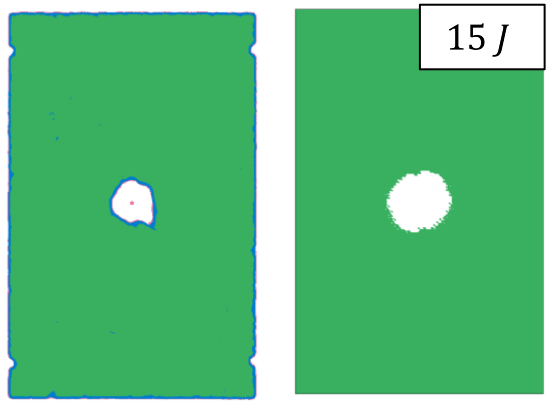


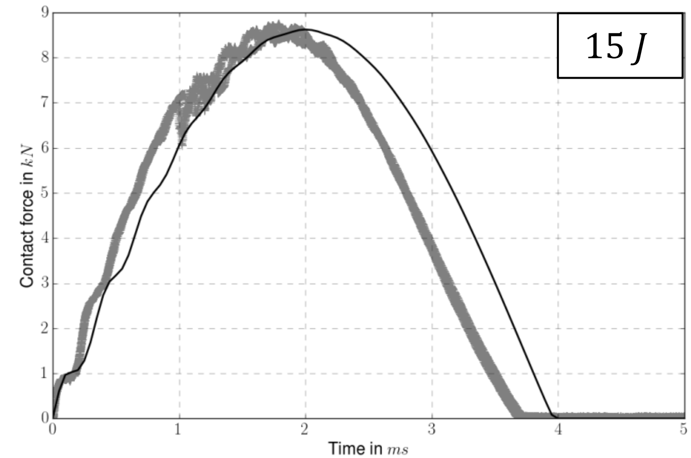
DLR

▪ Validation by means of single-drop tests

Experiments
Simulation



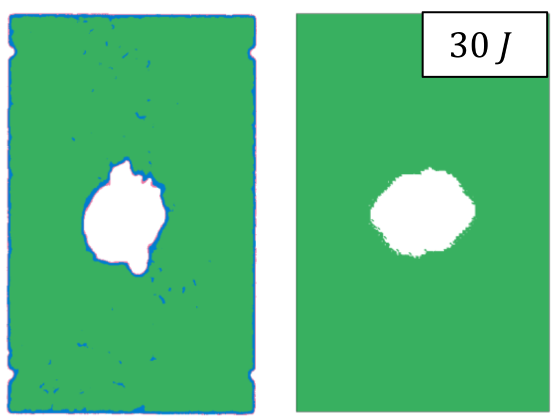


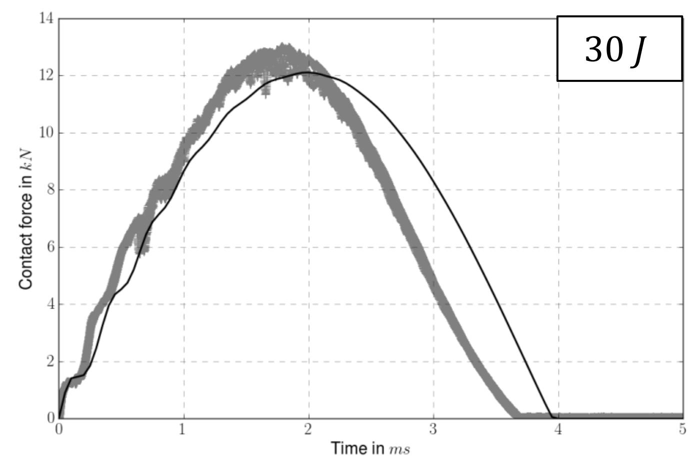


Impactor:
- stainless steel
- $3.95\ kg$
- $\varnothing\ 16\ mm$

Target:
- $4\ mm$ thickness
- $[(\pm 45, 0, 90)_2, \pm 45, 0]_s$

Projected delamination areas:
- LHS → C-scan result
- RHS → Simulation





Clean Sky 2

Damage initiation database (June 2018)

General purpose	Fiber breakage	Matrix cracking	Delamination
Max nominal	Hashin	Hashin (2D & 3D)	Hashin
Quad nominal	Chang & Chang	Chang & Chang	Puck
Linear interaction	Christensen	Chai	Chai
Quad interaction		Cuntze (2004 & 2012)	Choi & Chang
Norris interaction		Puck	Ochoa & Engblom
Polynomial (e.g. Tsai-Wu)		Wiegand	Lee
Yamada & Sun		VDI 2014	
Ha		Camanho	
		SPC3D (DLR)	

Availability

- Python, Java, Fortran
- Abaqus, Ansys, Nastran

DLR

Modeling strategy

Overall strategy:

- Finite shell element model in ABAQUS Standard (S8R5)
- Damage assessment in a linear perturbation step
- Major user-defined subroutines (URDFIL, USDFLD)
  - → obtain global displacements of each node for each relevant element at the start of each increment
  - → calculate nodal displacements in the shell COS
  - → through-the-thickness stress recovery …
  - → evaluation of damage initiation criterion in USDFLD

Three-dimensional stress state recovery:

- Transverse shear stresses
- Transverse normal stress

} Rolfes & Rohwer [2]

Transverse normal stress [2]:

$$G(z) = [c(z)A^{-1}B - d(z)]D^{*-1}$$

$$\sigma(z) = -\left[\{G_{11}, G_{32}\}R_{,x} + \{G_{31}, G_{22}\}R_{,y}\right] + p_0$$

Transverse shear stresses [2]:

$$F(z) = [a(z)A^{-1}B - b(z)]D^{*-1}$$

$$\tau_z(z) = -B_1 F(z) M_{,x} - B_2 F(z) M_{,y}$$

Modeling strategy

Damage severity assessment:

- DIC (Damage Influence Criterion
- Point stress criterion
- Rankine equivalent stress

} Tang et al. [3]

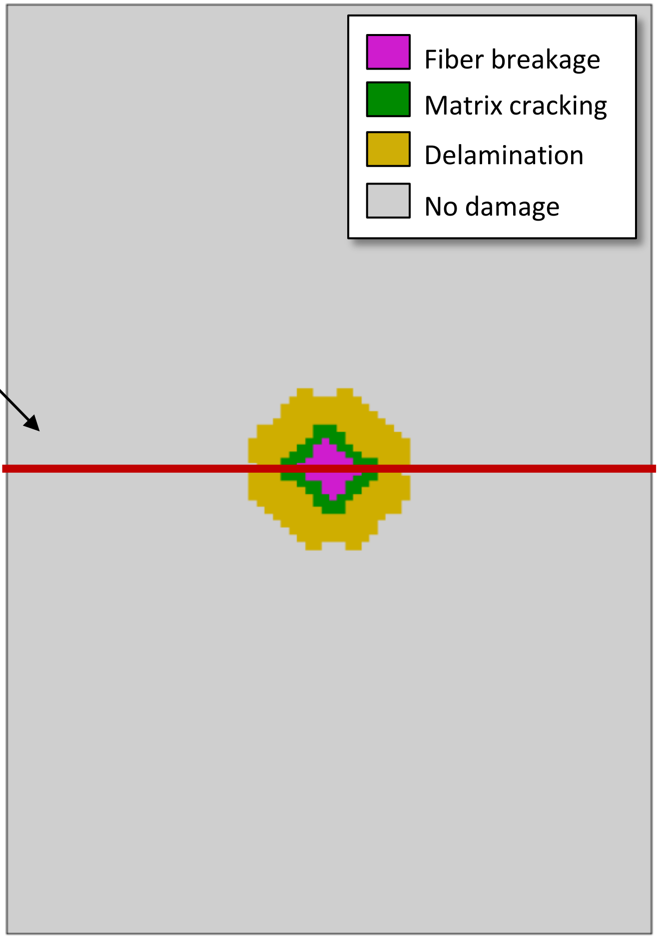
Stiffness reduction for each damage composition:

Elastic constants in *Pa*									$e_{FB} \geq 1$	$e_{MC} \geq 1$	$e_{DEL} \geq 1$
E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}	-	-	-
1.	E_{22}	E_{33}	0.	0.	0.	1.	G_{13}	G_{23}	X	-	-
E_{11}	1.	1.	0.	0.	0.	G_{12}	G_{13}	G_{23}	-	X	-
E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	1.	1.	1.	-	-	X
1.	1.	1.	0.	0.	0.	1.	1.	1.	X	X	-
E_{11}	1.	1.	0.	0.	0.	1.	1.	1.	-	X	X
1.	E_{22}	E_{33}	0.	0.	0.	1.	1.	1.	X	-	X
1.	1.	1.	0.	0.	0.	1.	1.	1.	X	X	X

Additional reduction due to sub-laminate buckling (multiple layers can form a sub-laminate stack j) [3]:

$$R_j = \frac{N_x/t_j}{\sigma_0}$$

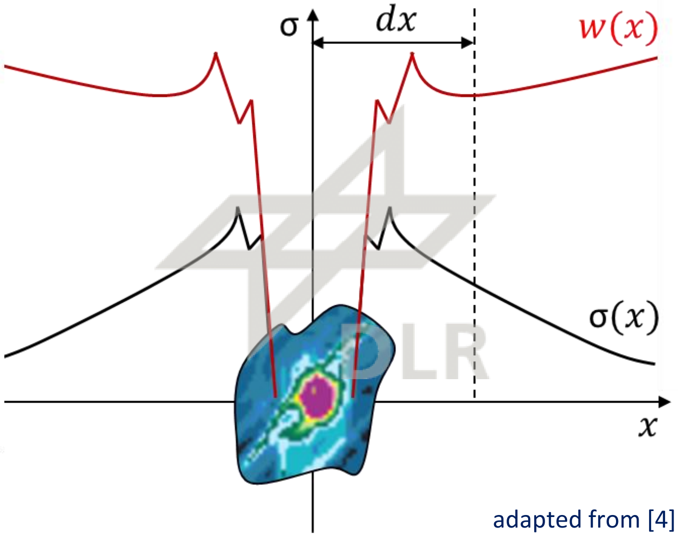
$$C_{dic} = R_j C_{dmg}$$



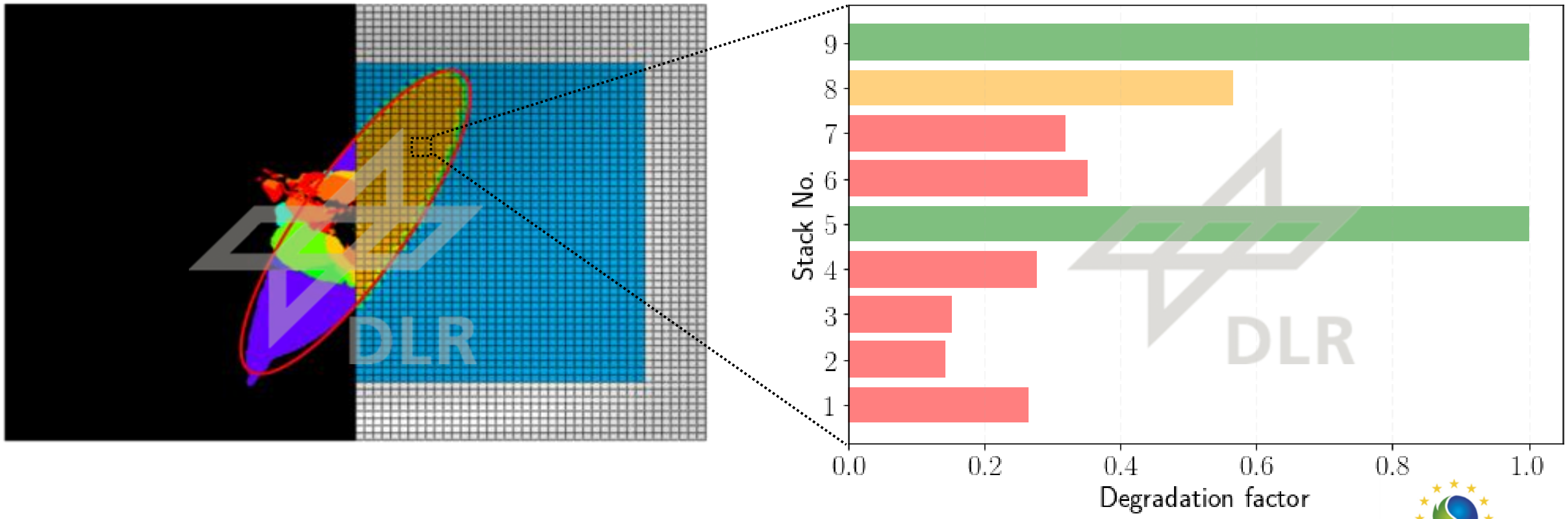
- Modeling strategy

Damage assessment workflow using the DIC [3]:

- Each damage mode (fiber, matrix & delamination) is idealized as an ellipse in the material coordinate system.
- A linear buckling analysis is used to determine knock-down factors for every delaminated stack.
- The cross-sectional stress perpendicular to the main load axis is evaluated → results in a knock-down factor w.r.t. the virgin residual strength of the laminate.



adapted from [4]



V. Numerical experiments

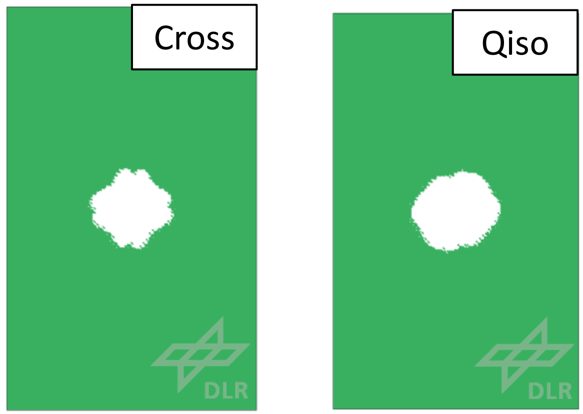
▪ Validation of the DIC by means of single-drop tests

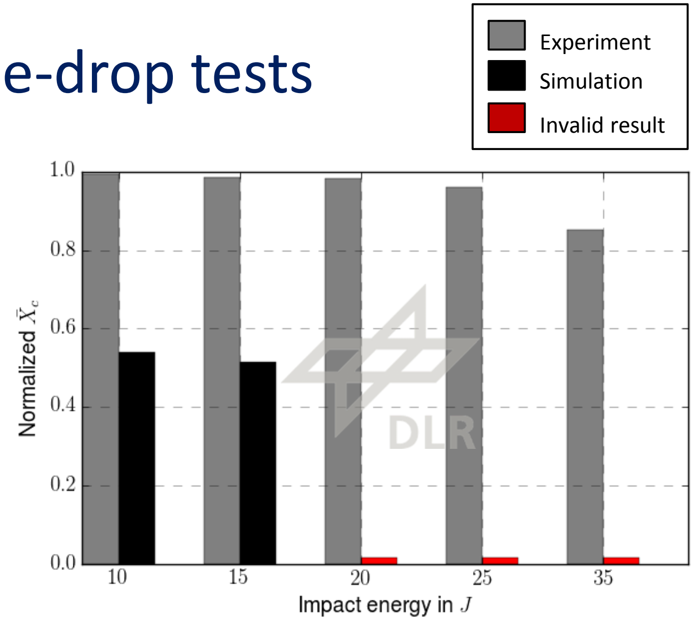
Short remarks:

- Validation pending
- Preliminary results are not acceptable

Target:

- $4\ mm$ thickness
- $[(\pm 45)_5, 45]_s$



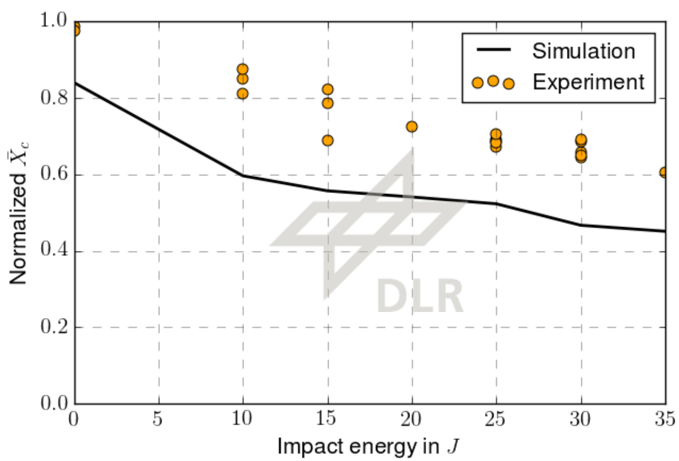


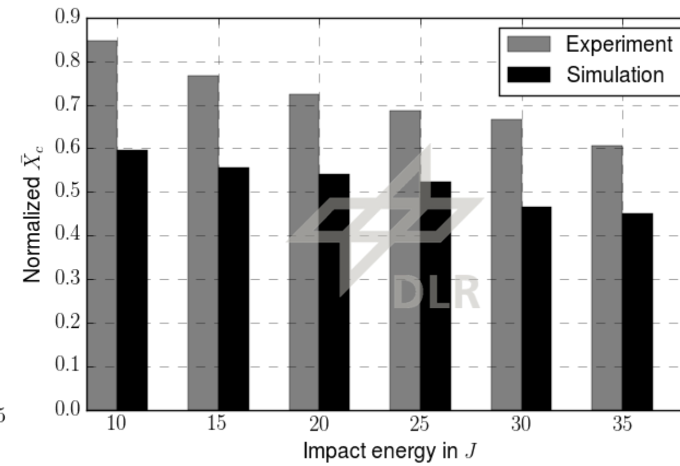
Short remarks:

- Strictly conservative
- Constant shift
- Acceptable

Target:

- $4\ mm$ thickness
- $[(\pm 45, 0, 90)_2, \pm 45, 0]$



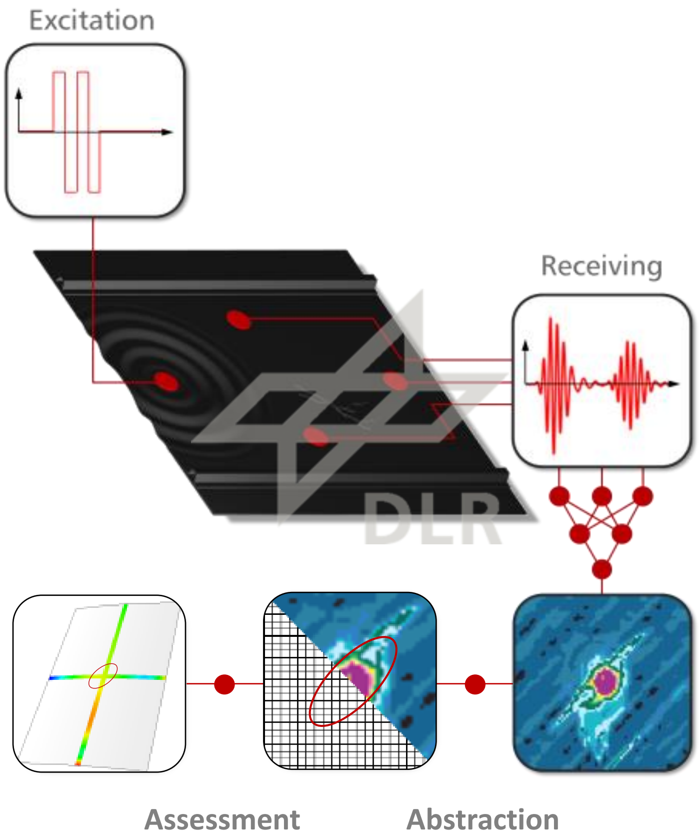


DLR-FA SHM demonstrator workflow:

- A small glass cylinder introduces a signal disturbance, which is located by the SHM system.
- The **D**amage **I**nfluence **C**riterion (DIC) simulation workflow is applied to a submodel of the panel surrounding the damaged area.

Use case:

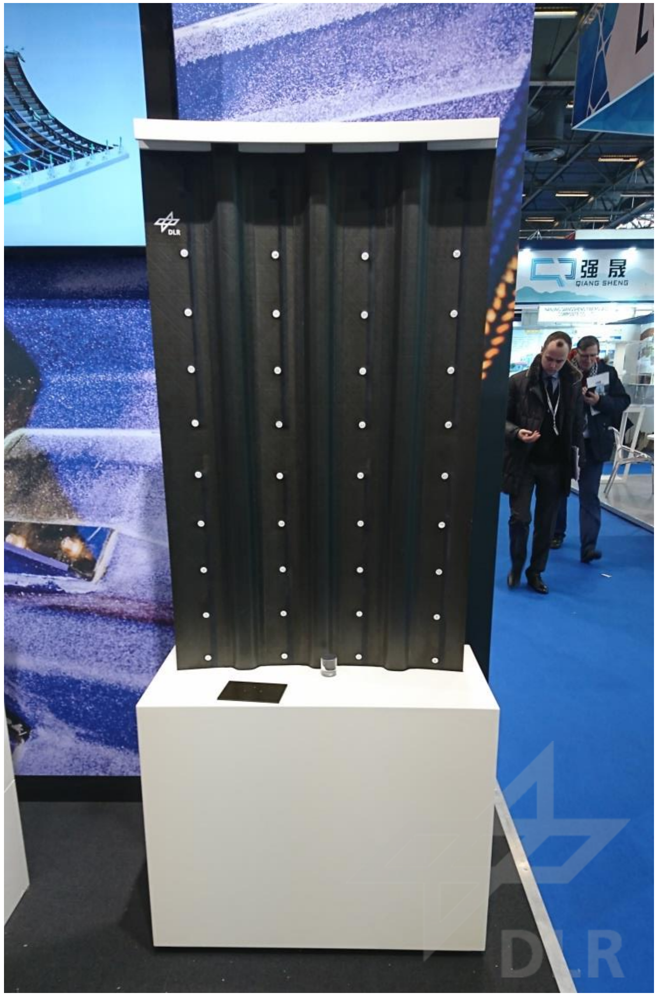
- Maintenance → Is damage in need of repair?



VI. Contributions to DLR-FA SHM demonstrator

Contributions to DLR-FA SHM demonstrator :

- Automated pre- & post-processing of ABAQUS simulation jobs with user-defined subroutines.
- Calculation of a local damage severity measure on panel level using the DIC.
- Damage severity assessment capability in **real-time**.



DLR-FA SHM demonstrator @JEC Composites 2018

VII. Concluding remarks

Validation of the DIC by means of single-drop tests:

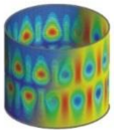
- Acceptable accuracy for quasi-isotropic laminates (conservative deviations)
- Almost constant shift in case of quasi-isotropic laminates → may indicate a systematic error
- Non-acceptable results for cross-ply laminates (no extreme value points in weight function)

Points to optimize:

- Modification or reimplementation of weight function in order to work properly for all layups
- Calculate through-the-thickness damage composition on-the-fly, if sufficient data can be provided by a SHM system (energy, maximum deflection, duration)

Next challenges:

- Implementation of a similar damage severity assessment workflow for multiple impact/damage problems
- Implementation of a low-fidelity delamination growth criterion under quasi-static loading for single and multiple damage



Thank you for your attention!

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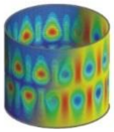

IX. References

[1] http://testcs.openimpact.be/green-regional-aircraft-gra (saved on 26.08.2017)

[2] Rolfes R., & Rohwer K. (1997). Improved transverse shear stresses in composite finite elements based on first order shear deformation theory. *Int J Numer Methods Eng,* 40, 51–60.

[3] Tang, X., Shen, Z., Chen, P., Gaedke, M. (1997). Methodology for residual strength of damaged laminated composites. In 38th Structures, Structural Dynamics, and Materials Conference (p. 1220).