STEFAN BOSSE[1*]
CHRISTOPH POLLE[2]

[1] Institute of Computer Science
Researchgroup Practical Computer Science
University of Koblenz

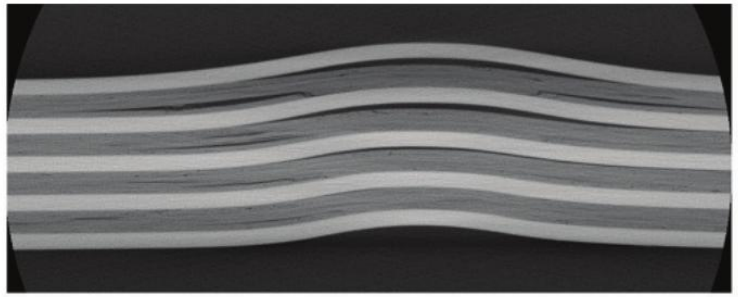
[2] Faseninstitut Bremen e.V.

university of koblenz
Computer Science

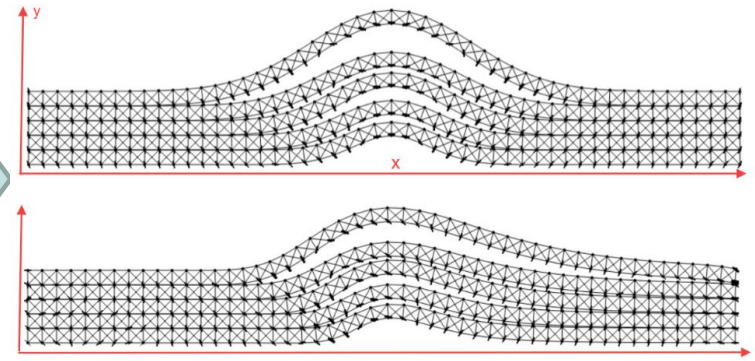
Praktische Informatik

Bild: Getty Images, Fancy/Veer/Corbis]

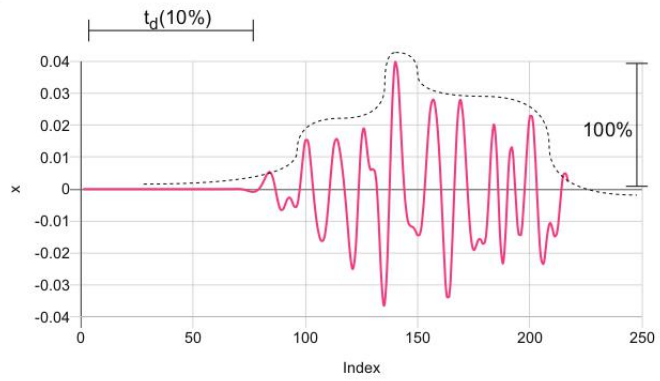
Real Damage



Physics-informed Surrogate Model



NDT: Improved Diagnostics



PHYSICS-BASED SURROGATE MODELING OF IMPACT DAMAGE IN MULTI-MATERIAL LAMINATES FOR ULTRASONIC DIAGNOSTICS AND ML DAMAGE PREDICTION

Stefan Bosse, Christoph Polle

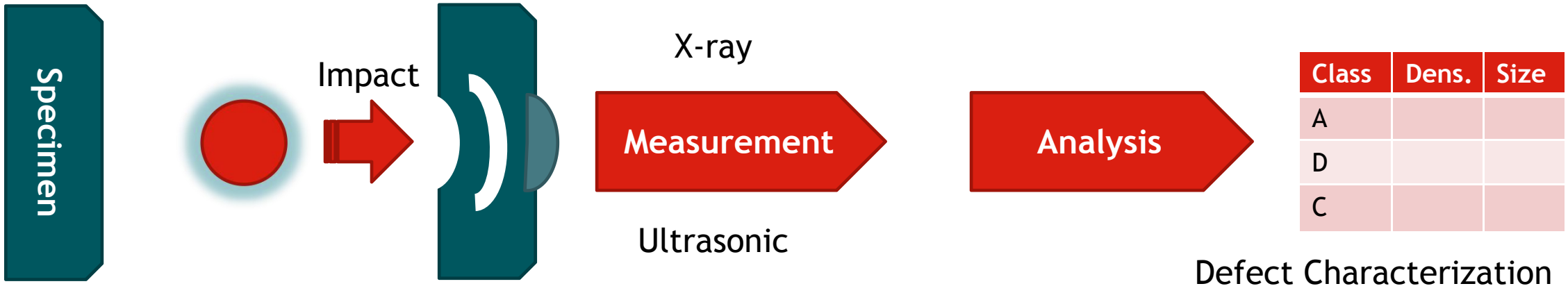
Praktische Informatik

university of koblenz
Computer Science

CONTENT

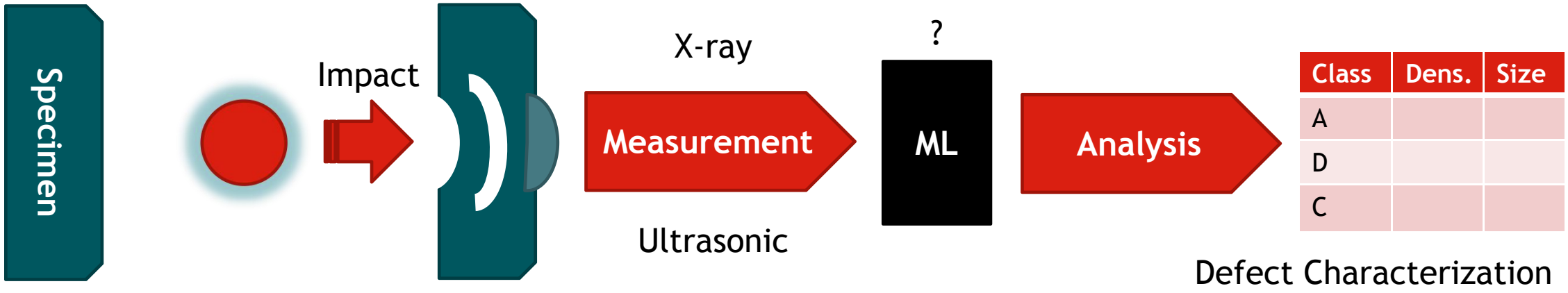
INTRODUCTION

- Impact damage can cause component failure, early fatigue, or other degradations (immediately or later on)
- Characterization of impact damage can be a challenge:
  - External deformation (simple)
  - Internal deformation (difficult)
  - Delaminations and cracks inside (very difficult)
- Depending on material and compositon (laminates), X-ray and Ultrasonic Testing can be used.



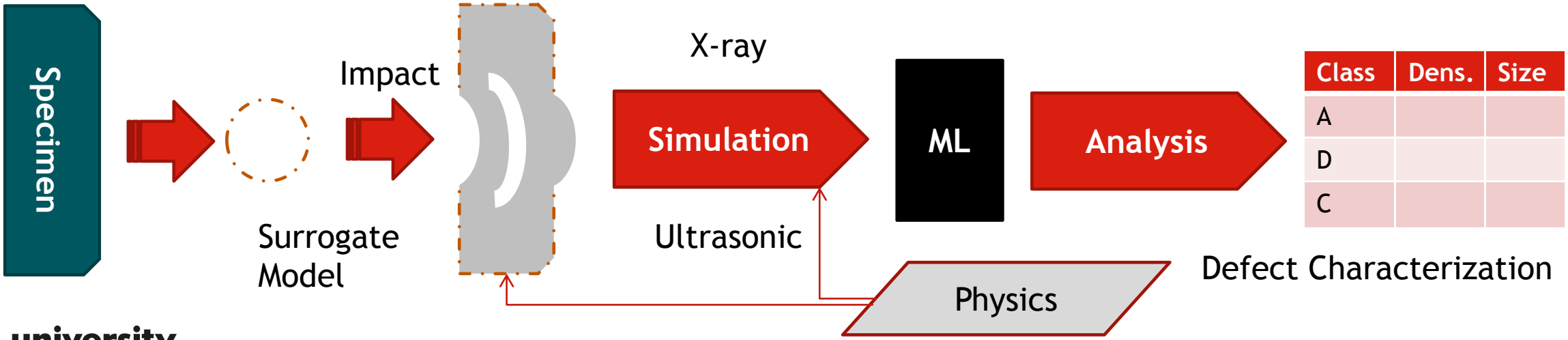
INTRODUCTION

- Measuring data has often only a weak correlation with relevant damage features
  - Delamination area, volume, thickness, layer location
  - Cracks can be very small compared to the initial deformation pattern
- The deployment of data-driven feature extraction models (aka. ML models) can be an option.
- But: ML models tend to strong specialization (even if statistical parameters of the model are fine)
- To support generalized prediction models, a dense and wide parameter space in the training data is required, **not available in experimental data!**

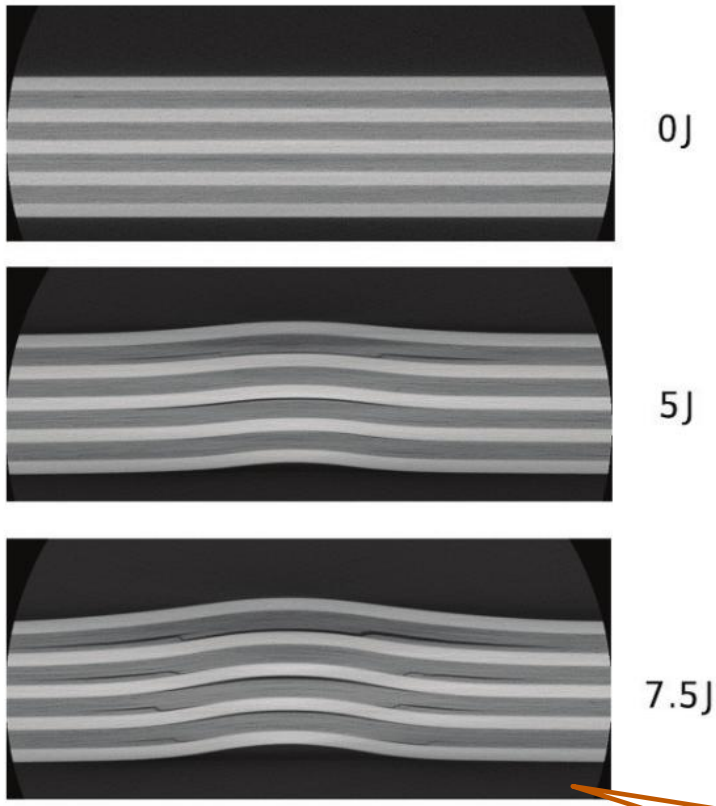


INTRODUCTION

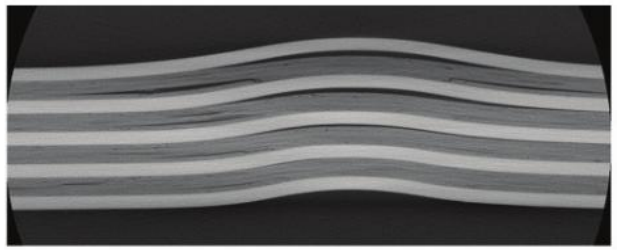
- Physics-based Simulation can be used to generate test and training data for ML training and validation of damage predictor models with high coverage of the parameter space.
- But: We need a **simplified and parameterizable surrogate model for impact damage**
  - A geometric model, two- and three-dimensional;
  - Satisfying material and physical constraints, e.g., constant mass-volume after deformation
  - Support for multi-material multi-layer materials, e.g., Fibre-Metal Laminates (FML)



IMPACT DAMAGE IN FIBRE-METAL LAMINATE PLATES

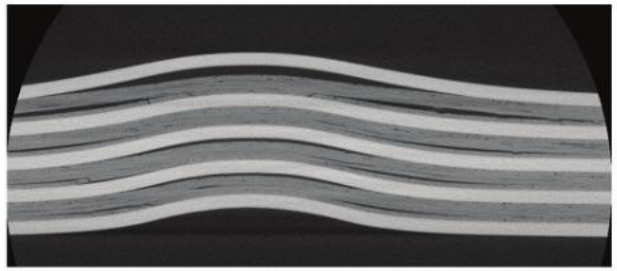


0J



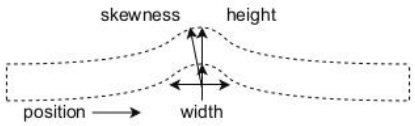
10J

5J



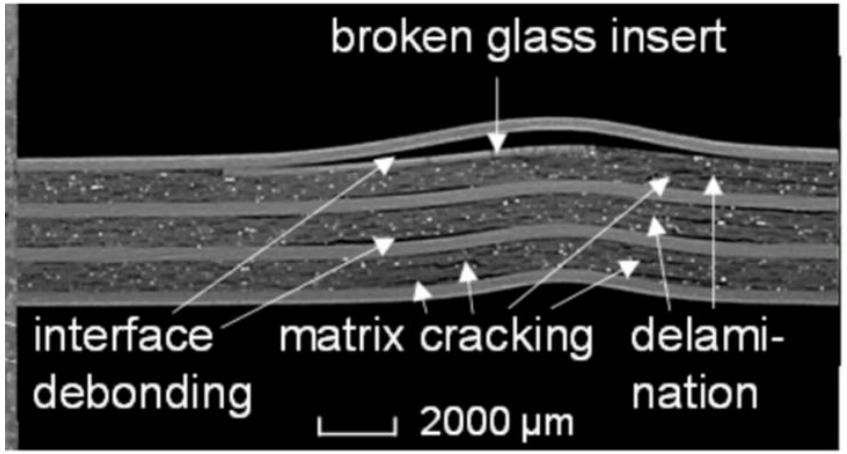
12.5J

7.5J



3 mm

X-ray CT material crosss sections for different impact energies



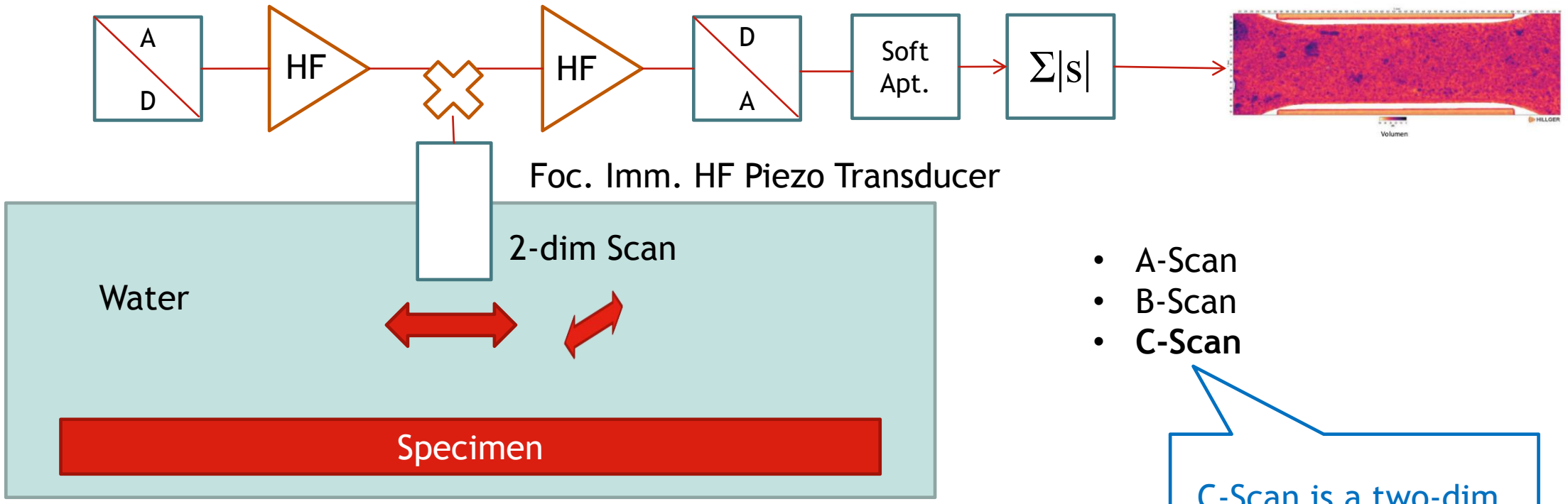
Chirag Shah, Stefan Bosse, and Axel von Hehl. Taxonomy of Damage Patterns in Composite Materials, Measuring Signals, and Methods for Automated Damage Diagnostics, Materials 15 (MDPI), no. 13 (2022): 4645

50 mm

NDT: IMMERSION MEASURING TECHNIQUE?

Bild: Rainer Haufe

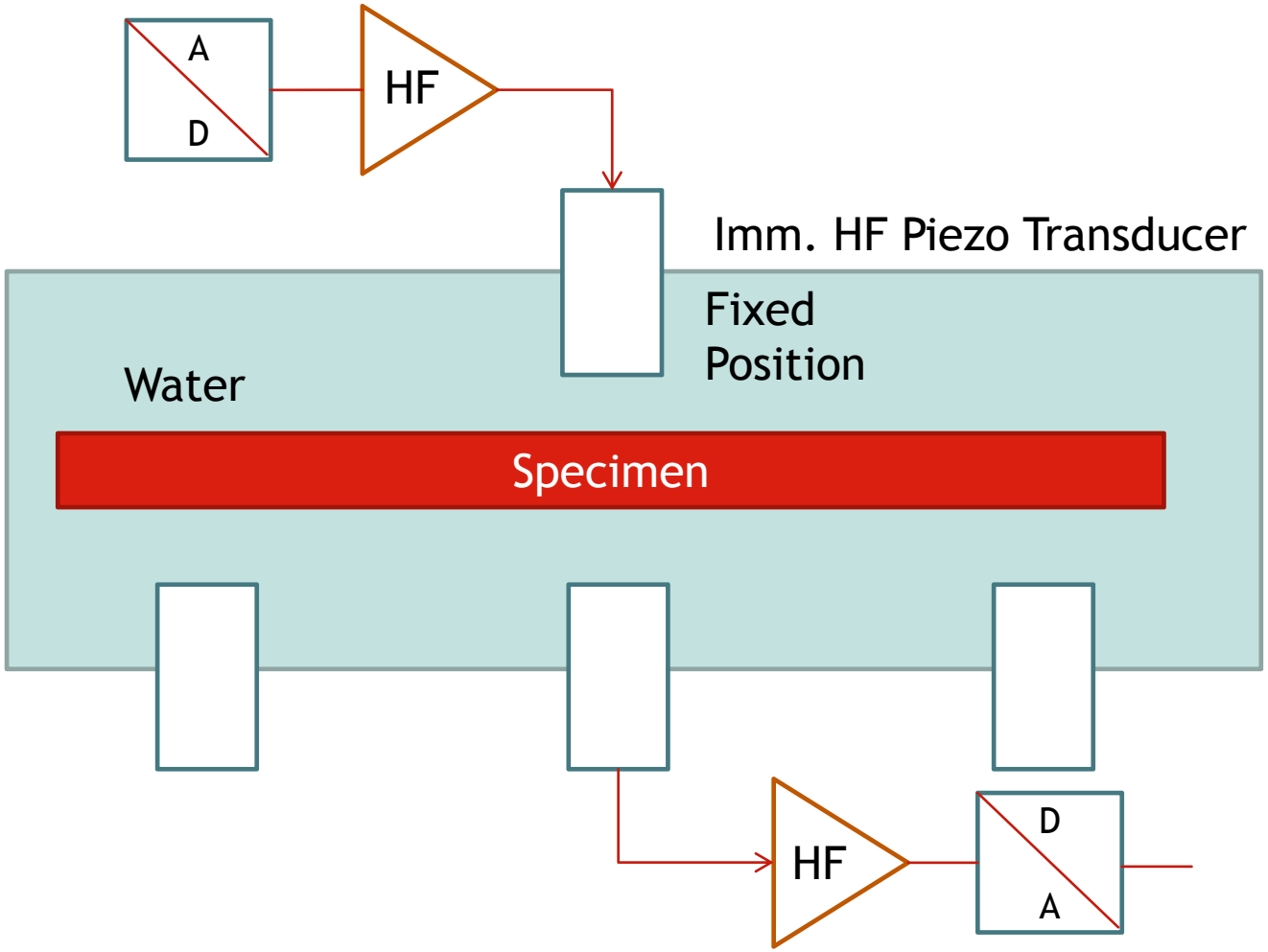
US DIAGNOSTICS: SCANNED IMMERSION PULSE-ECHO

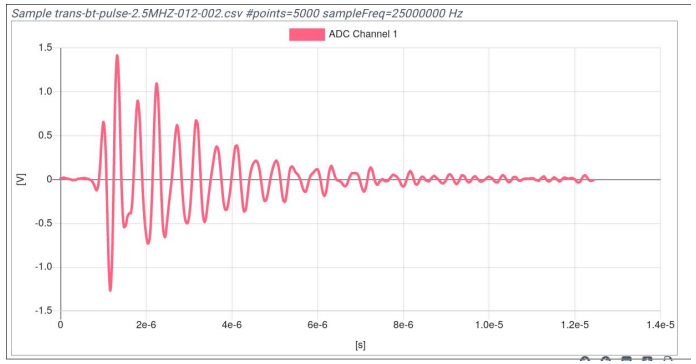


- A-Scan
- B-Scan
- **C-Scan**

C-Scan is a two-dim. amplitude image

US DIAGNOSTICS: TRANSMISSION / IMMERSION

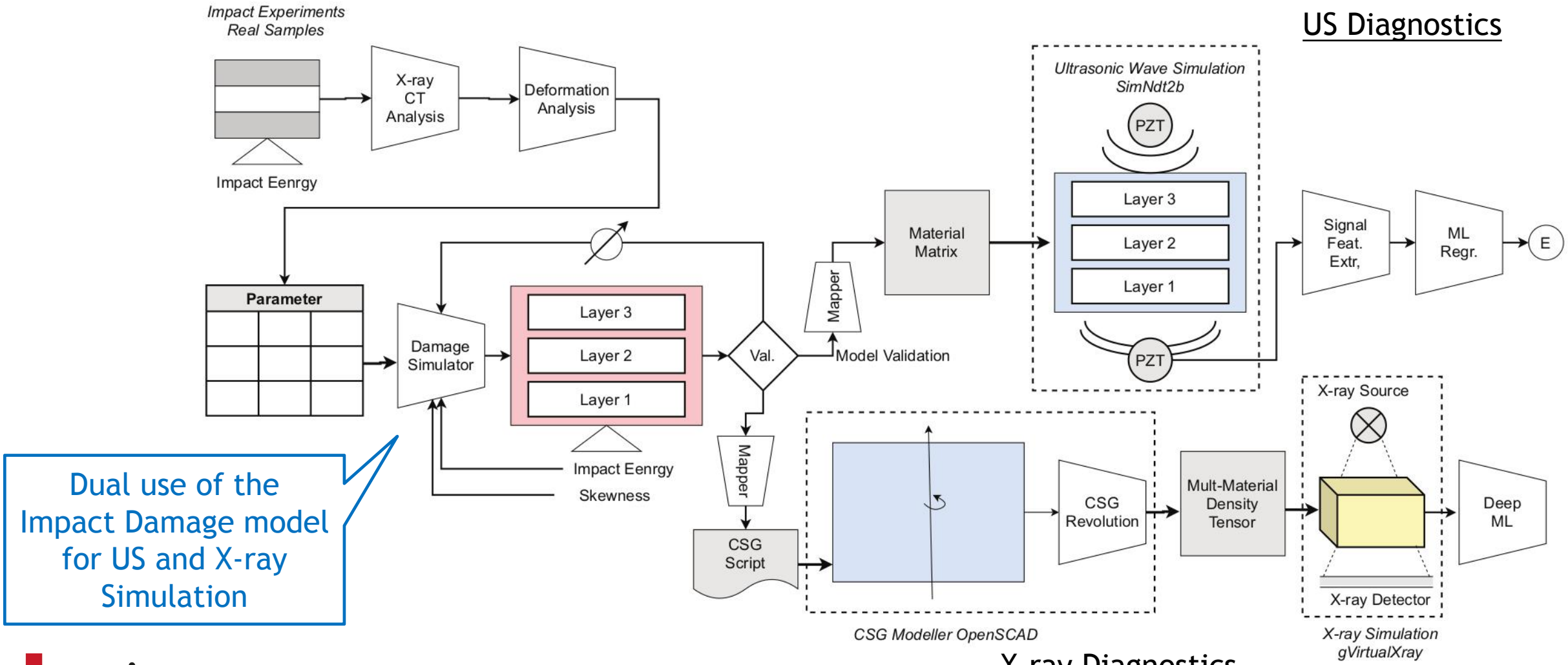




- A-Scan
- **B-Scan**
- C-Scan

B-Scan is a time-resolved signal

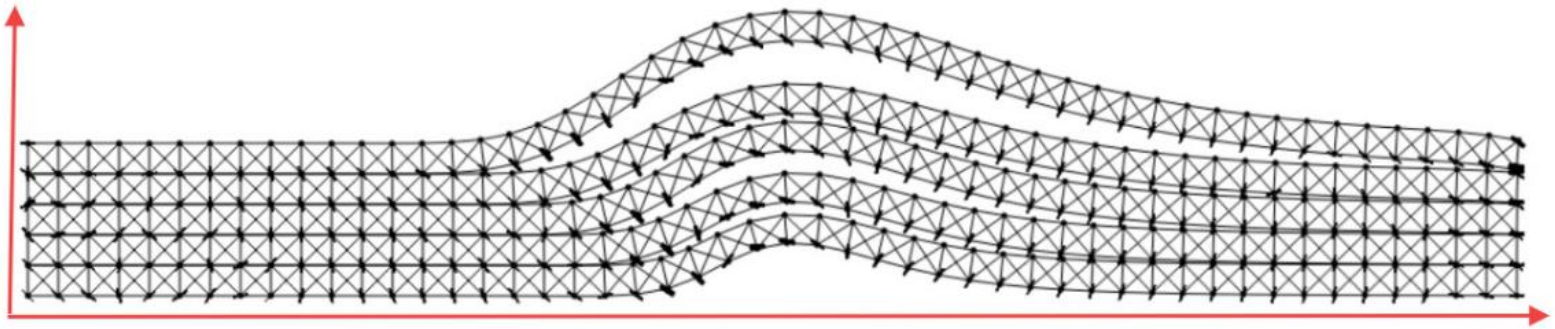
THE SIMULATION CONCEPT



Dual use of the Impact Damage model for US and X-ray Simulation

THE IMPATC DAMAGE SURROGATE MODEL

- We assume a **multi-layer material plate**. Each layer is modelled independently.
- The impact event, e.g., caused by a steel ball with a specific kinetic energy E, will cause deformation of the plate (and the layers).
- We consider a two-dim. cross section model satisfying the following constraints:
  - The mass-volume must be constant, i.e., the deformation will not change the mass and the enclosing volume of a layer
  - Layers may not intersect after the impact event wrt. individual deformation.
  - Deformation can be asymmetric (skewness).
  - Three dimensional model by rotation around center axis (symmetric only)

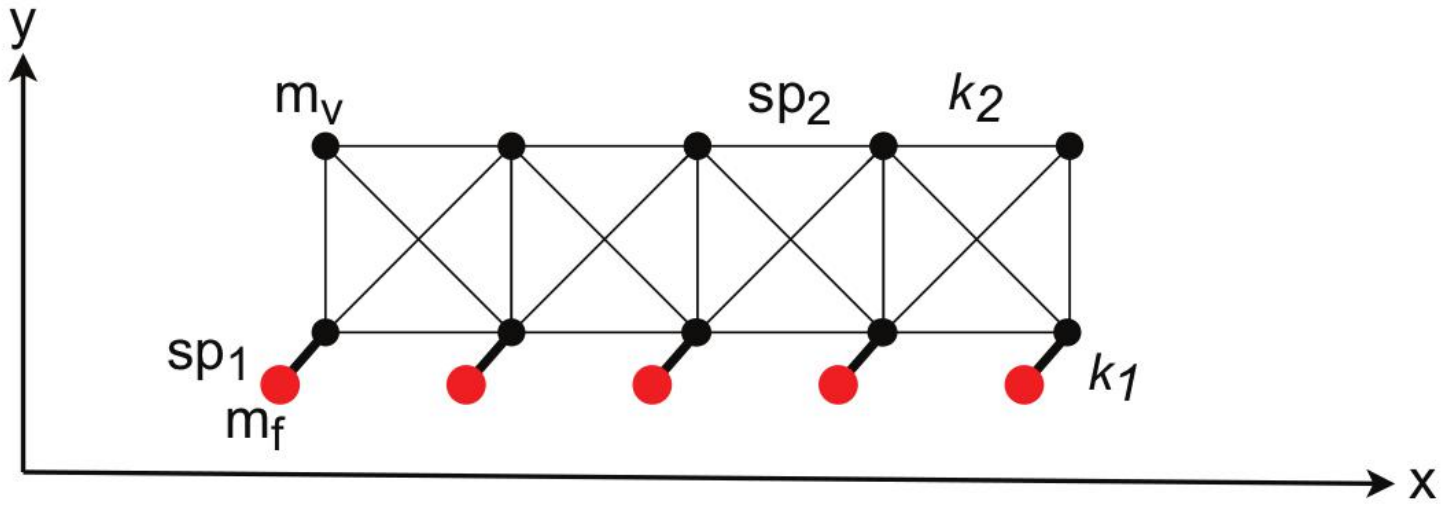


Constant mass-volume!

Avoid computational intensive FEM!

THE IMPACT DAMAGE SURROGATE MODEL

- To satisfy the constraints, a **mass-spring multi-body physics model** is used to model the deformation of one layer
- The nodes of each plate layer are free (top and bottom side)
- There are additional nodes on the bottom side at fixed positions driven by a deformation generator function.
- For each layer there is a **generator function**, a parameterized bell curve.



THE IMPACT DAMAGE SURROGATE MODEL

- Asymmetry can be covered by a skewed Gaussian function.
- Model is parameterized based on real measurements (X-ray CT)
- The mathematical generator function G for the deformation of each layer is given by:

$$G(x, x_0, \sigma, \alpha) = ke^{-\frac{(x-x_0)^2}{2(\sigma+\alpha(x-x_0))^2}}$$

$$L_i(y_0, D_i, S_i) : \mathbb{R}^3 \rightarrow \mathbb{R}^{W \cdot H}$$

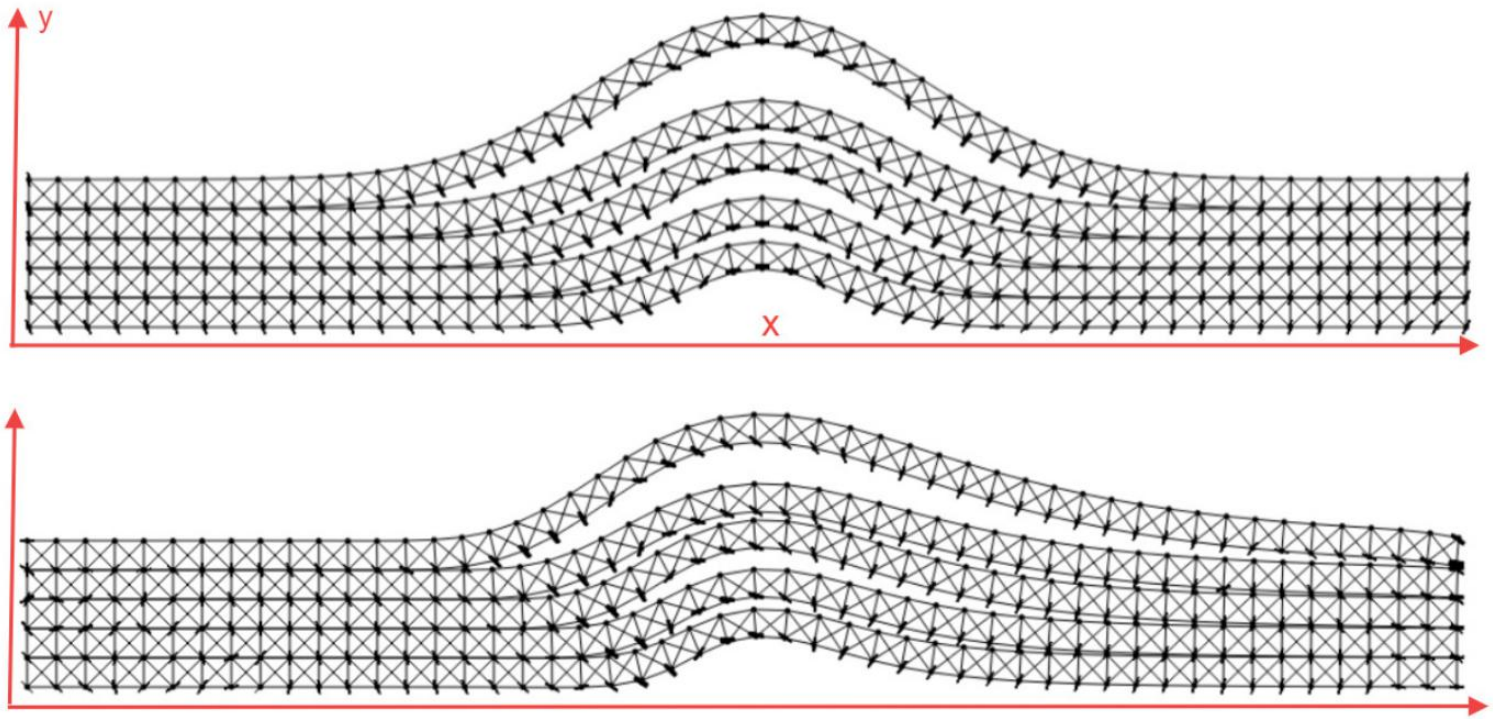
$$L_i(y_0, D_i, S_i) = \left\{ S_i G\left(x, \frac{W}{2}, D_i, \alpha\right), x \in \{0, 1, .., W-1\} \right\}$$

$$i \in \{1, 2, ..\}, D_i = D \cdot T_x^i, S_i = S \cdot T_y^i$$

THE IMPACT DAMAGE SURROGATE MODEL

- Examples of damage generation with five layers (alternating metal/glass material), E=20 J, R=5 mm, sc=50/mm.

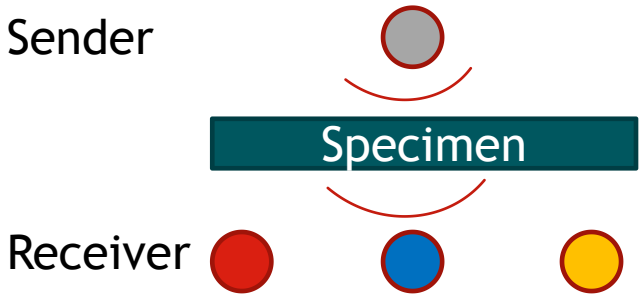
- (Top) Skewness A=0
- (Bottom) Skewness A=0.2

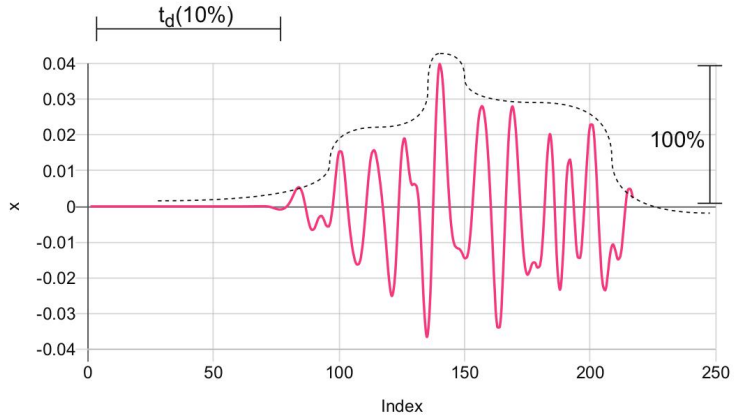


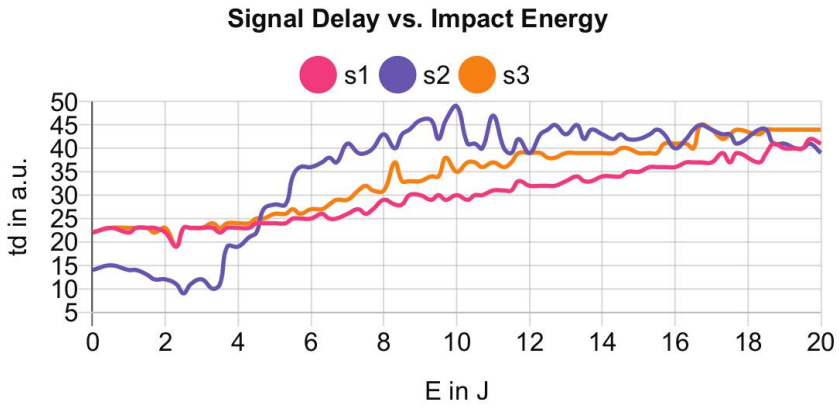
DATA-DRIVEN DAMAGE PREDICTOR MODEL

- To demonstrate the usefulness of the proposed physically-informed damage simulator for the generation of large synthetic data sets with high parameter variance we will derive relevant features from **Ultrasonic signals** in an **immersion measuring set-up.**

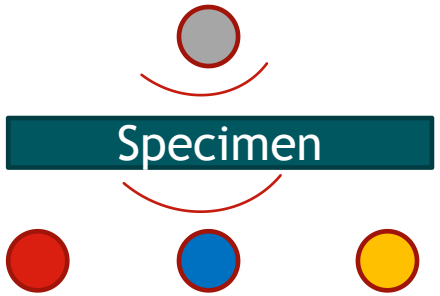
- Output of the predictor model is the original impact energy E,
- input are relevant features of three time-resolved Ultrasonic signals, here the signal delay

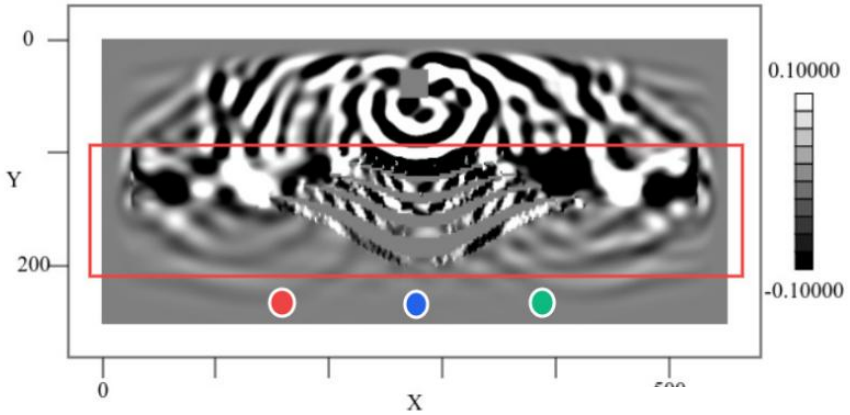


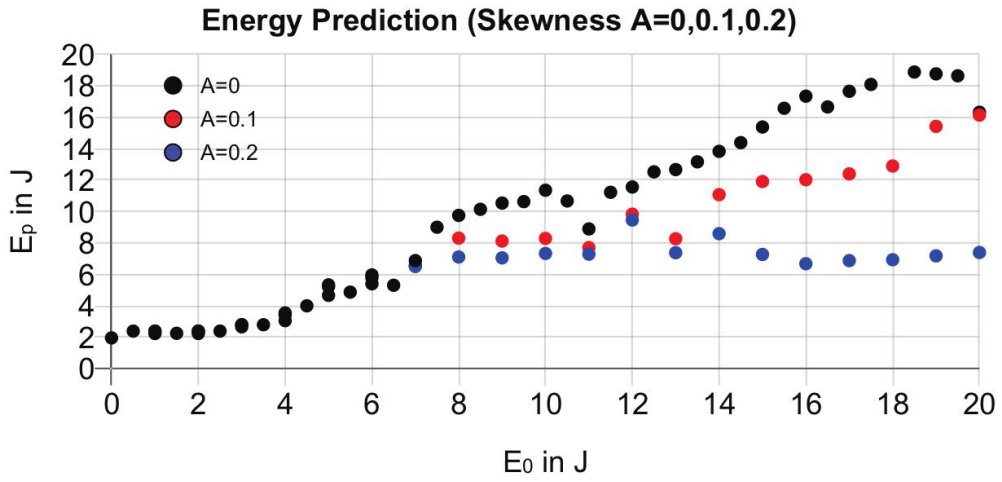




DATA-DRIVEN DAMAGE PREDICTOR MODEL

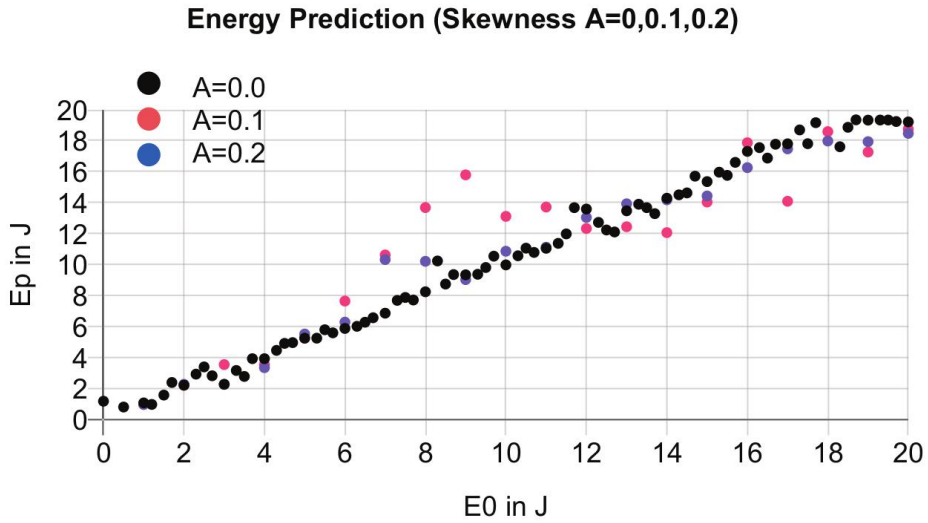






Left: Model trained with samples A=0

Right: Model trained with samples A=0,0.1, 0.2



CONCLUSION

Good data versa big data!

Simulation

- **Physics-based Simulation is used to generate synthetic measuring data with high parameter variance**
- X-ray (radioscopy or CT) as well as Ultrasonic testing require parameterized geometric material models
- Geometric models are calibrated with real data

Surrogate Model

- The **geometric surrogate model for impact damage** in laminates and composites bases on simple **multi-body mass-spring simulation**
- The model uses a bell curve function with skewness
- The layers of laminates are computed independently by a generator function

Machine Learning

- A ML predictor model was used to predict the impact energy by using features from Ultrasonic signals (immersion technique)
- The **prediction quality** depend significantly on the skewness of the impact damage pattern
- **Only by using a data set with broad parameter variance ensures model generalization**

THANK YOU

Stefan Bosse

sbosse@uni-koblenz.de

www.edu-9.de

Bild: Getty Images, Fancy/Veer/Corbis]