A new method for defects detection in CFRP composites using Wavelet Analysis and non-contact Lamb Waves propagation

Lea Lecointre*, Ryo Higuchi*, Tomohiro Yokozeki*, Masakatsu Mita**, Shota Tonegawa**, Naoki Hosoya**, Shin-ichi Takeda***

*Department of Aeronautics & Astronautics, The University of Tokyo, Bunkyo-ku, Tokyo, Japan

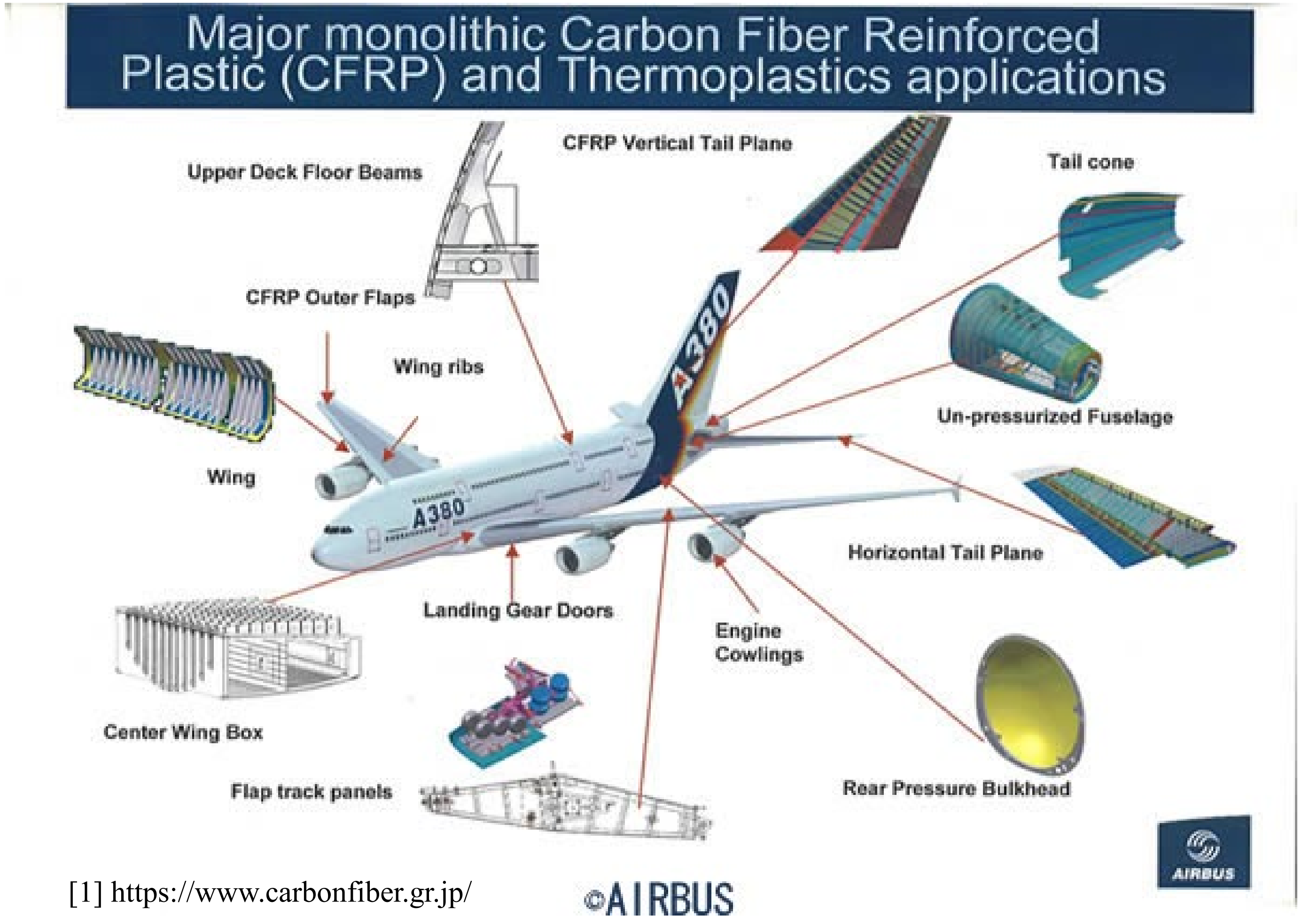
**Department of Engineering Science and Mechanics, Shibaura Institute of Technology, Koto-ku, Tokyo, Japan

***Aeronautical Technology Directorate, Japan Aerospace Exploration Agency (JAXA), Mitaka, Tokyo, Japan

Contents

The increasing use of CFRPs in Aerospace

- CFRPs: Carbon Fibers Reinforced Plastics

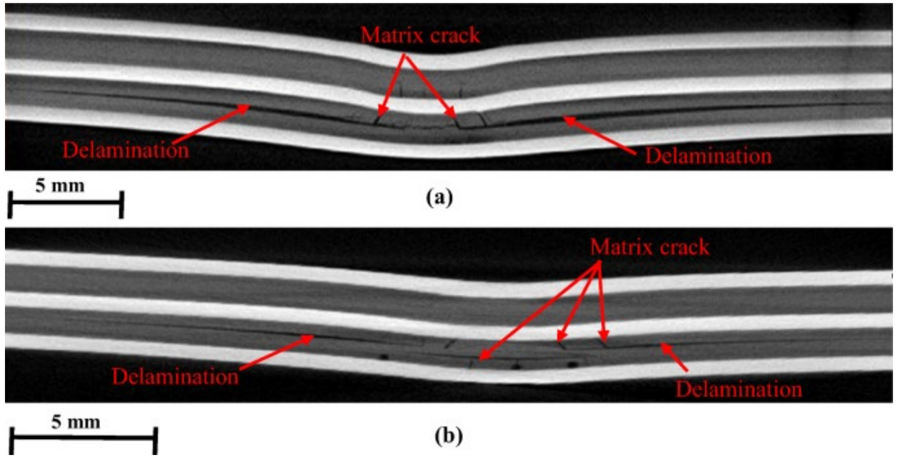


[1] https://www.carbonfiber.gr.jp/

- Combine high resistance and low weight

Some typical material densities (ton/m3)	
Aluminium	2.7
Iron	7.9
Titanium	4.8
CFRP	1.5-2.0

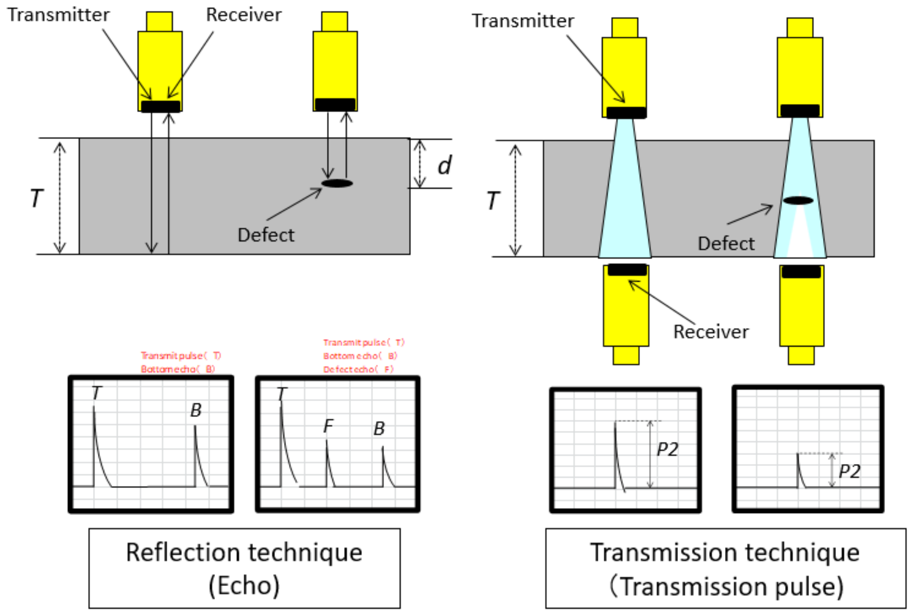
- An important limitation: the delamination



[2] Shi, Y., Pinna, C. & Soutis, C. Impact Damage Characteristics of Carbon Fibre Metal Laminates: Experiments and Simulation. Appl Compos Mater 27, 511–531 (2020)

Advances in the Ultrasonic Testing of CFRPs

- UT is the most commonly used method for the NDT of CFRP structures

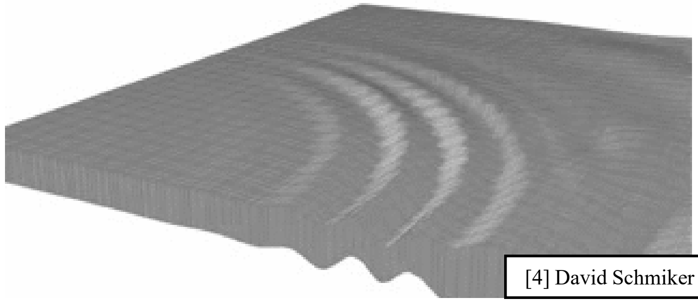


[3] https://www.gnes.co.jp/en/

- Important limitation: full scanning is time consuming

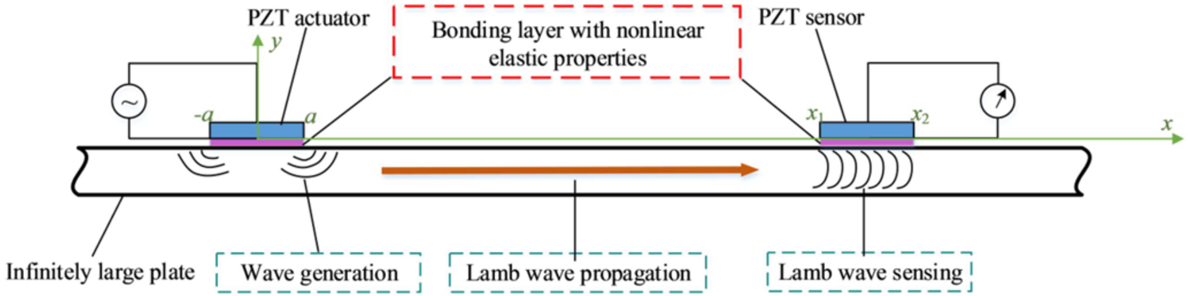
→ Can we avoid full part scanning?

- The Lamb Waves based techniques



[4] David Schmiker Youtube

Horace Lamb 1916
D.C. Worlton 1960s



[5] Shengbo Shan et al 2017 Smart Mater. Struct.

- Important limitation: applicability to aerospace industry (other than SHM)

→ Can we get rid of the bonded transducers?

Non-contact Lamb Waves methods & research objectives

- Some methods currently existing:
    - Air-Coupled Transducers
    - Laser thermoelasticity
    - Laser Ablation (LA)
- **Laser-Induced Plasma Shock Wave** (LIPSW)
- LIPSW are able to generate Lamb Waves propagation in various materials, including CFRP (Hosoya et al. 2018)

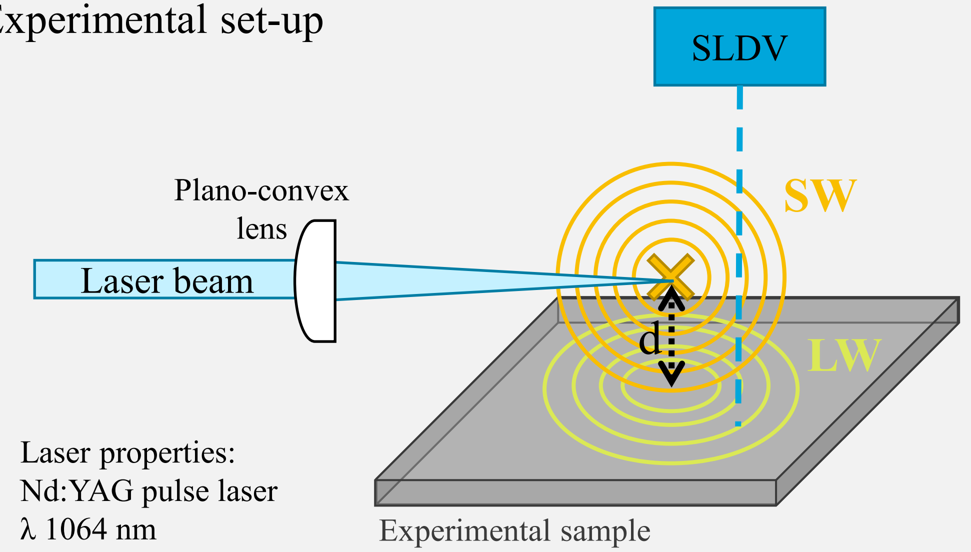
[6] Hosoya, N., Yoshinaga, A., Kanda, A., & Kajiwara, I. (2018). Non-contact and non-destructive Lamb wave generation using laser-induced plasma shock wave. *International Journal of Mechanical Sciences*, *140*, 486–492

→ Can LIPSW-excited Lamb Waves detect delamination?

- Lamb Waves features adapted to defects detection?
- Signal Processing technique adapted to the Lamb Waves features?

- **Objective**: assess the ability of LIPSW system to detect delamination in CFRPs
- **Method**:
    - Generate fully non-contact Lamb Waves propagation in several healthy and defected CFRP samples
    - Build Signal Processing algorithms adapted

Experimental set-up



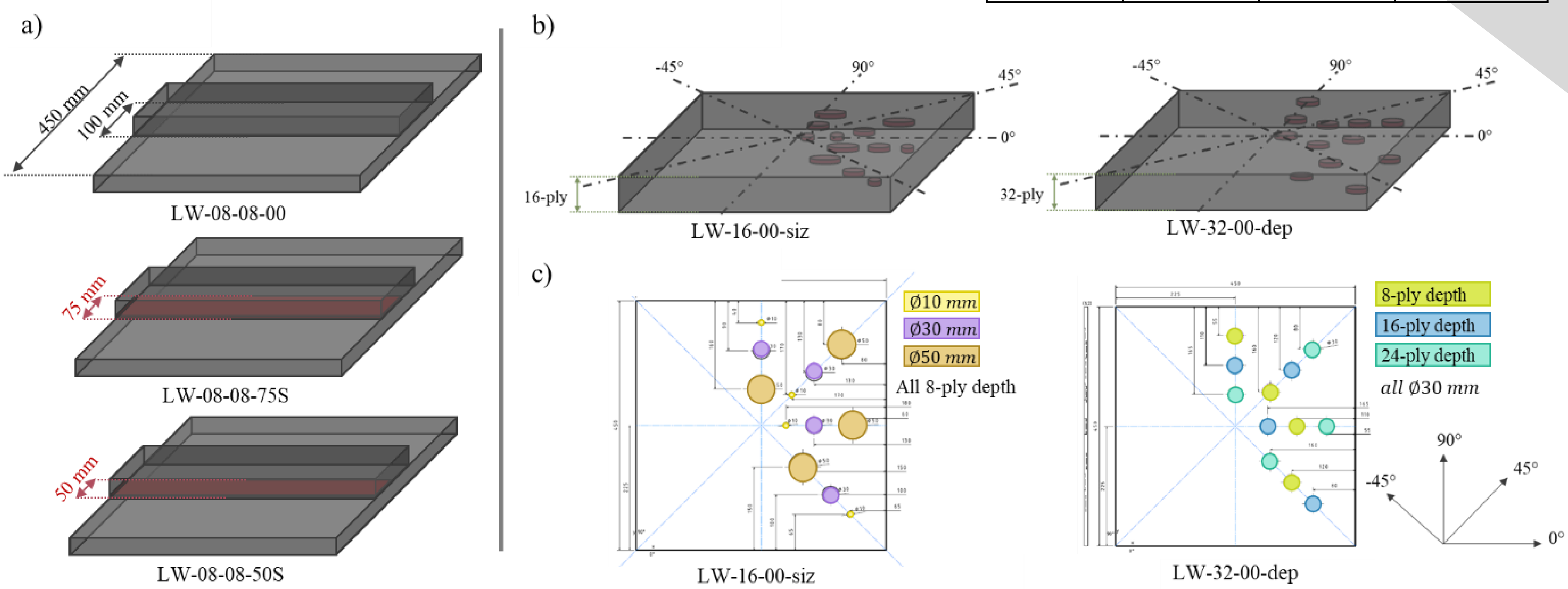
Laser properties:
Nd:YAG pulse laser
λ 1064 nm
Beam dia 9.5 mm
Pulse width 5 ns
Max output 850 mJ

Experimental samples

- **Two types of samples**: stiffened with large delamination (a) and flat with small round delamination (b)
- **Quasi-isotropic** lay-up
- **Artificial defects** created by insertion of Teflon film

CFRP properties

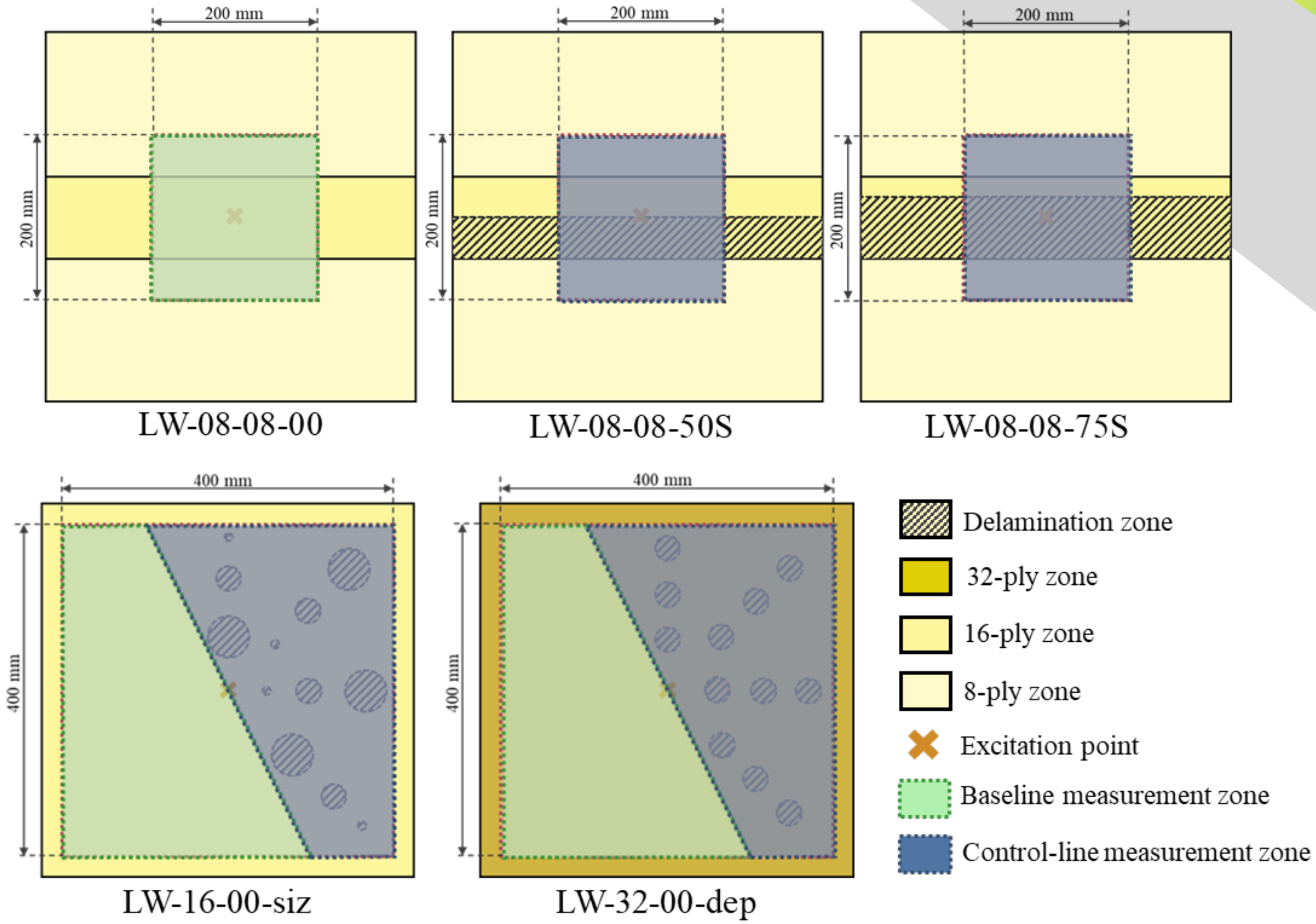
E1 [GPa]	E2 [GPa]	ν12	ν23
152	8.0	0.34	0.54
G12 [GPa]	**G23 [GPa]**	**Density [kg/m3]**	**Ply thickness [mm]**
4.03	2.52	1539	0.2



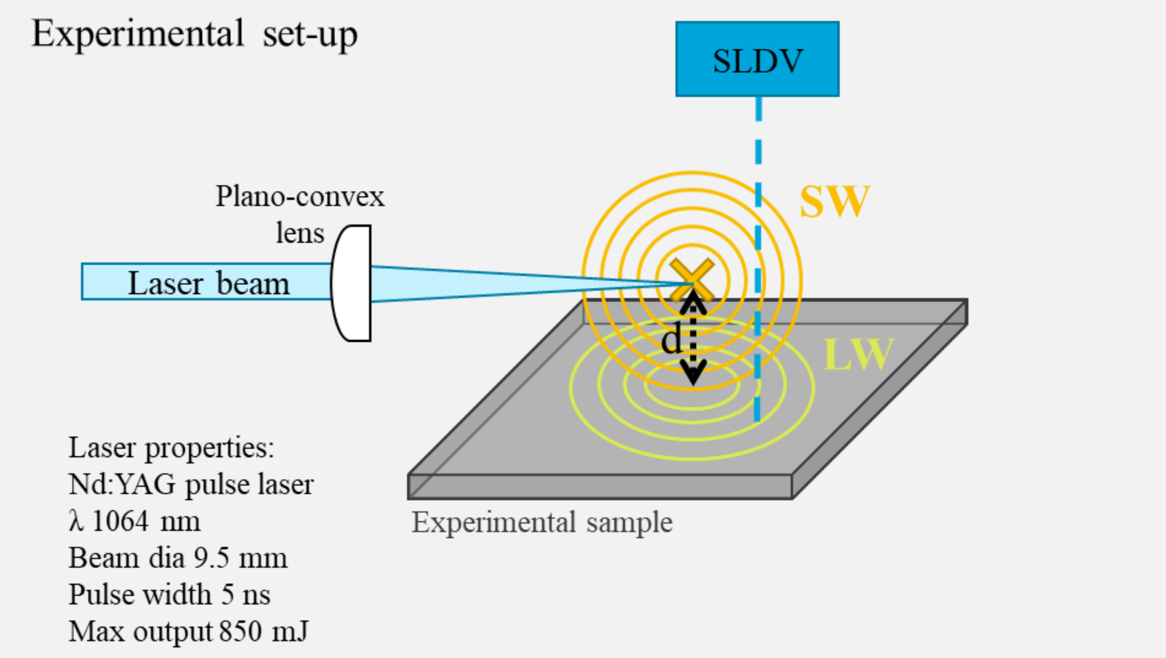
Data acquisition: baselines and control-lines

- **Baselines**: healthy zones
- **Control-lines**: zones containing defects directly comparable to the dedicated baseline

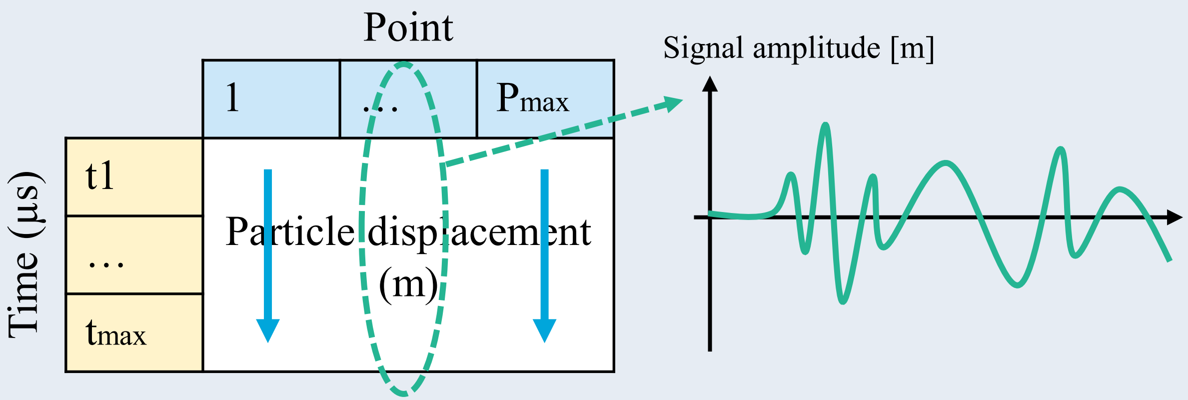
- Comparison between baselines and control-lines performed in the **Signal Processing algorithm** to calculate **Damage Indexes** (DIs)



Data acquisition: raw experimental data form

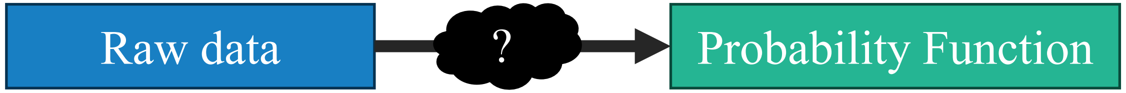


- At each measurement point, the SLDV records the **particle out-of-plane displacement over time**

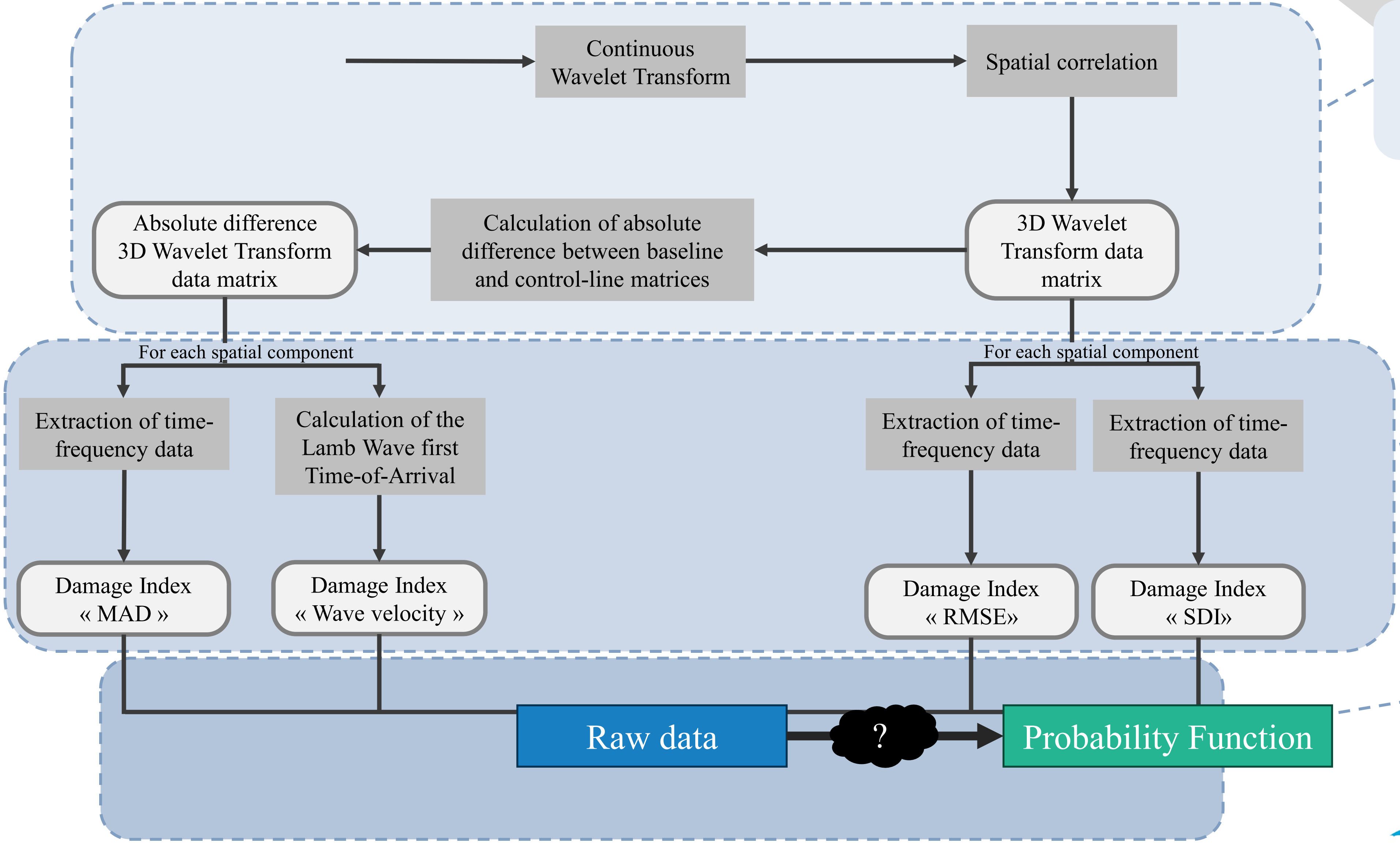


- **Raw experimental data**: time history out-of-plane displacement
- Expected output: **Probability Function** (a function assessing the defect presence at each point

$$PF(x,y) = \begin{cases} \rightarrow 0 \; if \; no \; defect \\ \rightarrow 1 \; if \; defect \end{cases})$$



Signal Processing algorithm



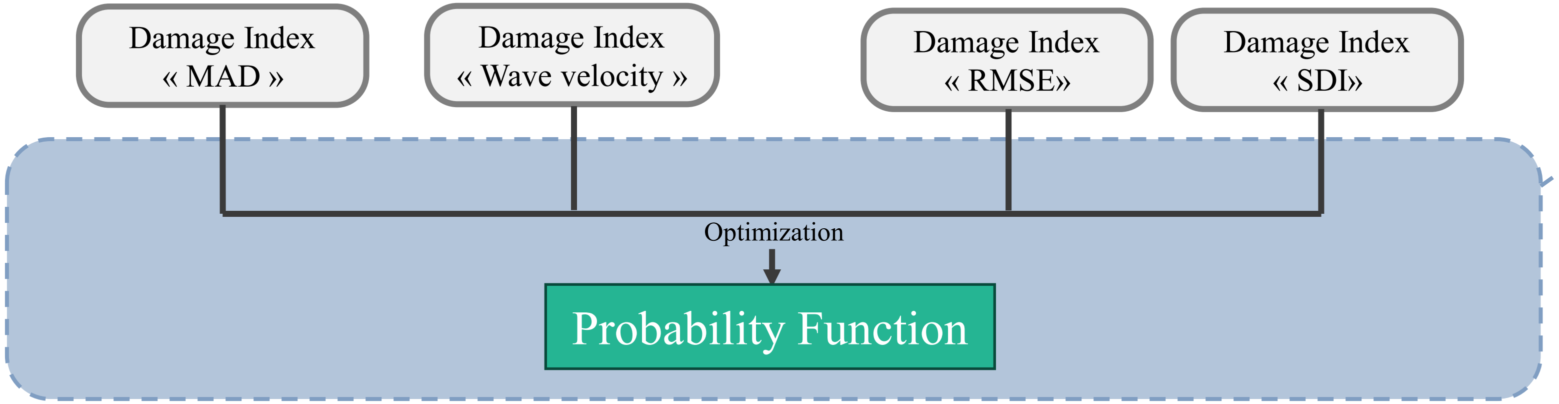
STEP 1:
EXTENSION OF THE DATA IN MULTI-DOMAIN USING WAVELET ANALYSIS

STEP 2:
CALCULATION OF DAMAGE INDEXES (DIS)

STEP 3:
OPTIMIZATION OF THE PROBABILITY FUNCTION

Optimization of the Probability Function

STEP 3:
OPTIMIZATION OF THE
PROBABILITY FUNCTION



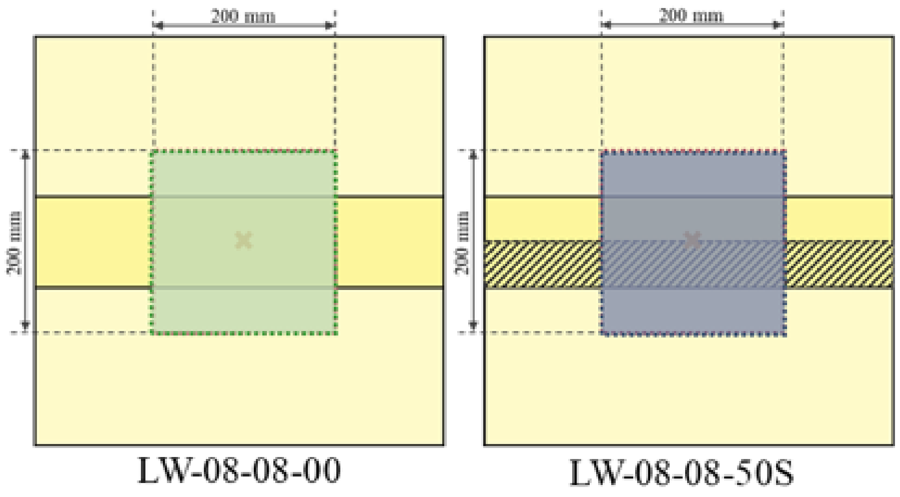
- Definition of a first Probability Function equation:

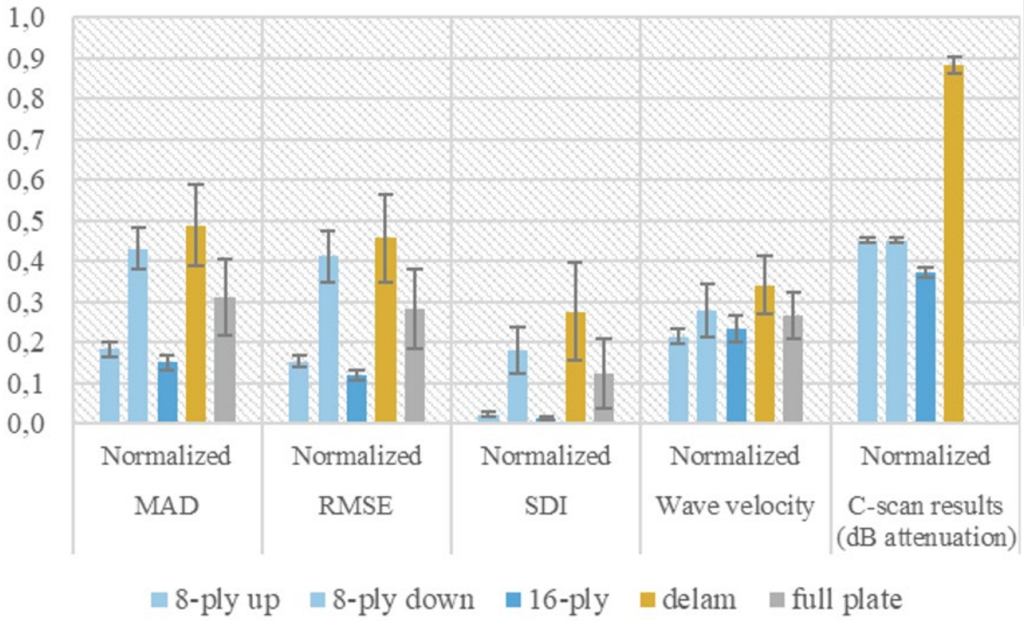
$$PF = \frac{1}{4}\left(\alpha\frac{RMSE}{RMSE_{max}} + \beta\frac{SDI}{SDI_{max}} + \gamma\frac{MAD}{MAD_{max}} + \varepsilon\frac{velocity}{velocity_{max}}\right)$$

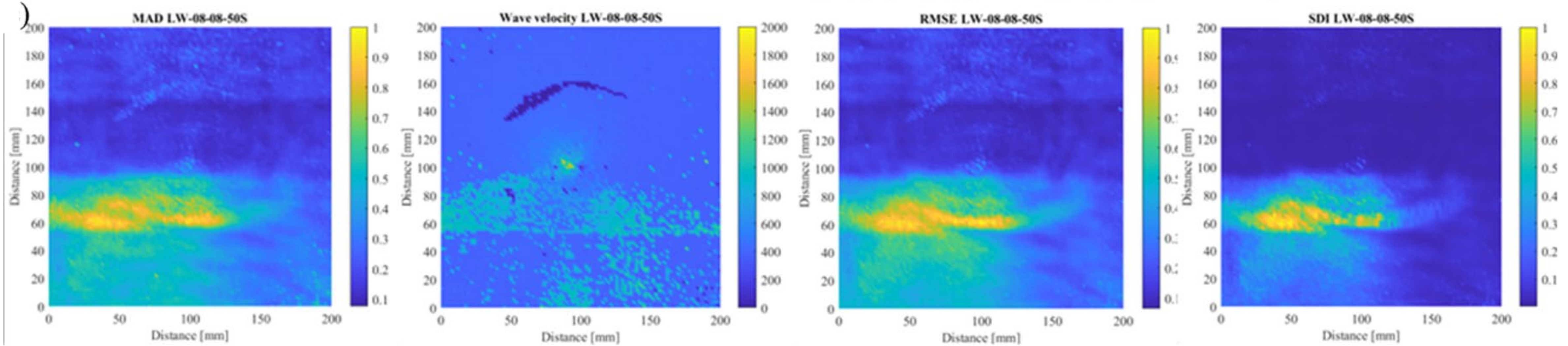
- Genetic algorithm
  - Minimize PF – Ref
  - $\alpha, \beta, \gamma, \varepsilon \in [0,1]$
  - $\alpha + \beta + \gamma + \varepsilon = 1$
- Reference:
  - PF = 1 in delamination zone
  - PF = 0 in healthy zone

- Result of the optimization algorithm:
  - $\alpha, \gamma, \varepsilon \rightarrow 0$ and $\beta \rightarrow 1$
  - **SDI is the best Damage Index to generate reliable cartographies**

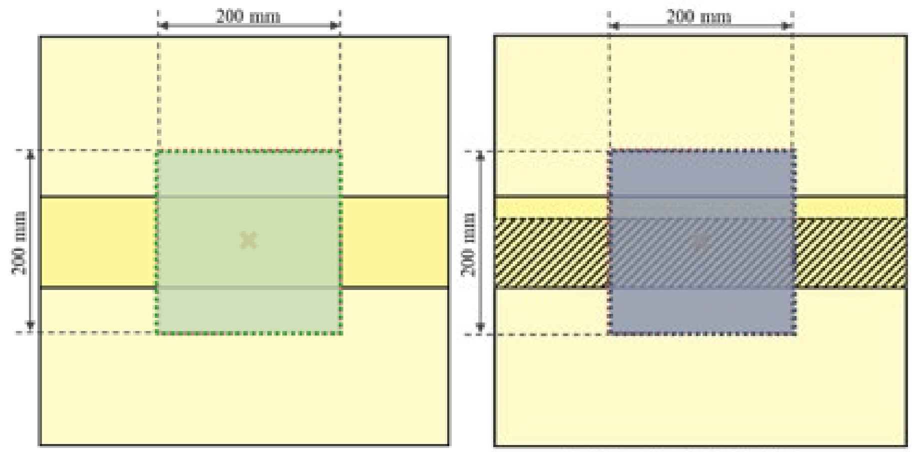
Results: LW-08-08-50S



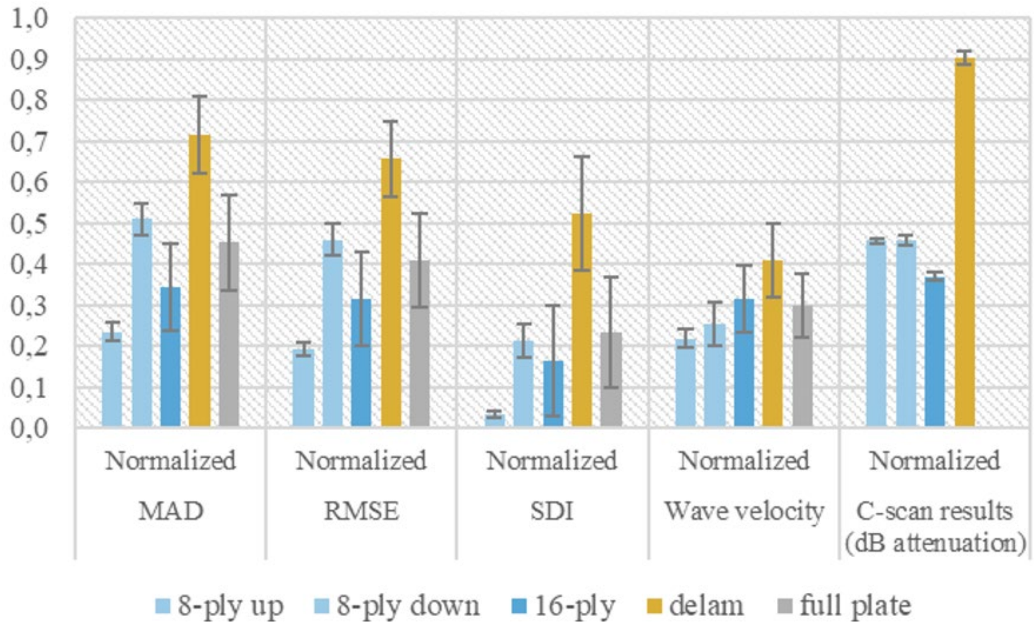


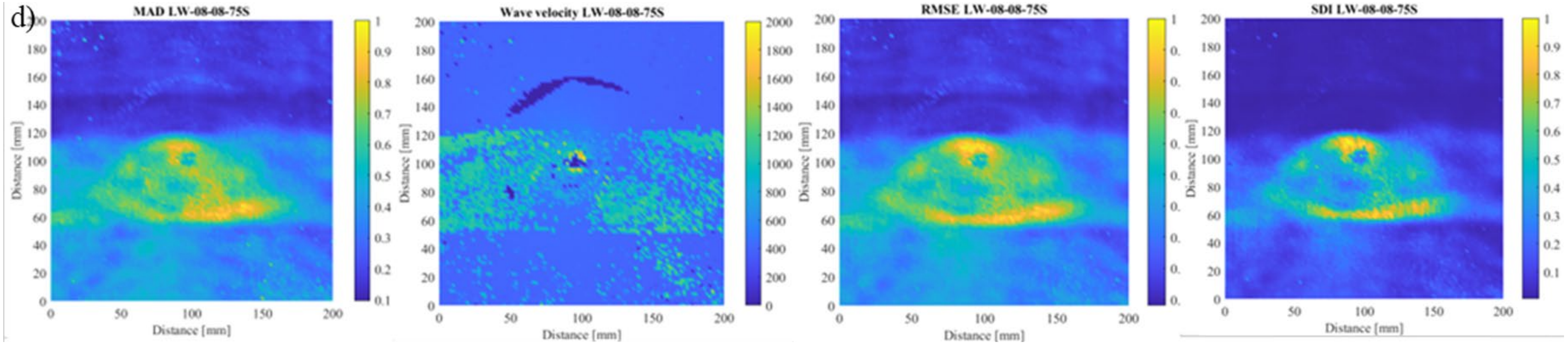


Results: LW-08-08-75S

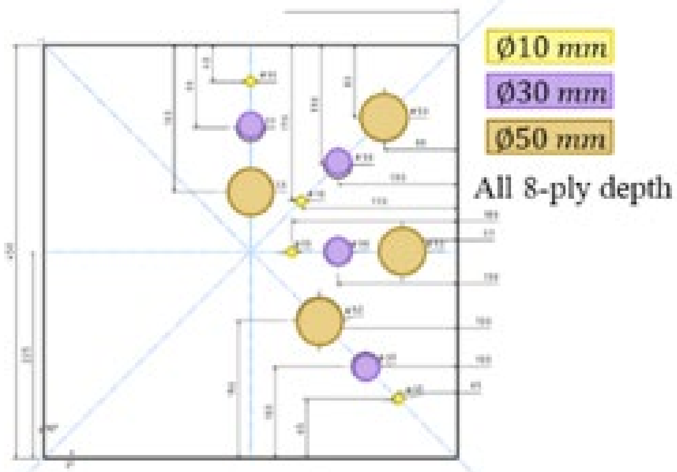


LW-08-08-00 LW-08-08-75S

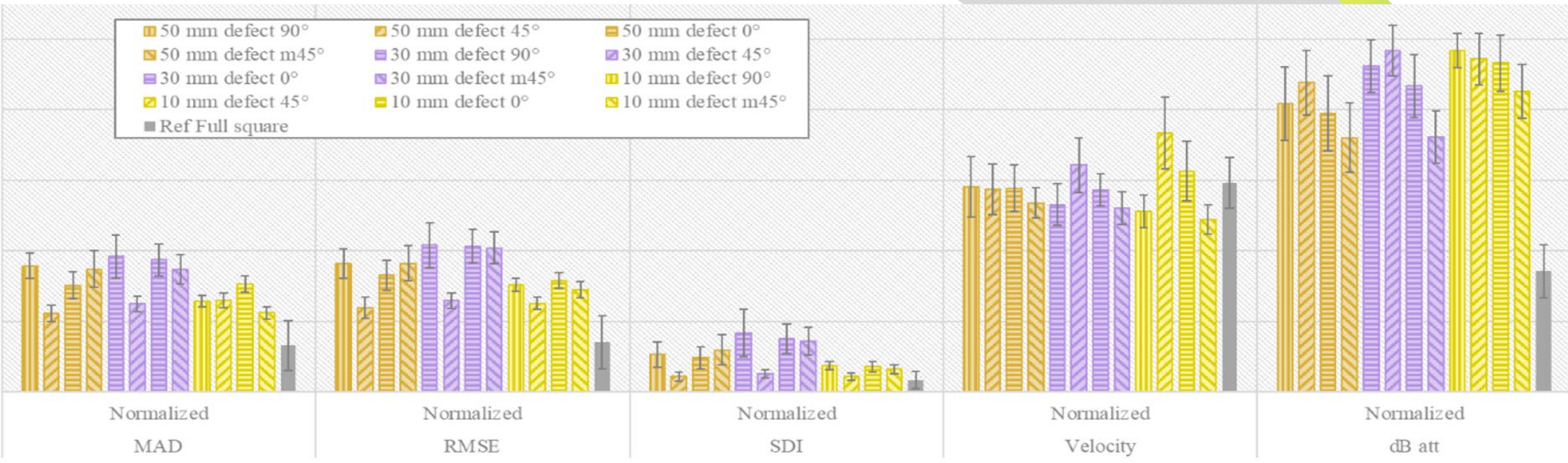


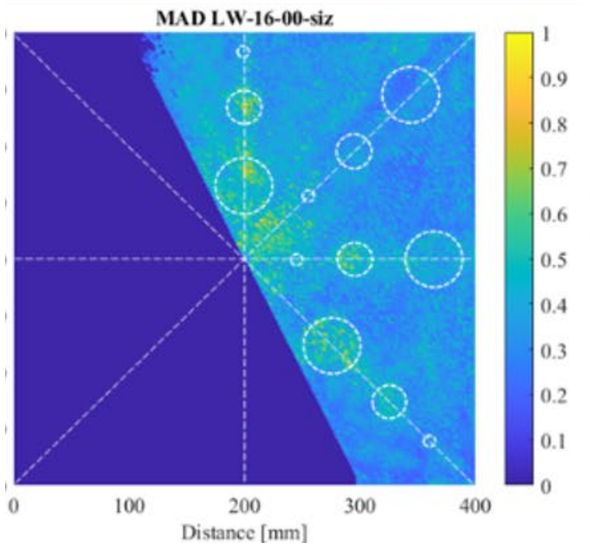


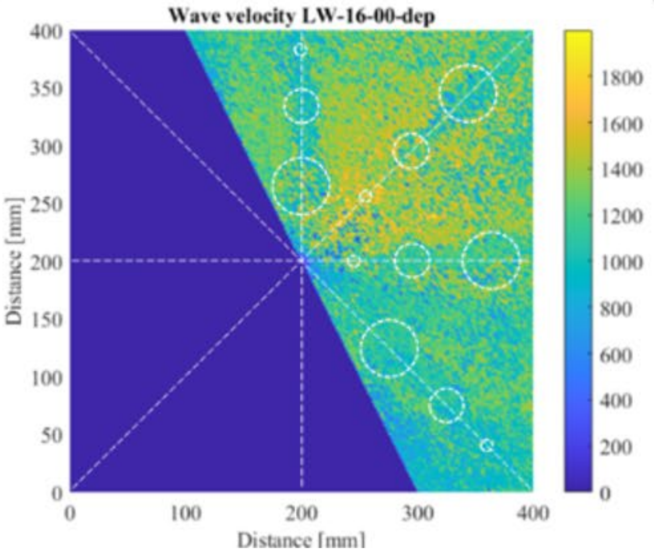
Results: LW-16-00-siz

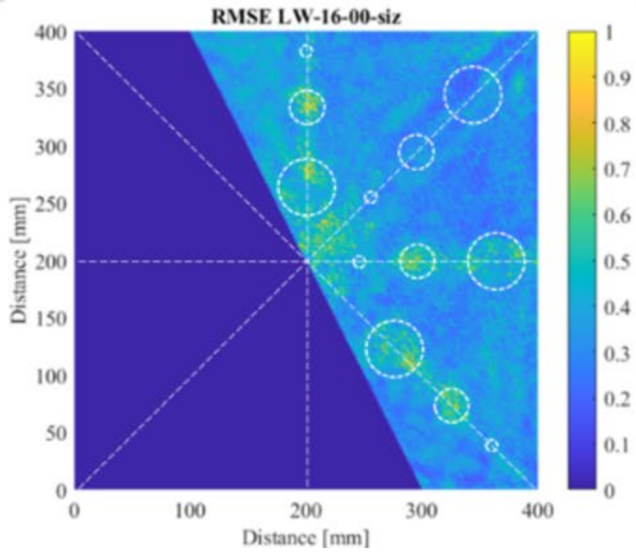


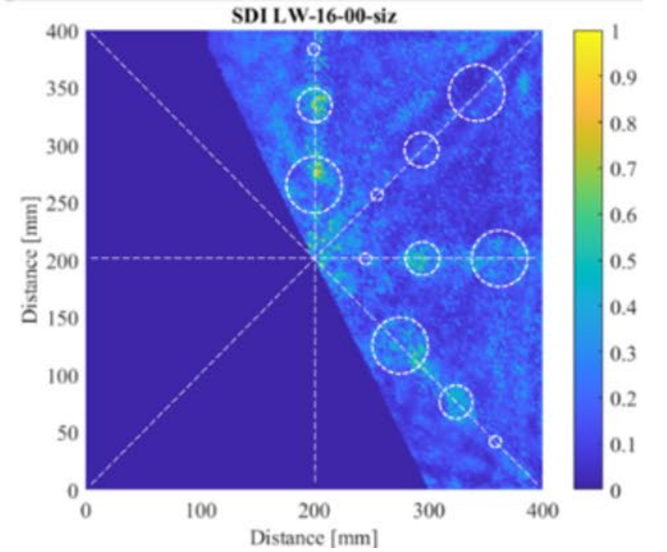
LW-16-00-siz



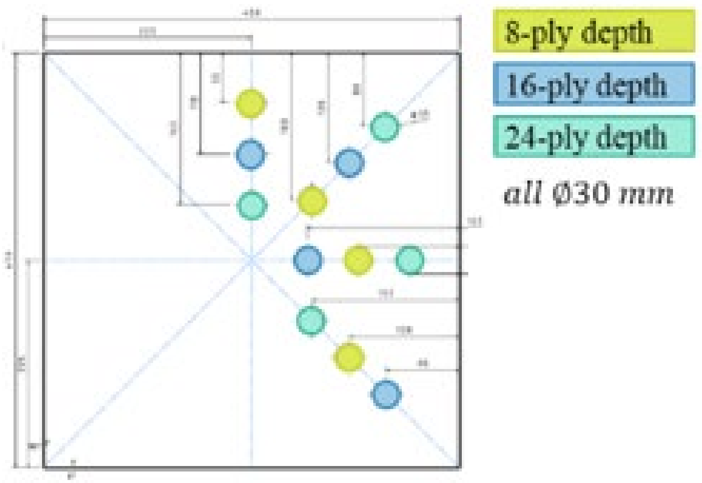




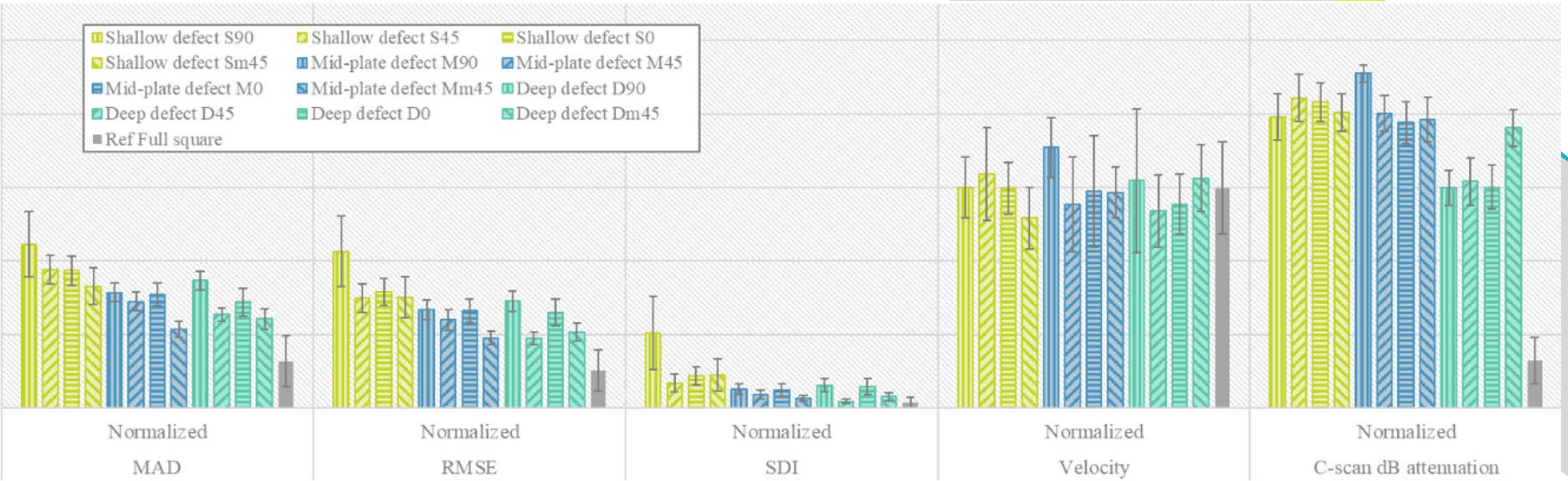


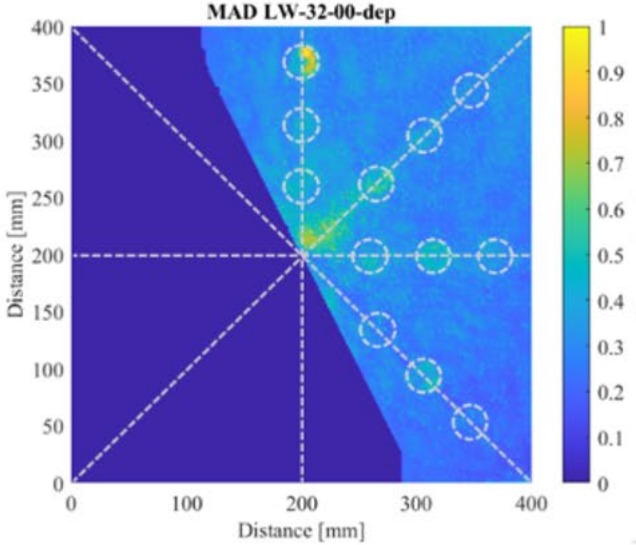


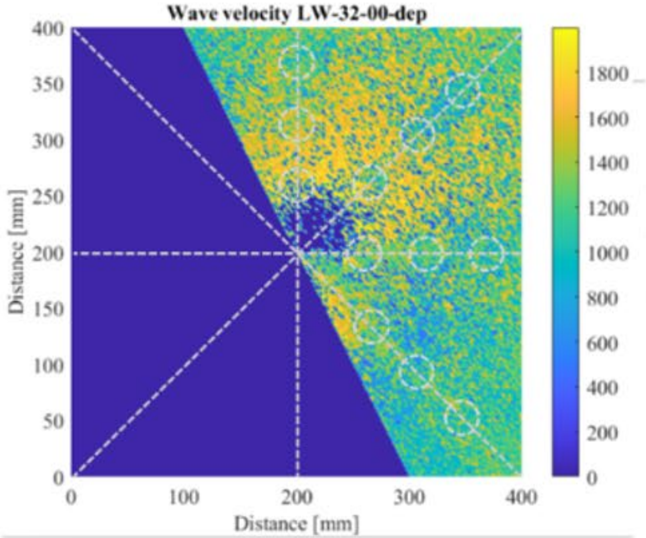
Results: LW-32-00-dep

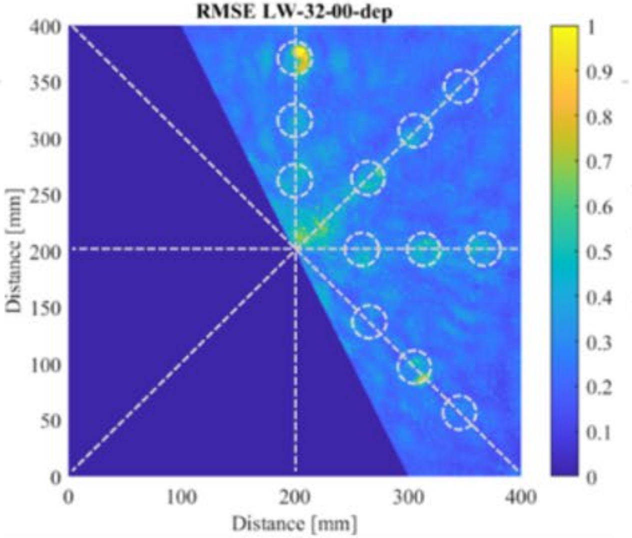


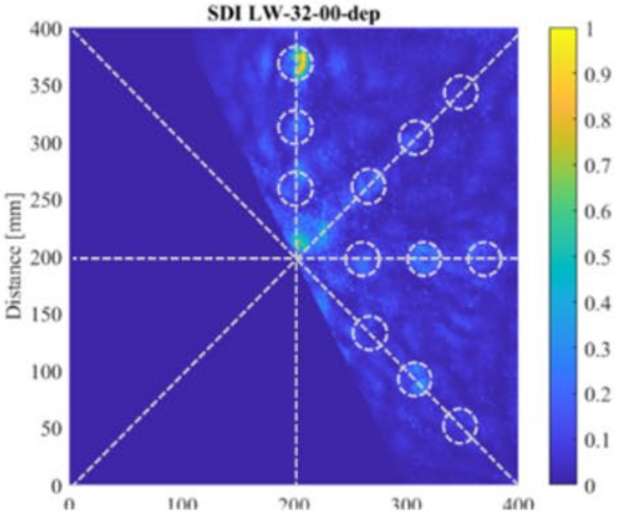
LW-32-00-dep











Conclusions and future perspectives

Background:

- Improvement of the **NDT efficiency** for **CFRPs** testing in aerospace industry
- **Non-contact** excitation and reception of **Lamb Waves** using LIPSW
- Objective: Assess the ability of LIPSW-excited Lamb Waves to **detect delamination** in CFRP

Method:

- Lamb Waves are generated experimentally in CFRP samples with a **fully non-contact system**
- A **novel Signal Processing algorithm** is build, using a Wavelet Analysis and Damage Indexes extraction

Results:

- The possibility to detect delamination is **qualitatively validated**
- The interest of the Wavelet Transform Analysis process is **proven**
- The accuracy of the method is still **unsufficient** compared with classic NDT method

Future perspectives:

- Improvement of the baselines
- Extension of the Damage Indexes
- Collection of more experimental data

Acknowledgements

芝浦工業大學
SHIBAURA INSTITUTE OF TECHNOLOGY

- Prof. Hosoya Naoki
- Tonegawa Shota
- Mita Masakatsu
- Suyama Mamoru

JAXA
Japan Aerospace Exploration Agency

- Dr. Takeda Shin-ichi

東京大学
THE UNIVERSITY OF TOKYO

- Prof. Yokozeki Tomohiro
- Prof. Higuchi Ryo

The authors thank the Japan Society for the Promotion of Science for their support under the Grant-in-Aid for Scientific Research programs (Grant No. JP22H01692).