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# WAVELET ANALYSIS METHOD FOR DEFECTS DETECTION IN CFRP WITH FULLY NON-CONTACT LAMB WAVES SYSTEM


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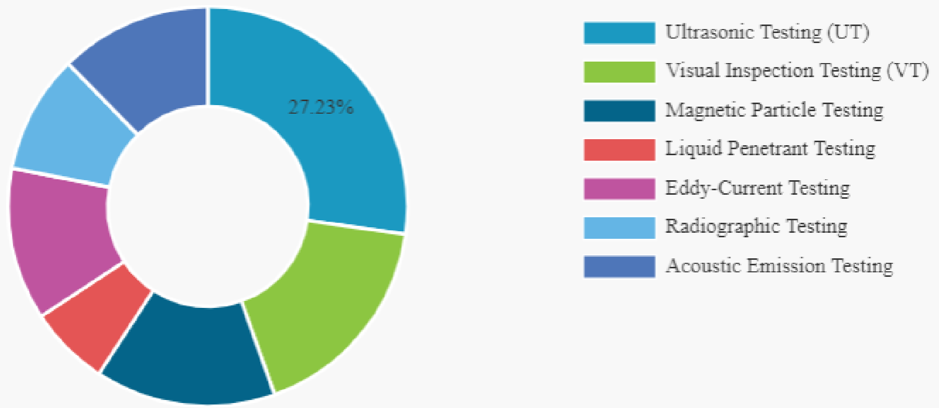
# Introduction

- The importance of **Ultrasonic Testing** for CFRP industry and research

Global Non-Destructive Testing (NDT) Market Share, By Technique, 2021

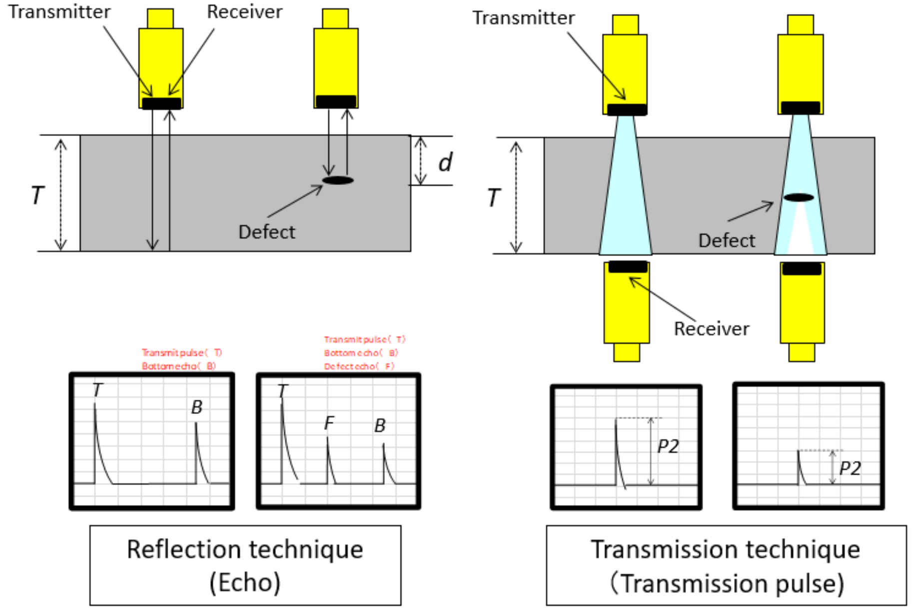
[1]




[2]

- Time-consumption: the biggest **disadvantage** of conventional Ultrasonic Testing systems

[3]



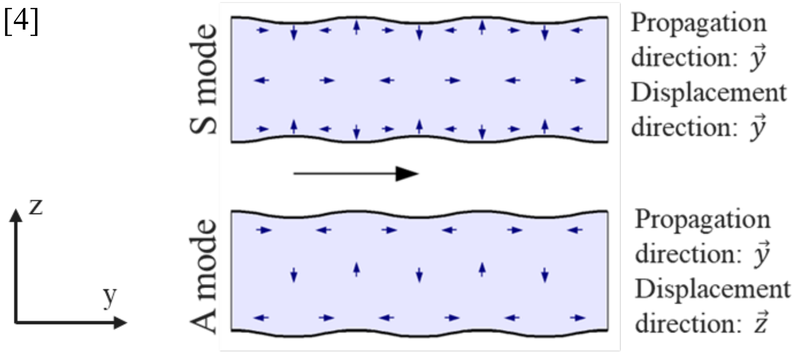

- **Lamb Waves propagation** as a promising technique for the improvement of Ultrasonic Testing systems
- In this study, the development of **signal algorithms adapted to a novel Lamb Waves control system** is investigated

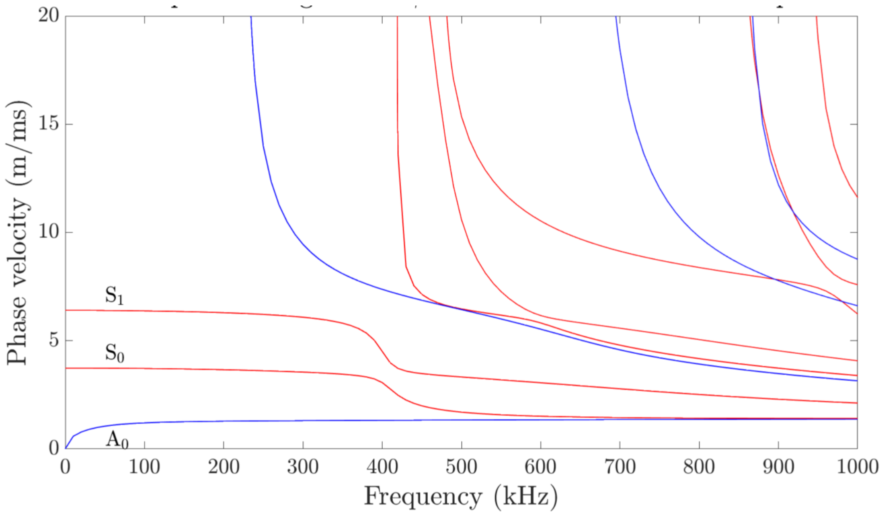
[1] Fortune Business insights « Non-Destructive Testing (NDT) market »
[2] http://www.worldofndt.com « Introduction to ultrasonic testing »
[3] https://www.gnes.co.jp/en/

# Lamb Waves testing

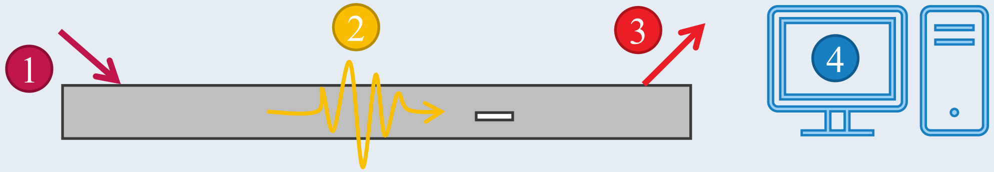
- **Lamb Waves**: mechanical waves propagating in the in-plane directions of thin structures
- Two infinite sets of **propagation modes** which velocity is highly dependent on the wave frequency

[4]




- Lamb Waves **defects detection system**:




1. Excitation of the Lamb Waves
2. Propagation and interaction with the medium
3. Reception (measurement) of the waves
4. Signal Processing of the measured signal to obtain information

- Challenges and **research leads**

- In **this study**:
  - **Laser-Induced Plasma Shock Wave**
  - Plates with several types of **artificial delamination**
  - **Signal Processing algorithm** based on a **Wavelet Transform analysis**

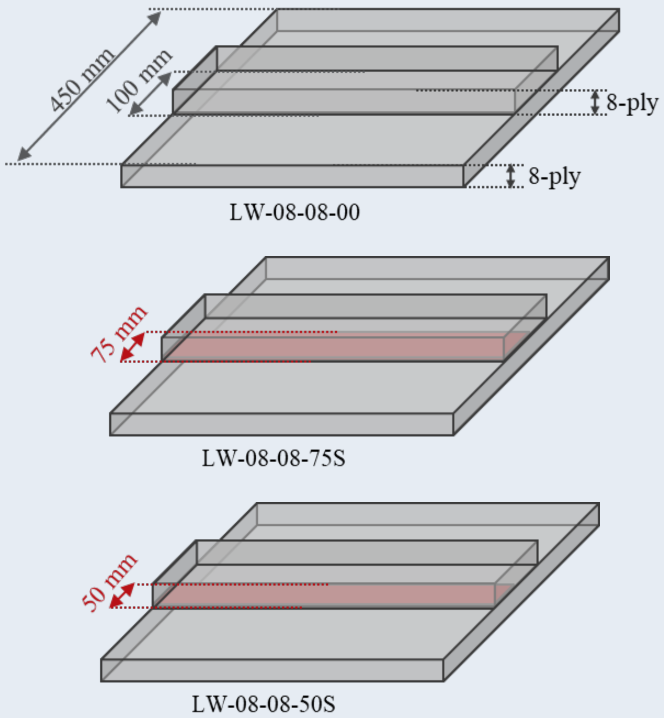
# Experimental samples

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

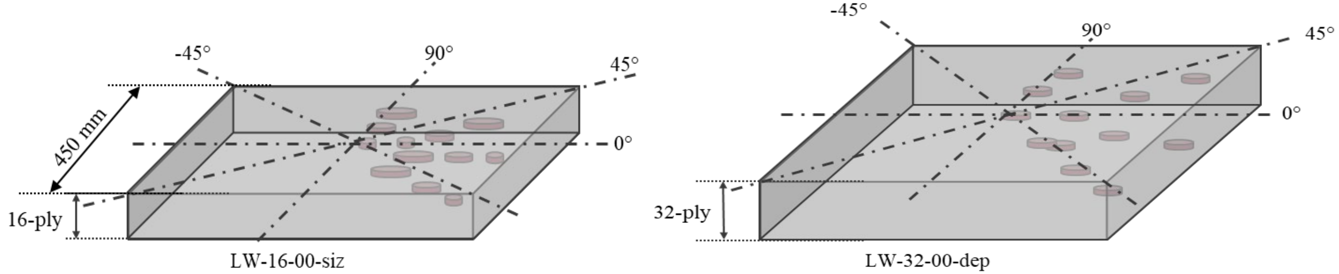
- **CFRP properties**

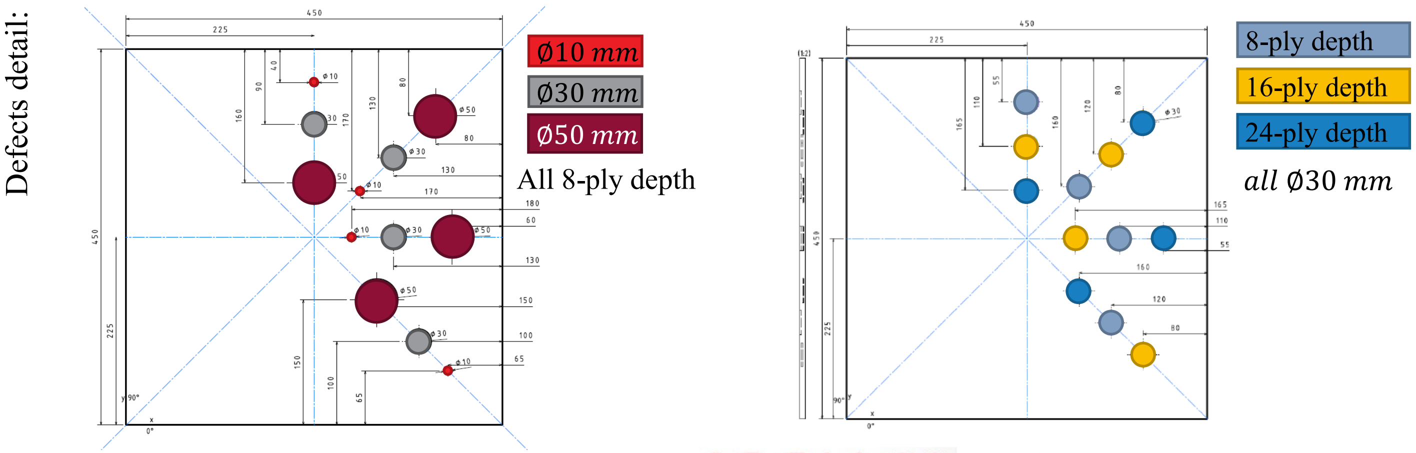
| E1 [GPa] | E2 [GPa] | ν12 | ν23 |
|---|---|---|---|
| 152 | 8.0 | 0.34 | 0.54 |
| G12 [GPa] | G23 [GPa] | Density [kg/m3] | Ply thickness [mm] |
| 4.03 | 2.52 | 1539 | 0.2 |

- **Stiffened samples lay-up: [45/0/-45/90]s (bottom) + [-45/0/45/90]s (top)**

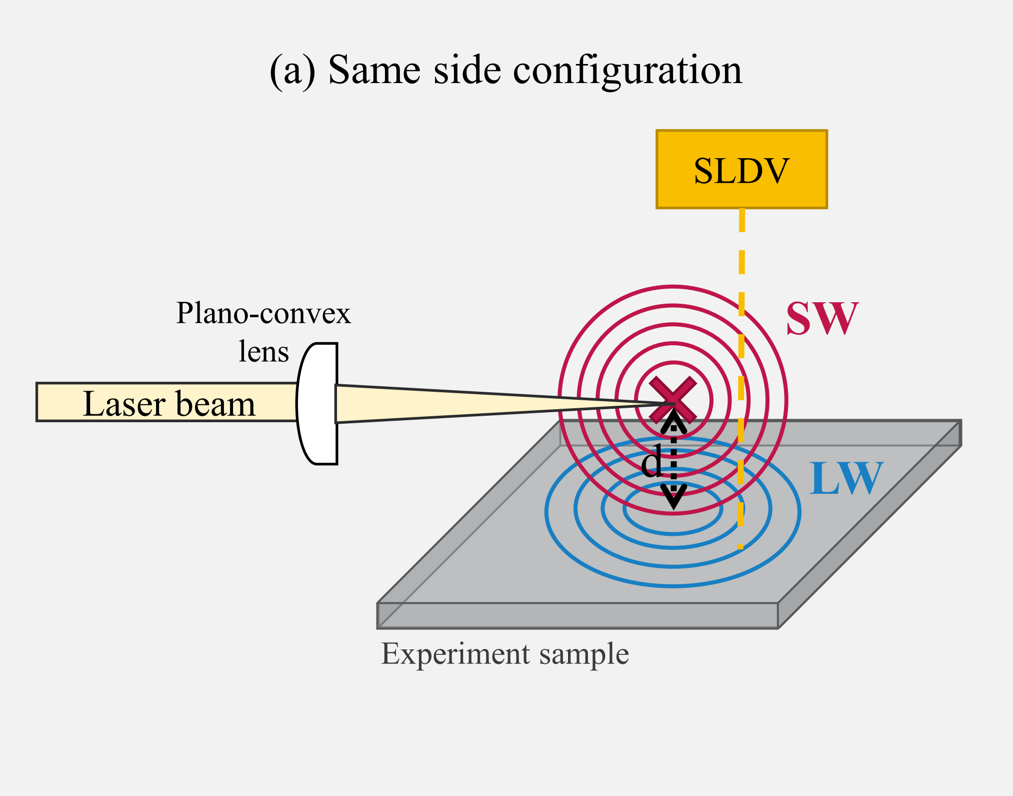


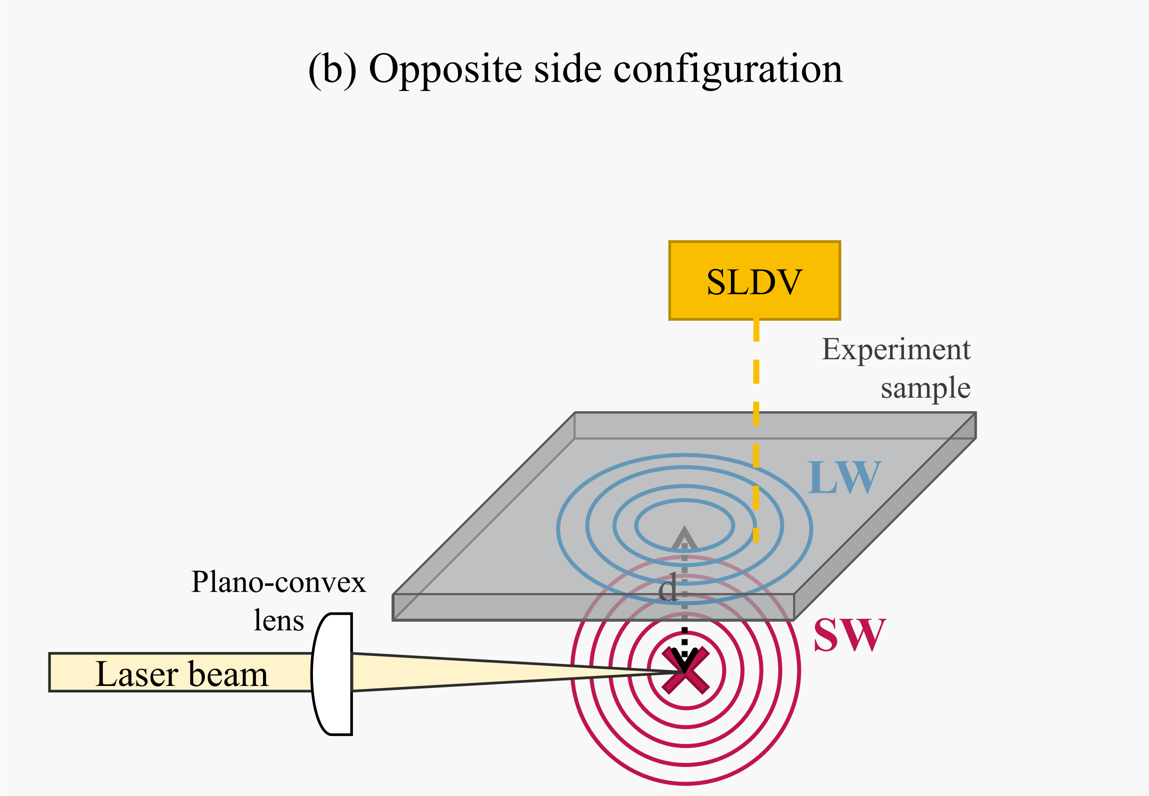

- **Small delamination sample lay-up: [45/0/-45/90]2s**



# Experimental set-up



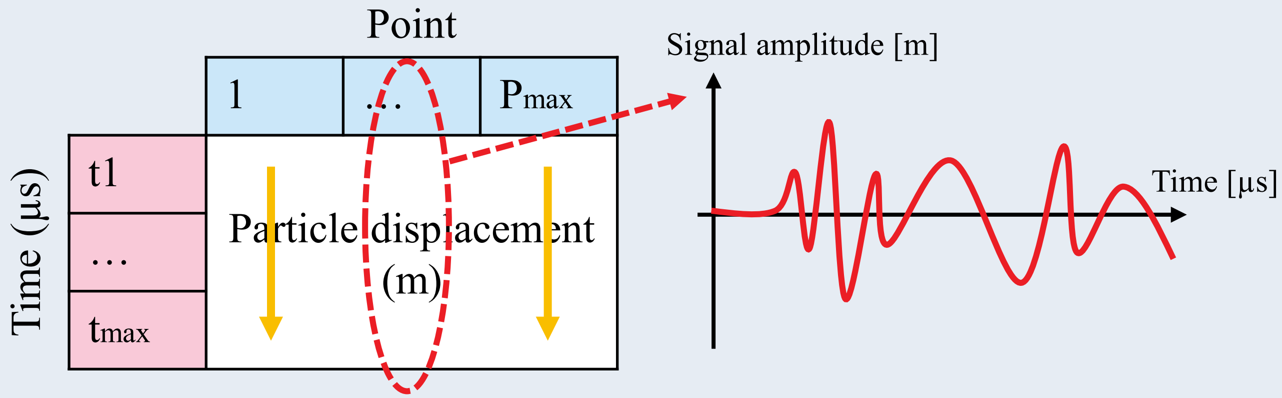




Laser properties:
Nd:YAG pulse laser
λ 1064 nm
Beam dia 9.5 mm
Pulse width 5 ns
Max output 850 mJ

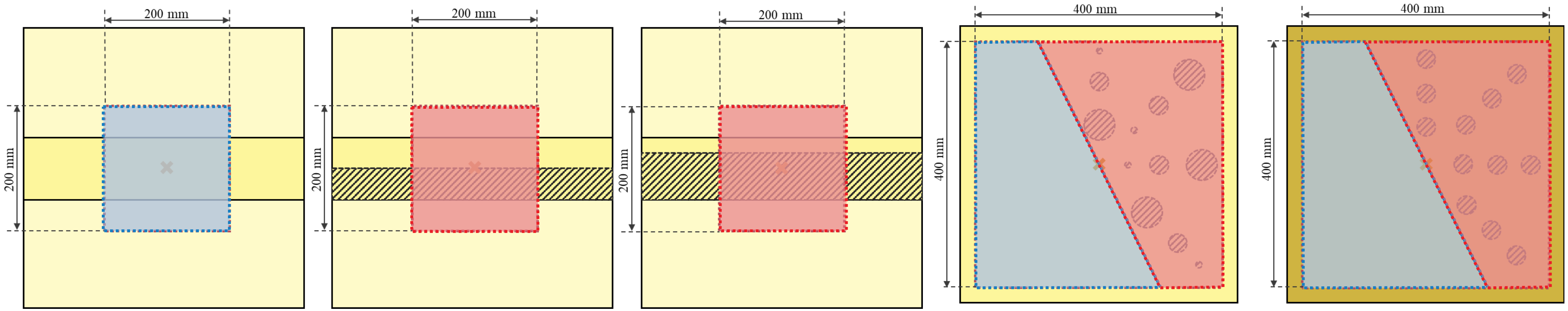
1. Focalisation of laser by lens
2. Generation of a plasma at a distance d from the sample's surface + generation of shock waves
3. Shock waves encountering the surface generate a propagation of Lamb Waves
4. A Single Laser Doppler Vibrometer (SLDV) measures the out-of-plane surface displacement

# Data acquisition

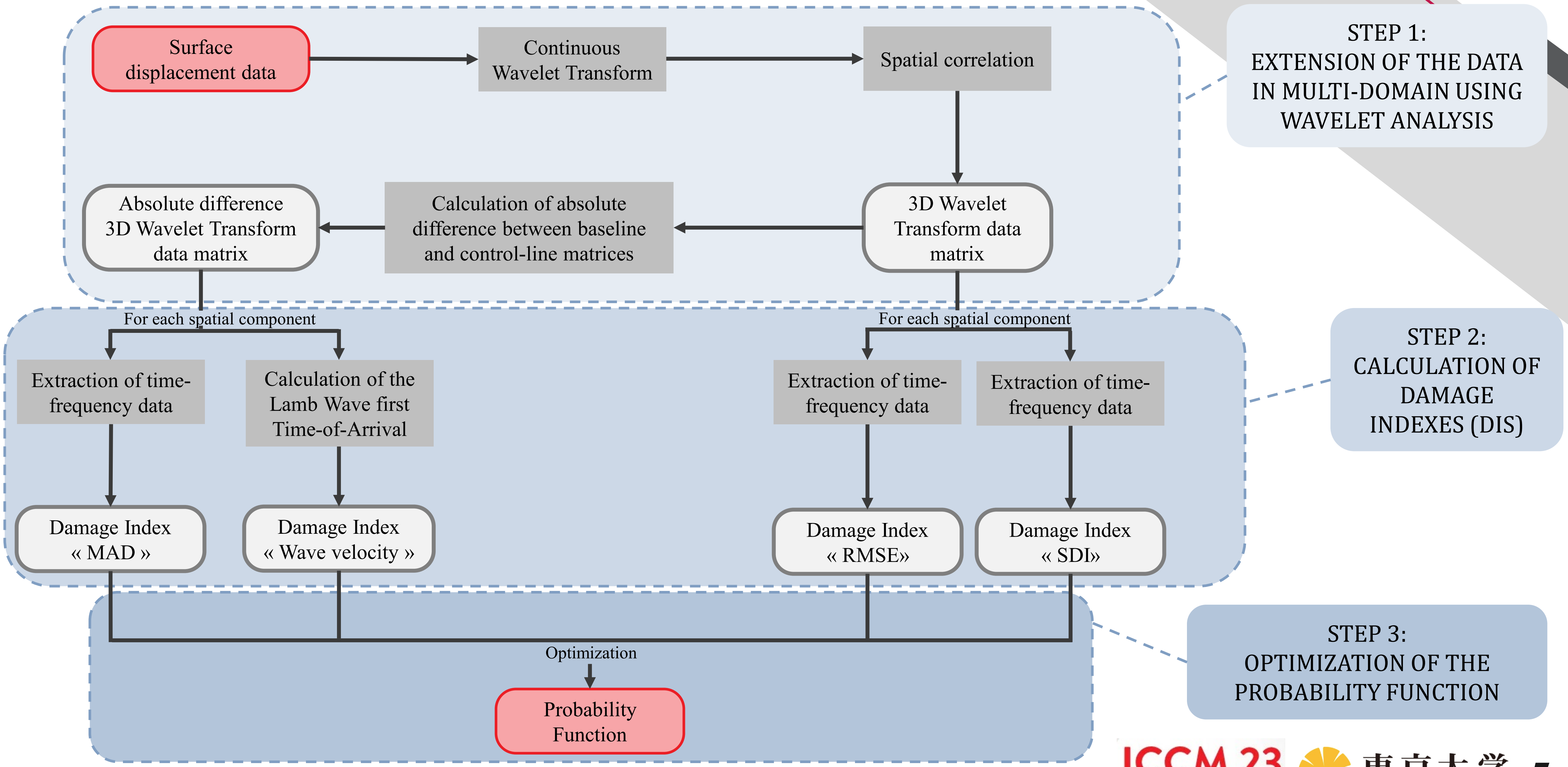
- At each measurement point, the SLDV records the **particle out-of-plane displacement over time**




- Measurement of different zones:
  - **Baseline** zones
  - **Control-line** zones



# Signal Processing algorithm

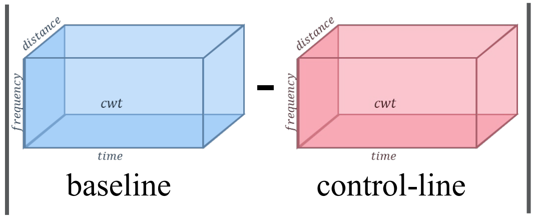



Algorithm details in appendix

# Calculation of Damage Indexes

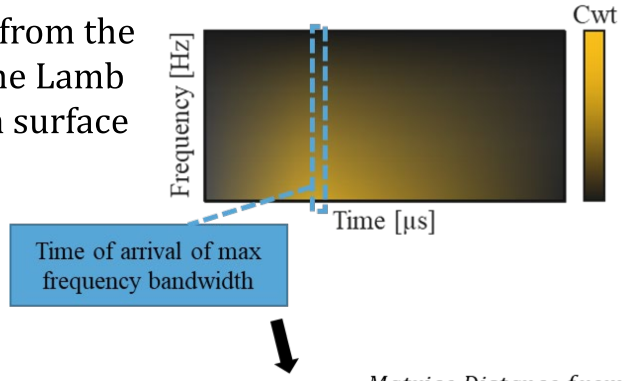
## MAD: Mean Absolute Difference

Mean cwt value in the time-frequency domain of the absolute difference matrix at each surface point




## Wave velocity

Velocity calculated from the time-of-arrival of the Lamb Wave signal at each surface point




$$\textit{Matrice wave velocity} = \frac{\textit{Matrice Distance from center}}{(\textit{Matrice ToA} - \textit{ToA excitation})}$$

## RMSE: Root Mean Squared Error

Root Mean Squared Error of each pixel of the time-frequency images of baseline and control-line

$$RMSE(X) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(i_{baseline} - i_{control\ line}\right)^2}$$

## SDI: Structural Dissimilarity Index

Structural Dissimilarity Index of each pixel of the time-frequency images of baseline and control-line

$$SDI = \frac{1}{2}\left(1 - \boldsymbol{l}(BL, CL) \times \boldsymbol{c}(BL, CL) \times \boldsymbol{s}(BL, CL)\right)$$

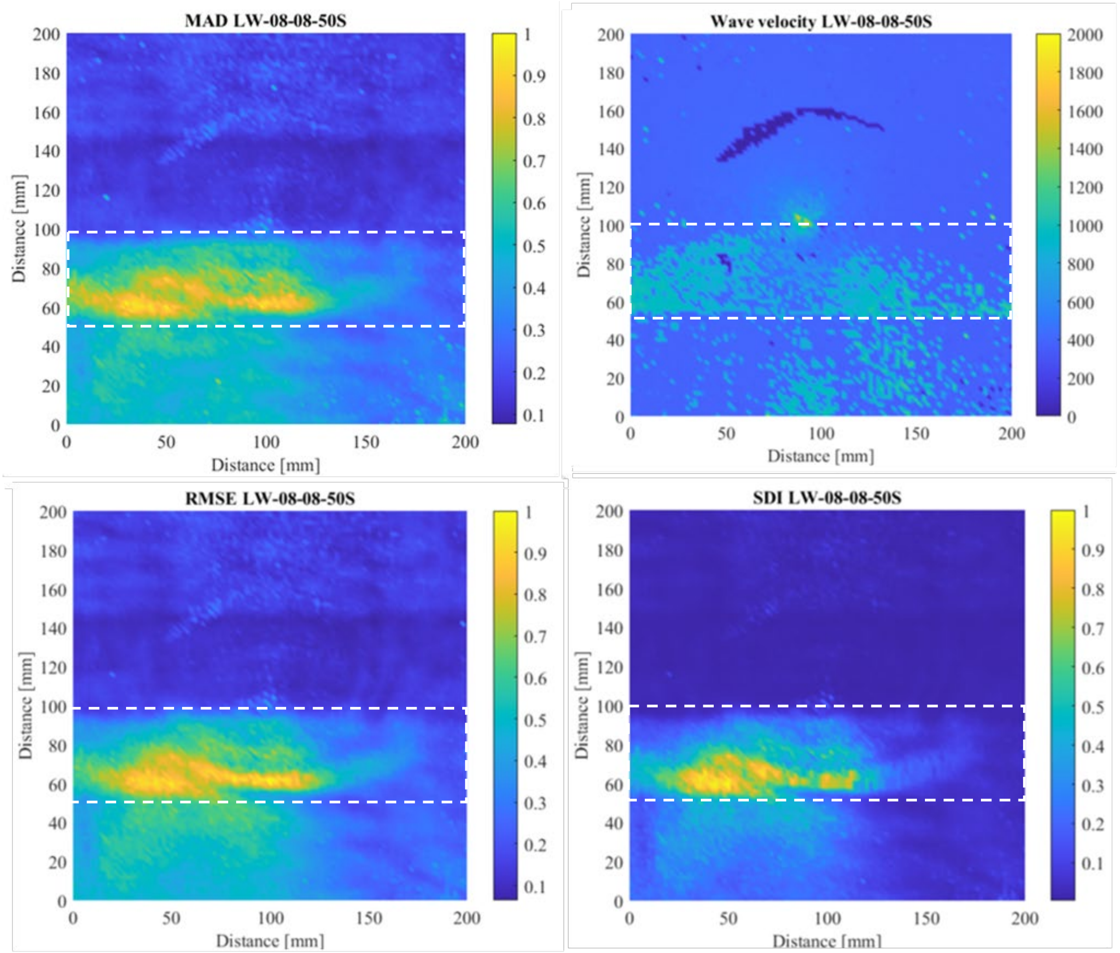
$$\boldsymbol{l}(\boldsymbol{BL}, \boldsymbol{CL}) = \frac{(2\mu_{BL}\mu_{CL} + c_1)}{(\mu^2{}_{BL} + \mu^2{}_{CL} + c_1)}$$

$$\boldsymbol{s}(\boldsymbol{BL}, \boldsymbol{CL}) = \frac{(cov_{BLCL} + c_3)}{(\sigma_{BL}\sigma_{CL} + c_3)}$$

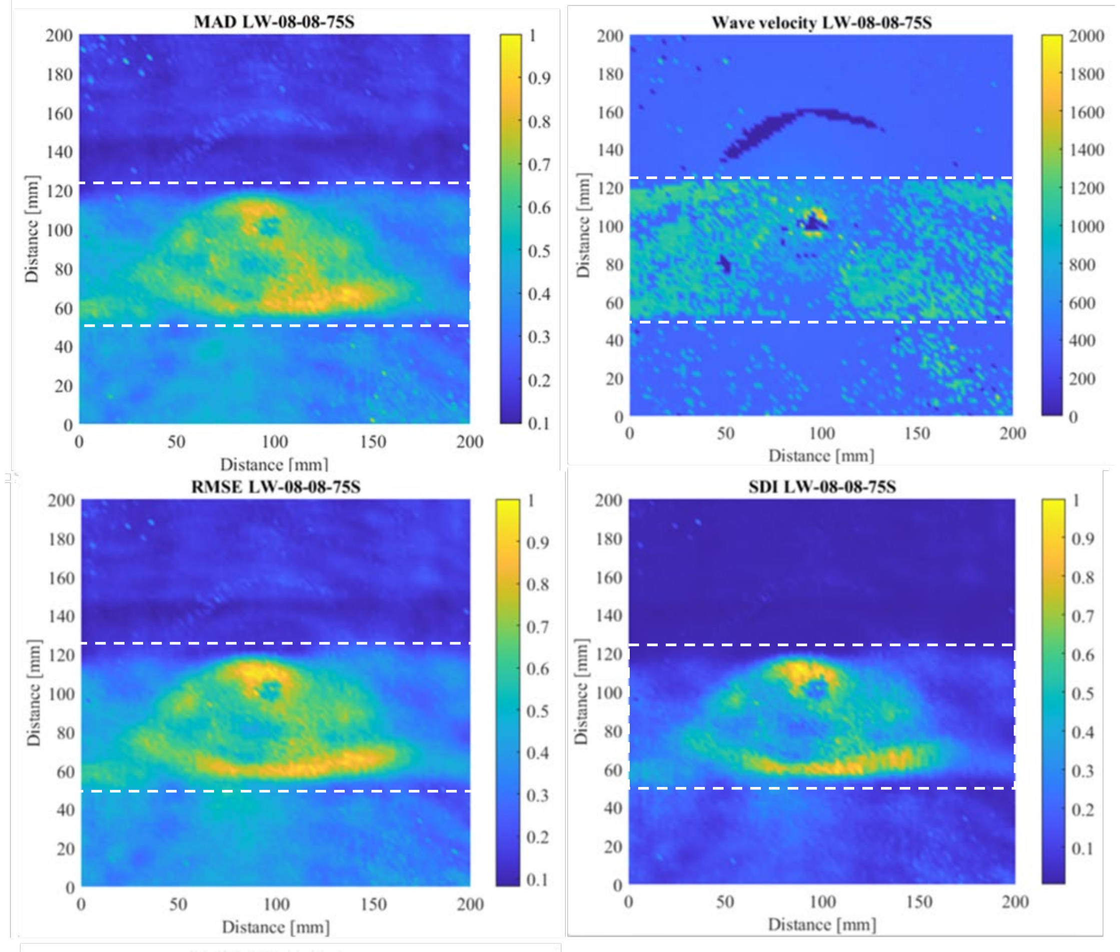
$$\boldsymbol{c}(\boldsymbol{BL}, \boldsymbol{CL}) = \frac{(2\sigma_{BL}\sigma_{CL} + c_2)}{(\sigma^2{}_{BL} + \sigma^2{}_{CL} + c_2)}$$

# Results: stiffened samples

LW-08-08-50S

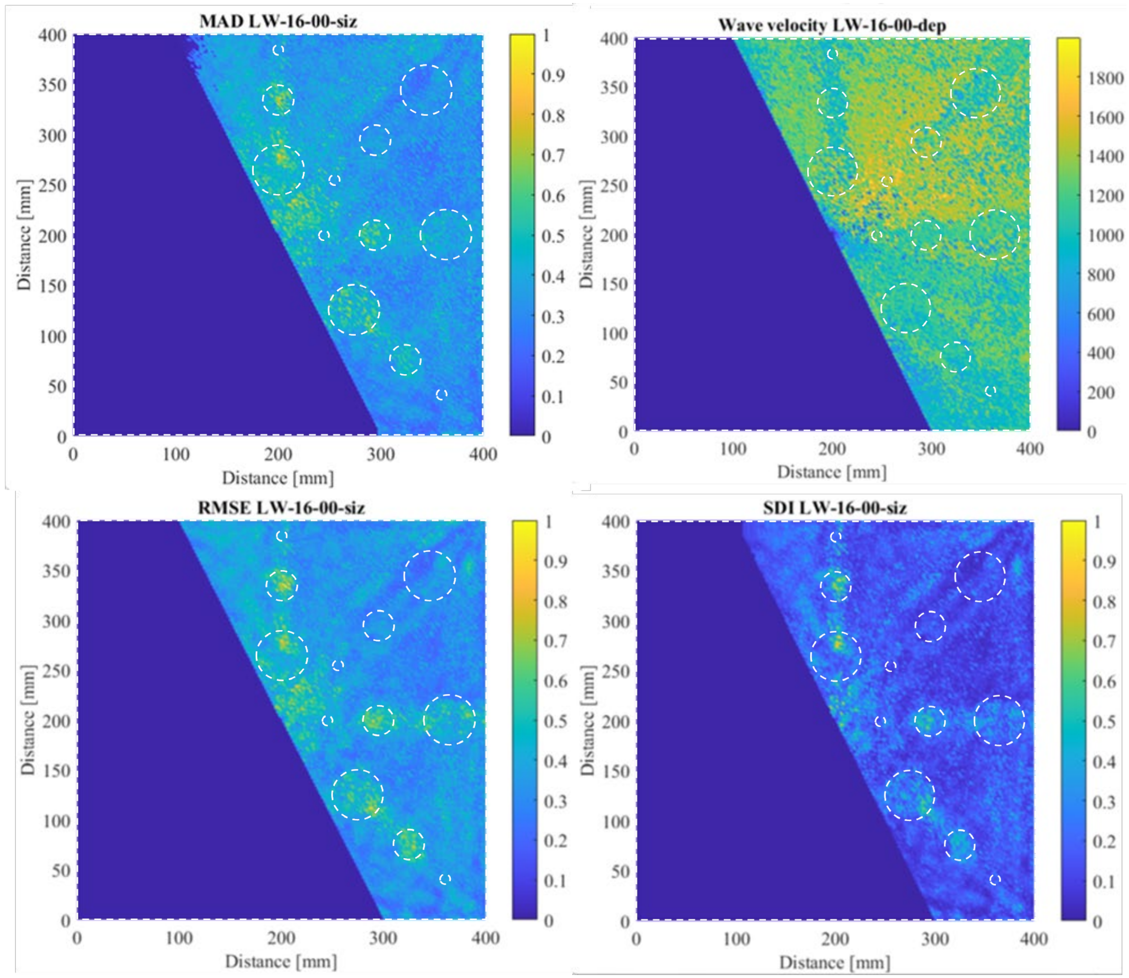



LW-08-08-75S

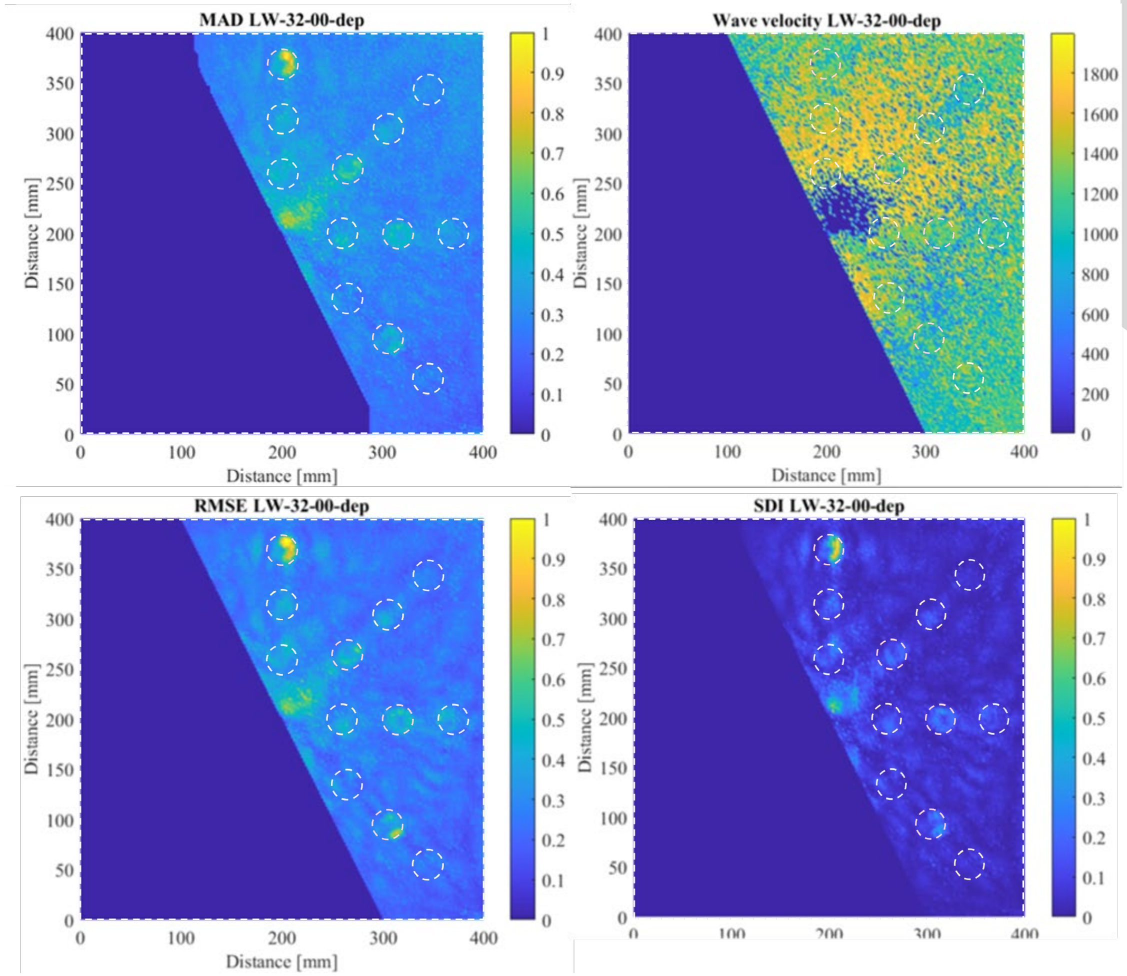


# Results: small delamination samples

LW-16-00-siz

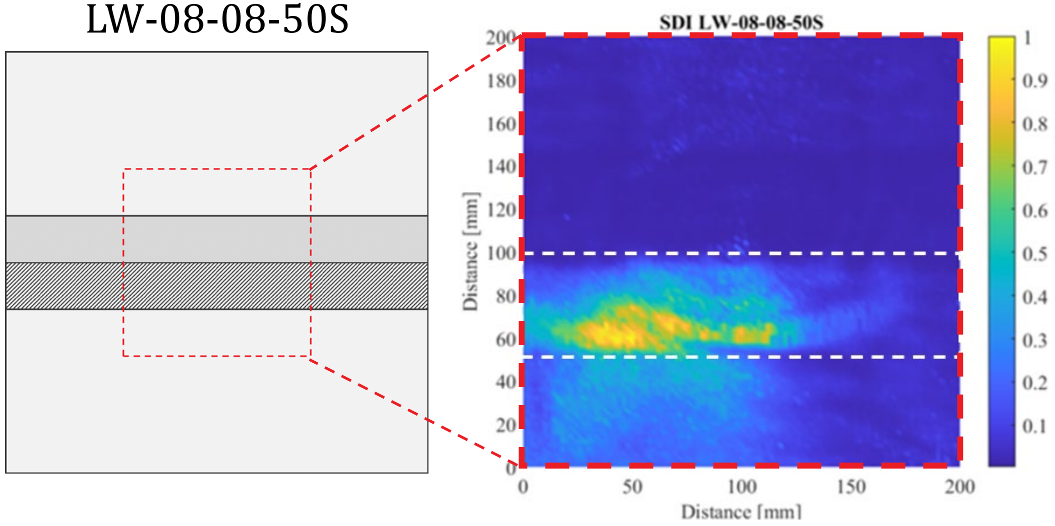


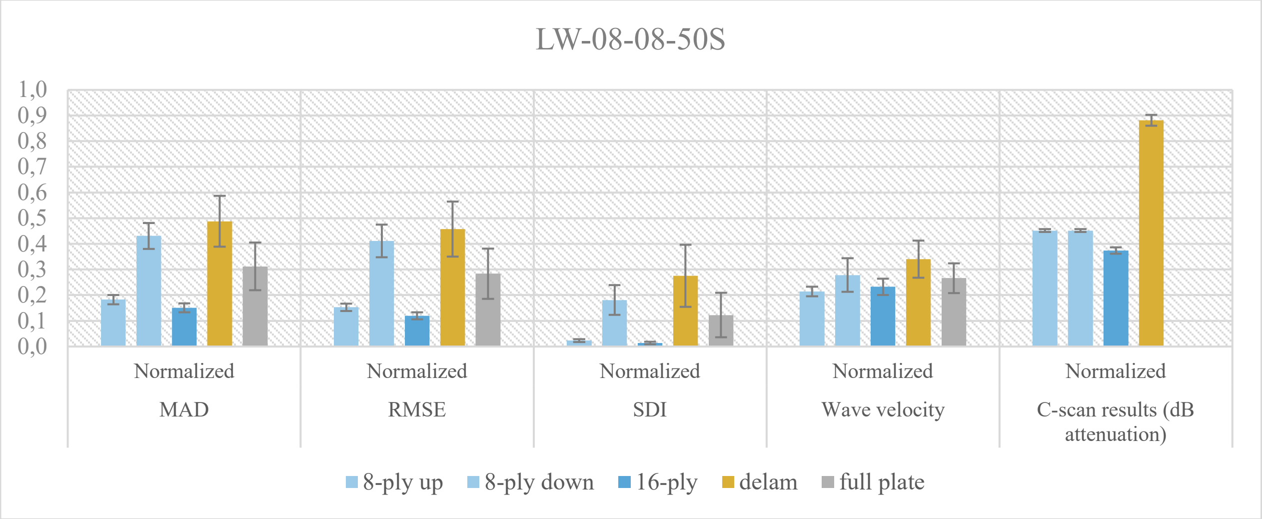

LW-32-00-dep



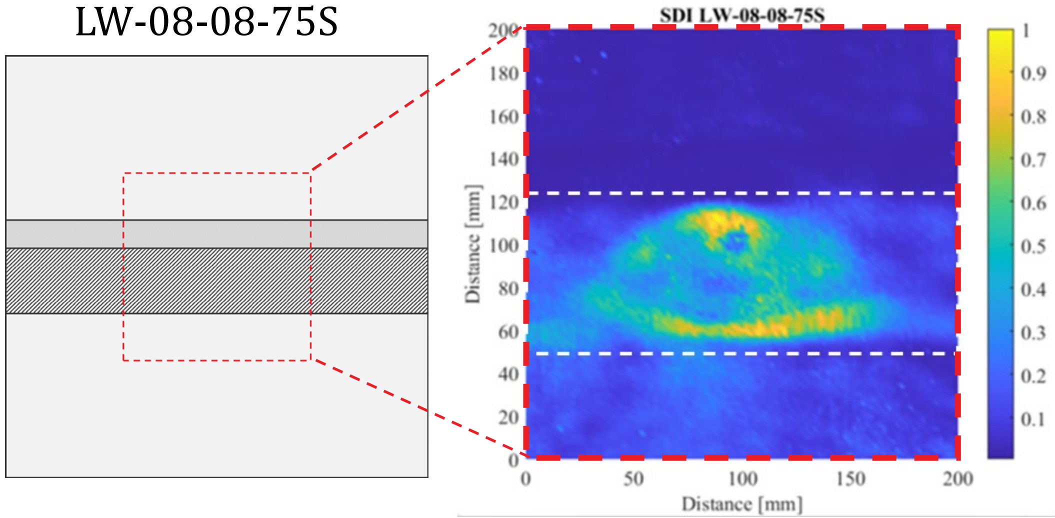
# Results: quantitative analysis (1/2)

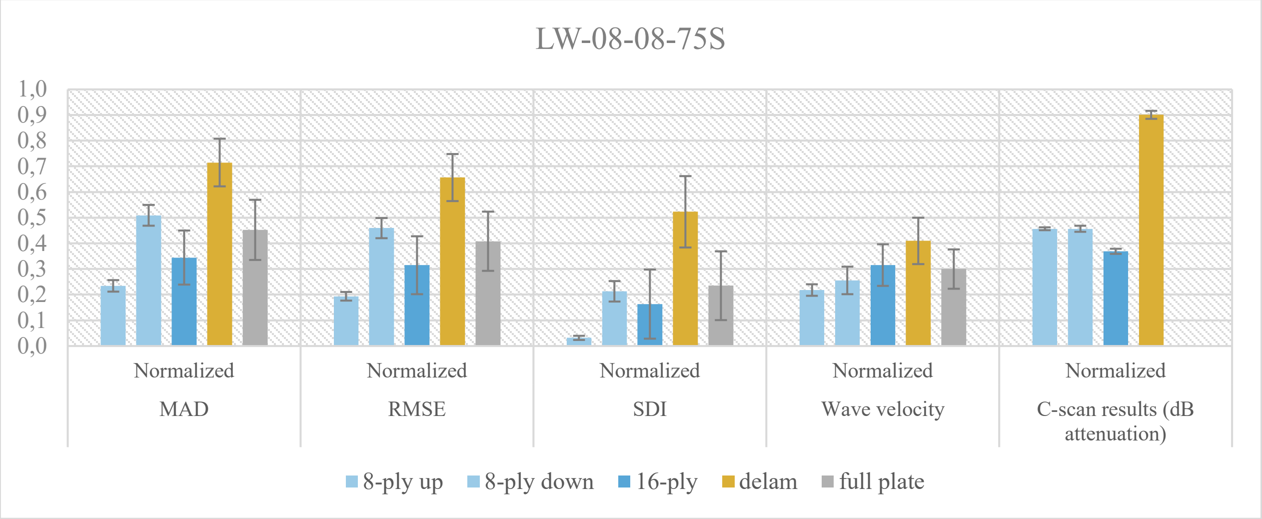
LW-08-08-50S



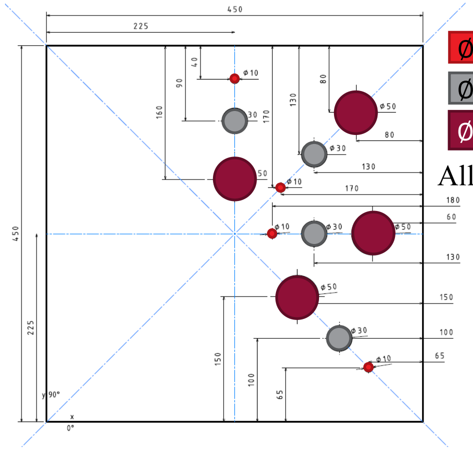

LW-08-08-75S



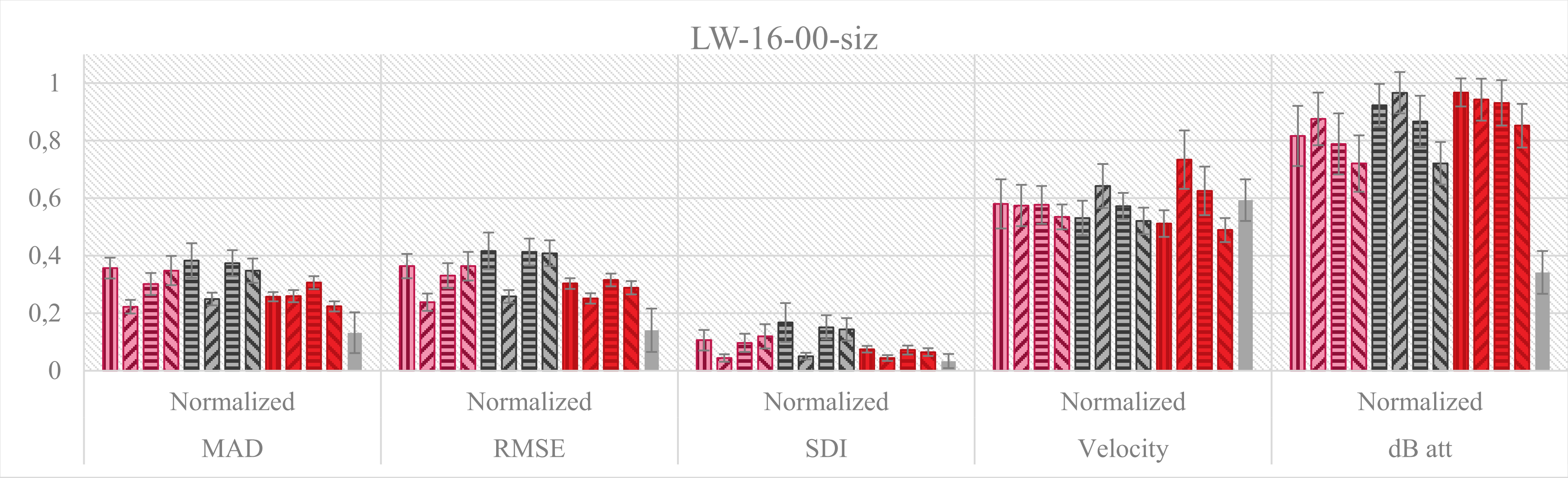



# Results: quantitative analysis (2/2)

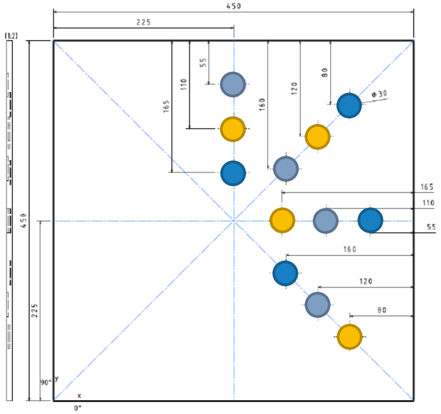
LW-16-00-siz



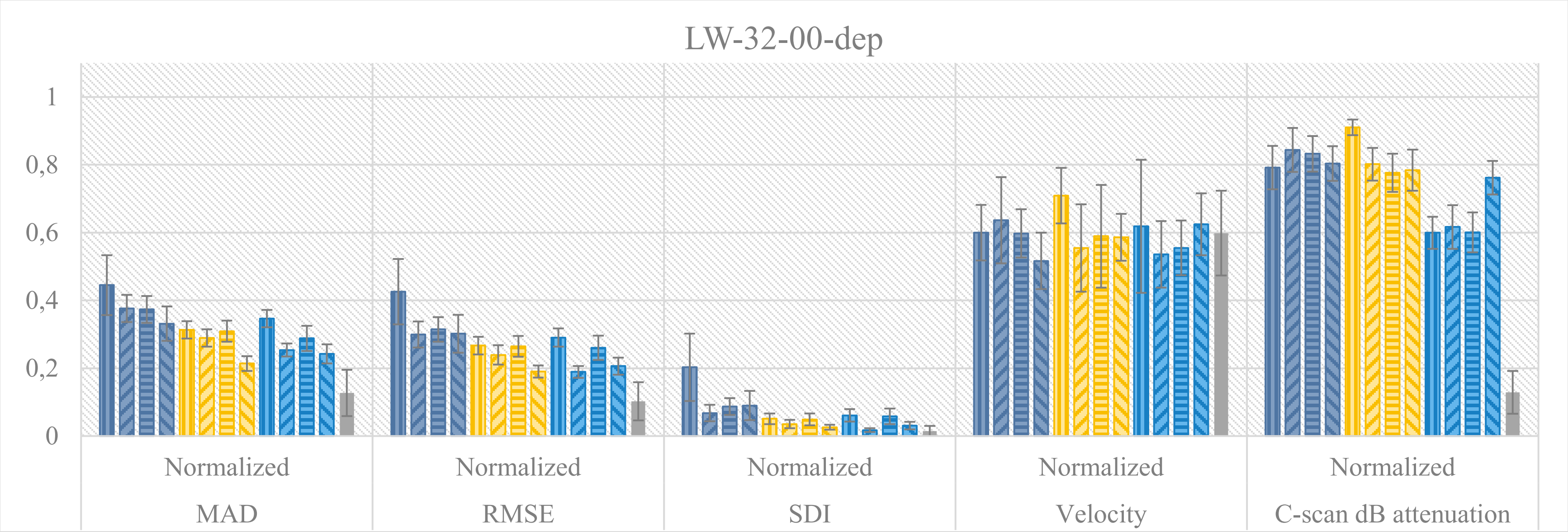
Ø10 *mm*
Ø30 *mm*
Ø50 *mm*
All 8-ply depth




LW-32-00-dep



8-ply depth
16-ply depth
24-ply depth
*all Ø30 mm*



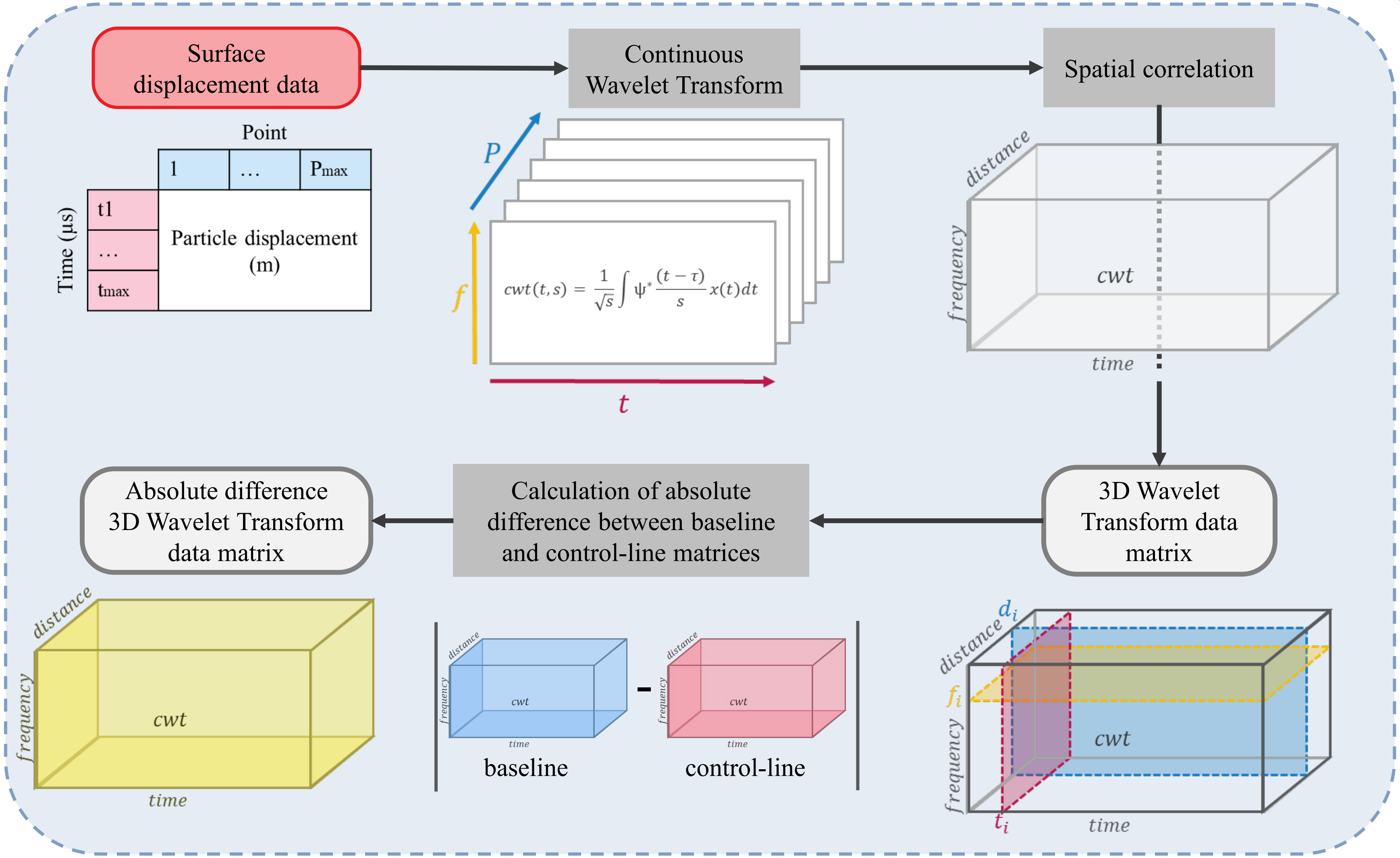
# Conclusion

- Innovative system using **Laser-Induced Plasma Shock Wave** for the generation of Lamb Waves in CFRP composites
- Development of efficient **Signal Processing method** to adapt this wave excitation system
  - Wavelet Analysis of the signals
  - Extraction of Damage Indexes based on time-frequency data and on image processing
  - Optimization and vizualisation of the Probability Functio
- Validation of the ability to **qualitatively detect artificial defects**
- Quantitatively, still not as efficient as conventional UT method
- Leads for the **next improvements**:
  - Generating better baselines with numerical simulation
  - Investigating new DIs
  - Extending the database and eventually exploiting deep learning

# Appendix 1: Data acquisition details

| Sample type | Recording time $t_{max}$ [µs] | Sampling frequency $F_s$ [MHz] | Time samples $T_S$ | Passband filter [kHz] |
|---|---|---|---|---|
| Stiffened samples | 800 | 2.56 | 2048 | [8 – 600 ] |
| Small delamination sample | 1600 | 3.125 | 5000 | [10 – 600 ] |

# Appendix 2: Wavelet Analysis




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

# Appendix 3: Calculation of Damage Indexes

STEP 2: CALCULATION OF DAMAGE INDEXES (DIS)

Absolute difference 3D Wavelet Transform data matrix

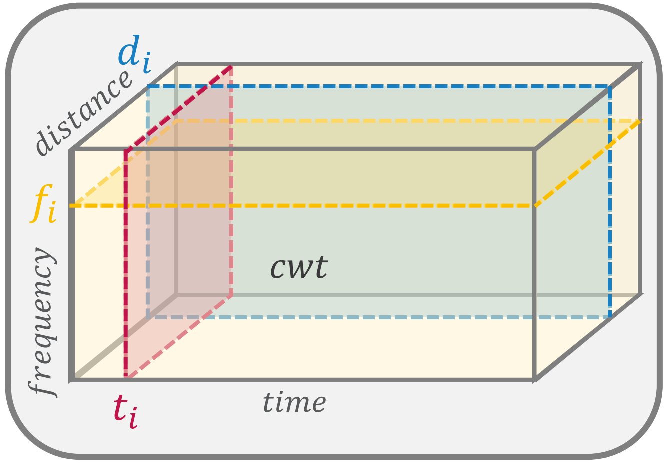
For each spatial component

- Extraction of time-frequency data → Damage Index « MAD »
- Calculation of the Lamb Wave first Time-of-Arrival → Damage Index « Wave velocity »

3D Wavelet Transform data matrix

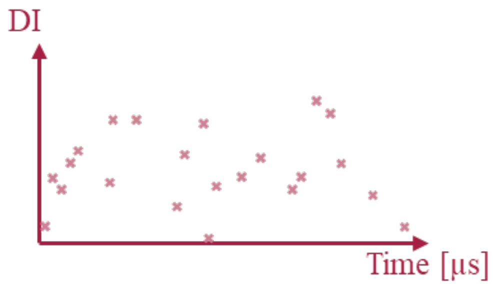
For each spatial component

- Extraction of time-frequency data → Damage Index « RMSE»
- Extraction of time-frequency data → Damage Index « SDI»



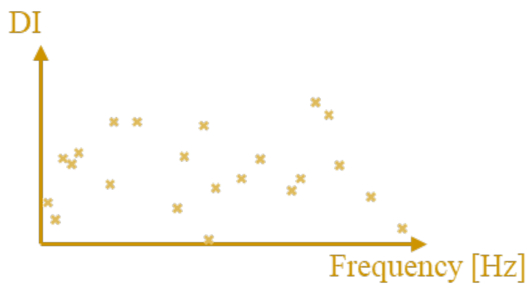

Analysis of **spatial-frequency image**: DI calculation for each $t_i$ value

- Curve of **DI evolution with time**



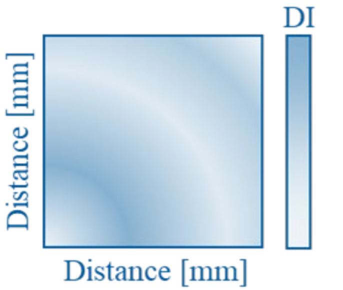

Analysis of **spatial-time image**: DI calculation for each $f_i$ value

- Curve of **DI evolution with frequency**

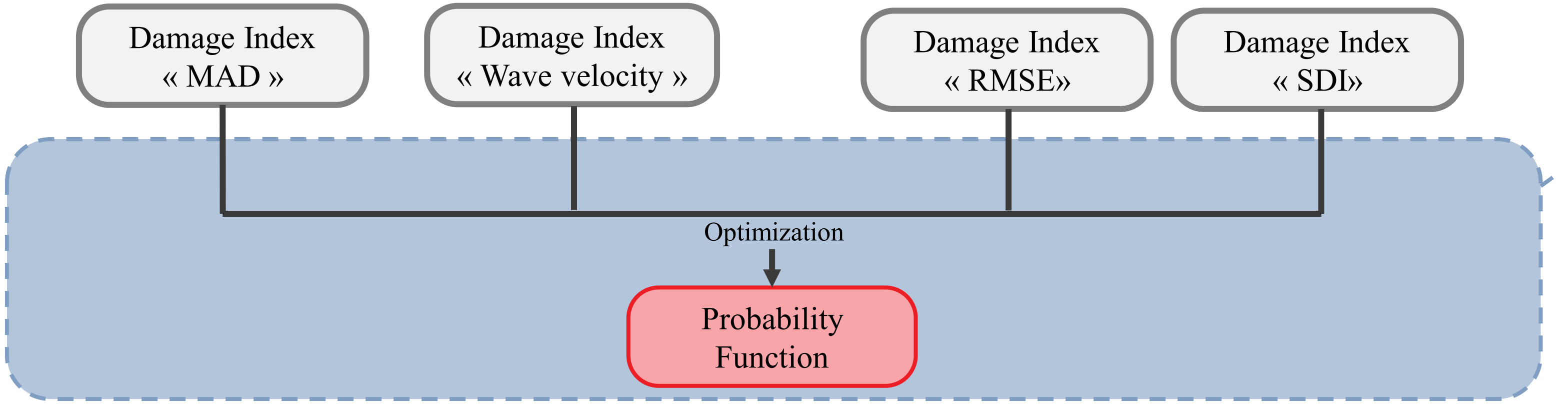



Analysis of **frequency-time image**: DI calculation for each d value

- Cartography of **DI at each sample point** of distance $d_i$



# Appendix 4: 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:
  - $\alpha, \gamma, \varepsilon \to 0$ and $\beta \to 1$
  - SDI is the best Damage Index to generate reliable cartographies