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The evaluation of bonding quality through multidimensional data fusion

Elena Jasiūnienė, Vaidotas Cicėnas, Gawher Ahmad Bhat

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Abstract: Adhesive bonded structures have attracted significant interest from various industries including those involved in transportation such as the aerospace, rail, marine, and automotive. due to their advantageous properties. Adhesives possess the capability to join complex structures and dissimilar materials, distribute load homogenously by offering high strength-to-weight ratio. However, the use of adhesive bonds is constrained by the absence of reliable techniques for their non-destructive evaluation.

The aim of this study is to enhance the reliability of nondestructive testing of adhesive joints by means of the multidimensional data fusion of the ultrasonic and radiographic data to broaden their application areas. Data fusion can be defined as a process of combining data from various sources to generate more complete and accurate data thereby improving accuracy.

In this study adhesive joints featuring various types of bonding defects were investigated employing radiography and conventional pulse-echo ultrasonic techniques. Subsequently, a data fusion was implemented integrating the data acquired by different techniques. The investigation also involved the development and refinement of advanced data processing techniques, particularly designed for data fusion applications.

The work highlights the necessity of a comprehensive non-destructive evaluation to assess the quality of the adhesive bonds. Consequently, the application of multi-dimensional data fusion of radiographic and ultrasonic data has yielded more comprehensive results.

Keywords: data fusion, nondestructive evaluation, Ultrasonic testing, Radiographic Inspection, Adhesive bonded structures

The evaluation of bonding quality through multidimensional data fusion

Elena JASIŪNIENĖ*, Vaidotas CICĖNAS, Gawher Ahmad BHAT

Lithuania

KAUNAS

~410 500

POPULATION

Kaunas University of Technology

KAUNAS UNIVERSITY OF TECHNOLOGY

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9	FACULTIES
8	INSTITUTES
2	INTEGRATED CENTRES OF RESERCH, STUDIES AND BUSINESS
4	CAMPUS IN 3 CITIES
23	STUDENT ORGANIZATION

ACADEMIC STAFF:

>1000

STUDY PROGRAMS:

108

NUMBER OF STUDENTS:

>7400

OF ALUMNI ARE IN EMPLOYMENT WITHIN 12 MONTHS

82 %

UŽ KIEKVIENOS TECHNOLOGIJOS - ŽMOGUS

Bonding quality evaluation
Multi-dimensional data fusion

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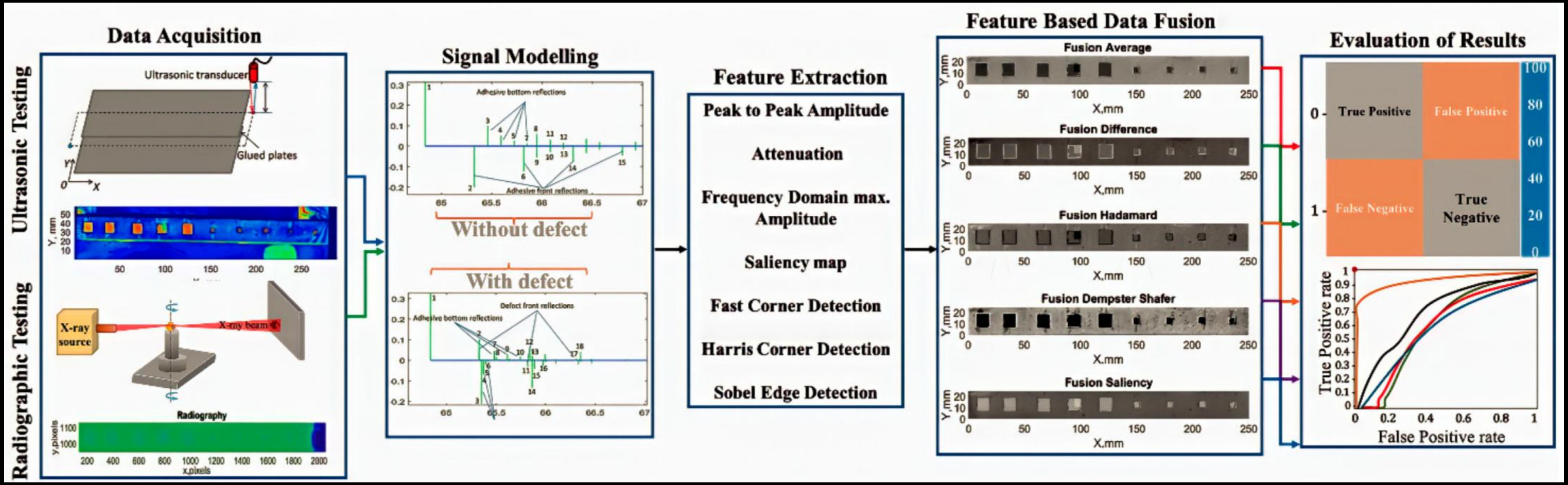
OBJECTIVE

to enhance the reliability of non-destructive evaluation for adhesively bonded aerospace components by development of novel multidimensional data fusion techniques, which will combine the information obtained by ultrasonic and X-ray NDT methods



Jasiūnienė, E.; Yilmaz, B.; Smagulova, D.; Bhat, G. A.; Cicėnas, V.; Žukauskas, E.; Mažeika, L. Non-destructive evaluation of the quality of adhesive joints using ultrasound, X-ray, and feature-based data fusion // Applied sciences. Basel : MDPI. ISSN 2076-3417. 2022, vol. 12, iss. 24, art. no. 12930, p. 1-20.
DOI: 10.3390/app122412930.

Adhesive bonds in aicrafts

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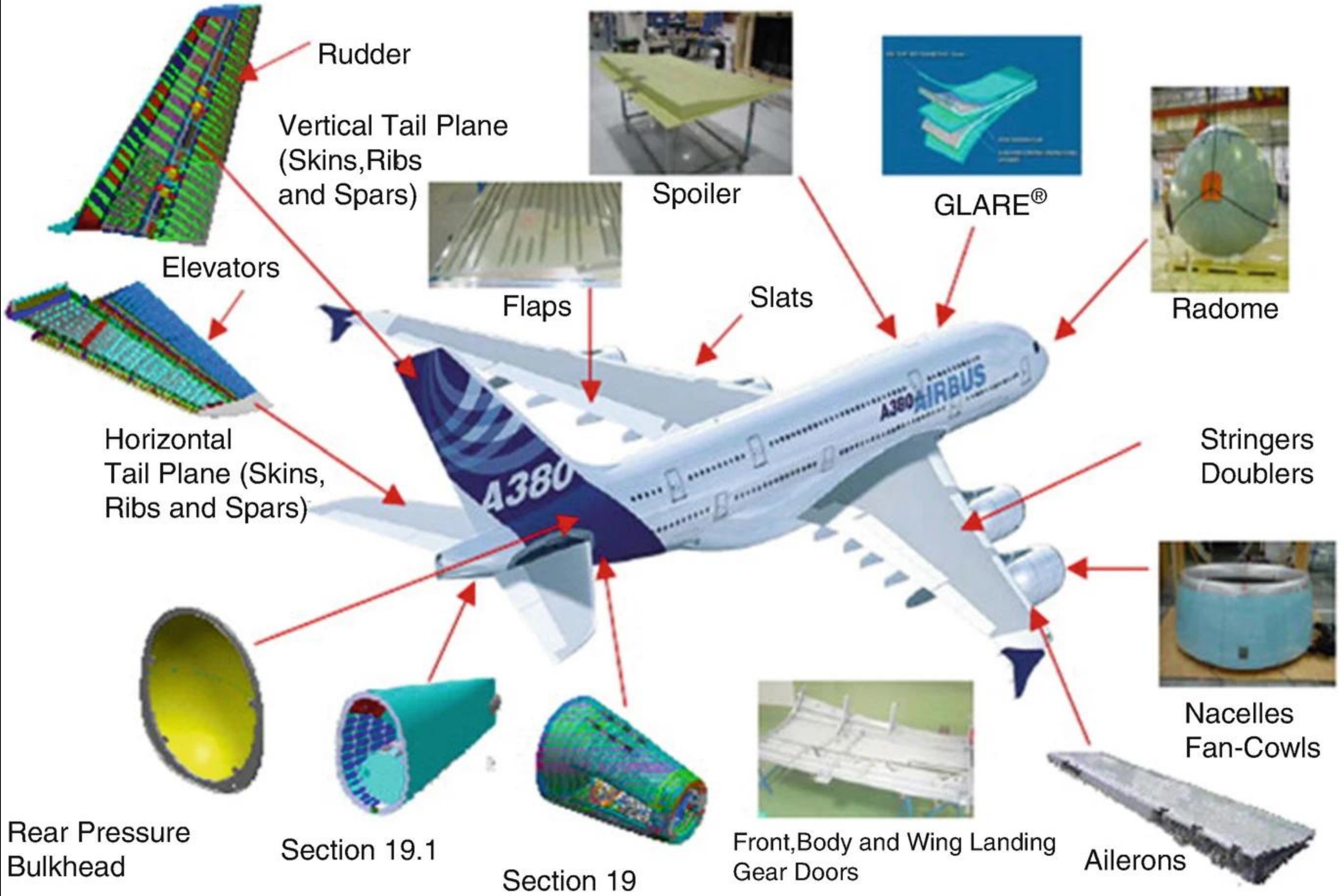

Adhesive bonds are used extensively, but only in secondary structures

Source *https://link.springer.com/chapter/10.1007/978-3-030-35346-9_12/figures/1*

Object of interest - Adhesive joints

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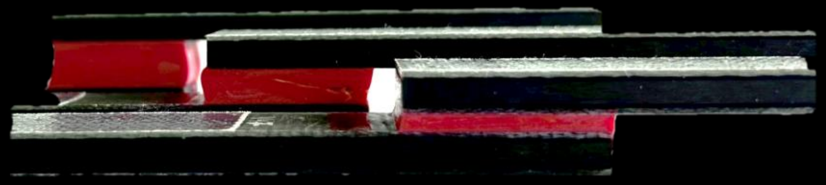
Advantages of adhesive joints:

- ✓ Can join wide range of materials
- ✓ Allow joining dissimilar materials
- ✓ Distributes stress more evenly – enhanced fatigue resistance
- ✓ Excellent load bearing capacity
- ✓ Can simplify assembly process – faster production, reduced costs
- ✓ Weight reduction
- ✓ More environmentally friendly

Disadvantages of adhesive joints:

- Sensitivity to aging, degradation
- Sensitivity to temperature
- Surface preparation
- Strength variability



Defects in adhesive joints

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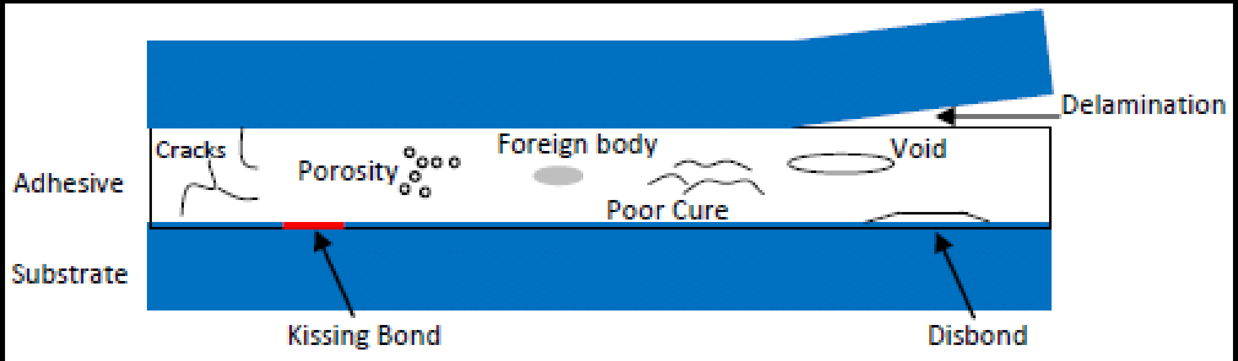

- Disbonds
- Inclusions
- Voids/porosity
- Weak bond due to surface contamination
- Weak joint due to improper curing conditions

Reliable NDT techniques are required to detect all types of defects or weak bonds

Why assessing the quality of adhesive bonds is not simple?

Adhesive bonds investigated

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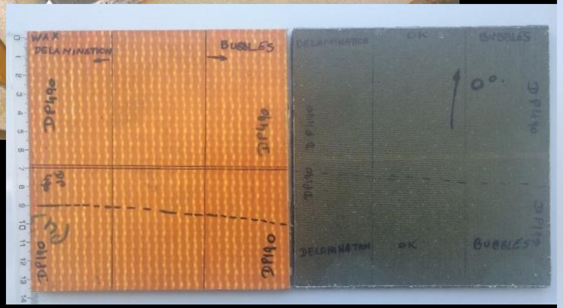
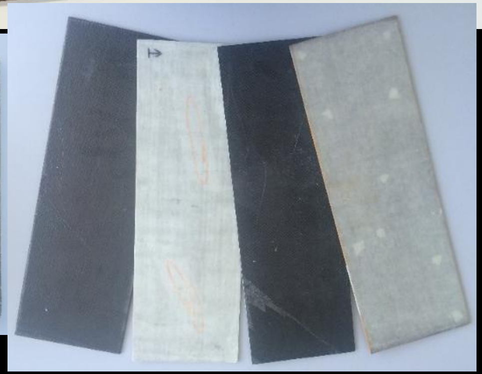
- Aluminum-aluminum lap joints provided by COTESA GmbH; FL Technics.

- Composite-metal samples provided by AP&M; ITA; Walker Technical Resources; FL Technics





- CFRP/CFRP lap joints provided by COTESA GmbH; FL Technics

- CFRP/metal with pins samples provided by Swerea SICOMP AB

Adhesive bonds, unprocessed results

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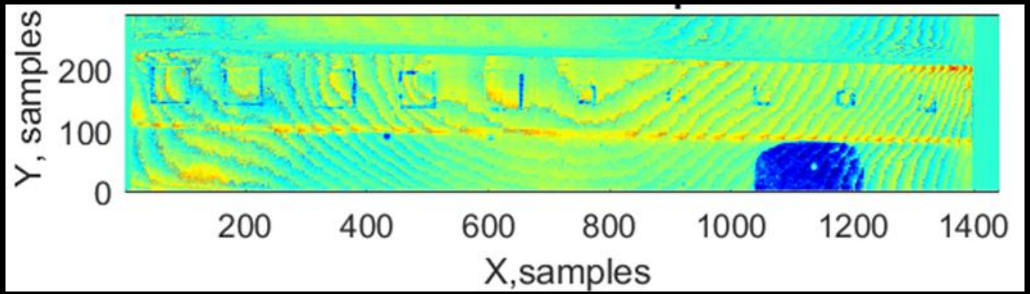

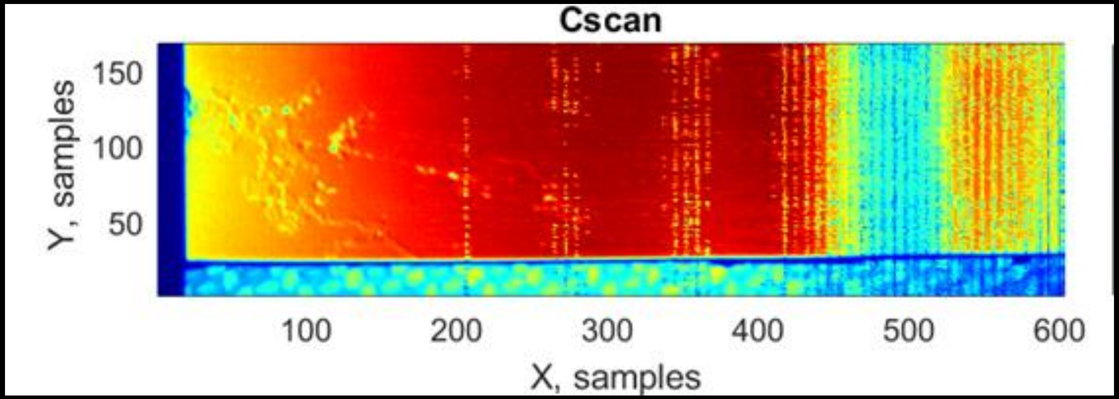

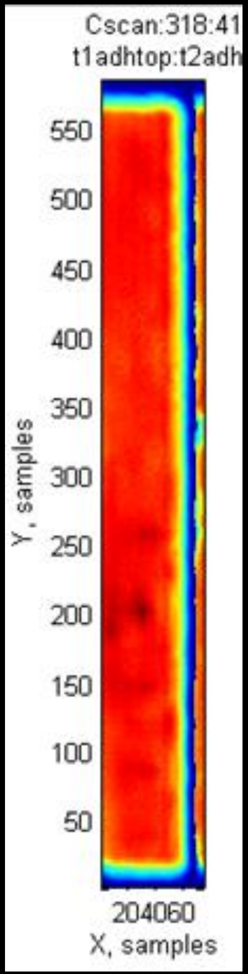

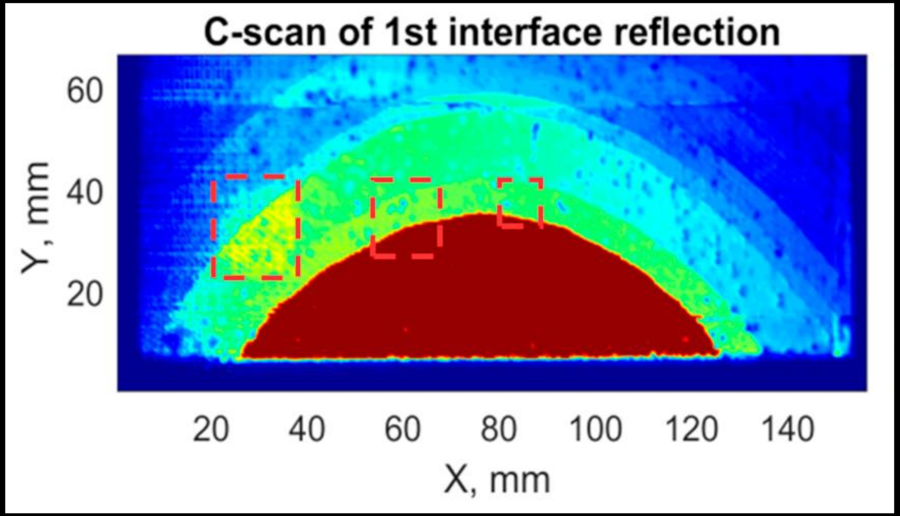

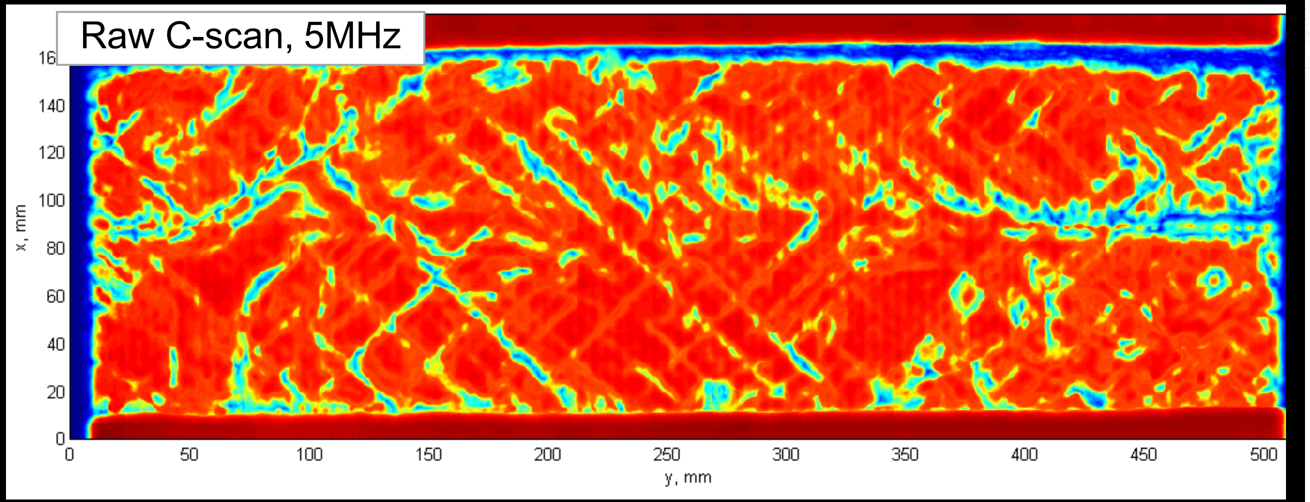

Inspection – simple sample vs adhesive joint

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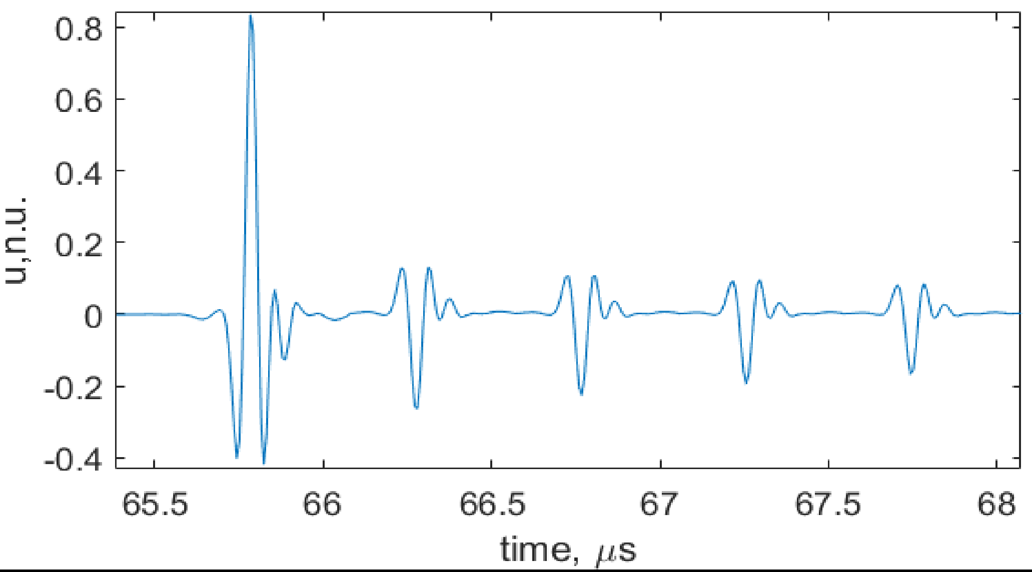
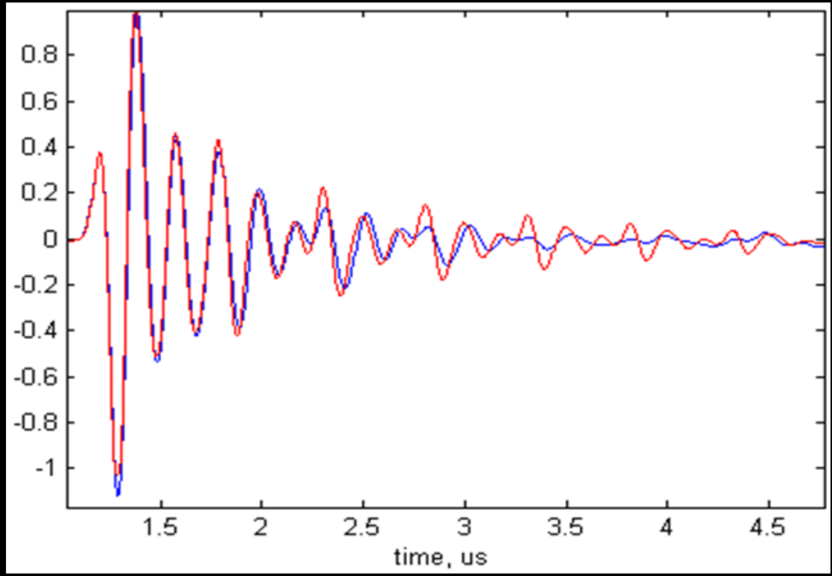


Simple structure



Adhesive joint

Data aquisition

Ultrasound institute, research infrastructure

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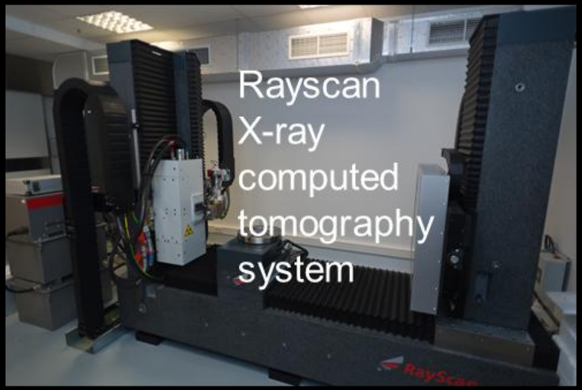

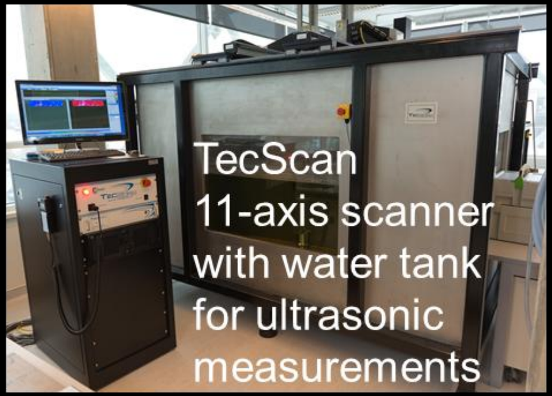

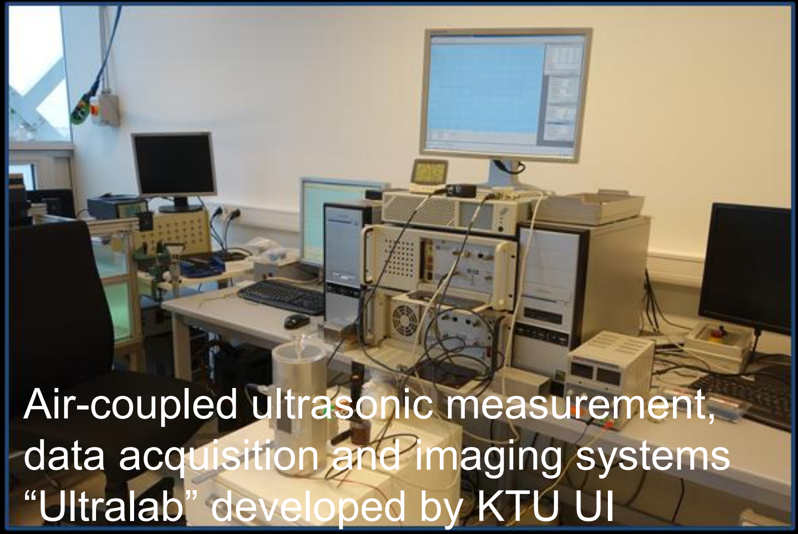

And much more

Bond quality evaluation using ultrasonics

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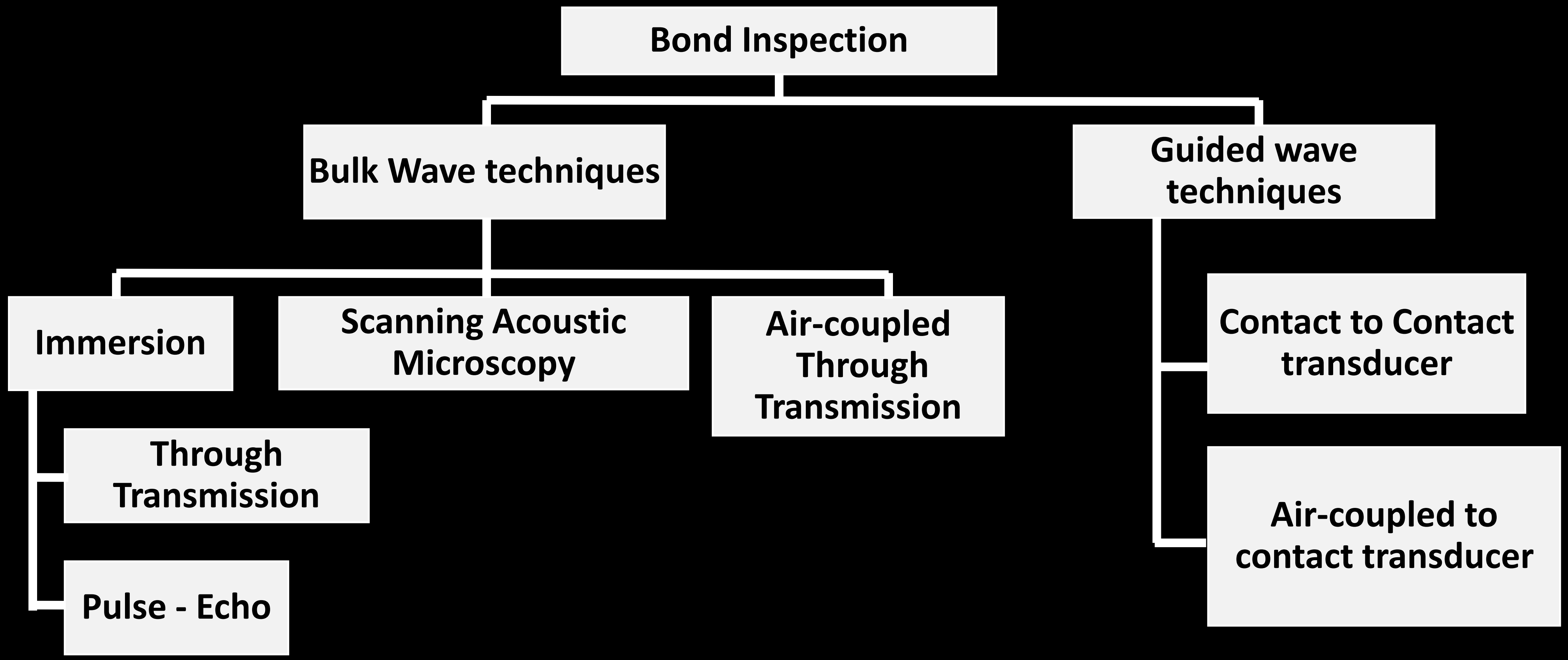

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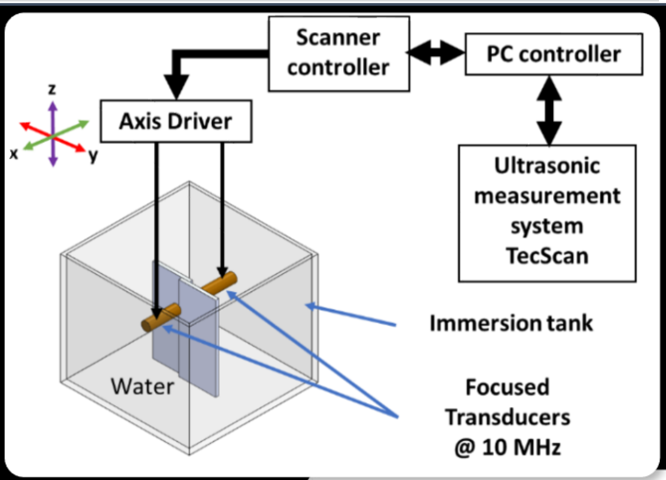
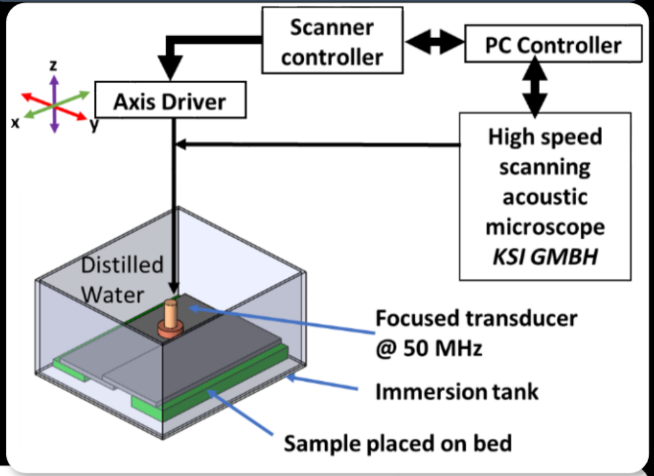
Bond quality evaluation using ultrasonics

Bulk Wave techniques	Guided Wave techniques

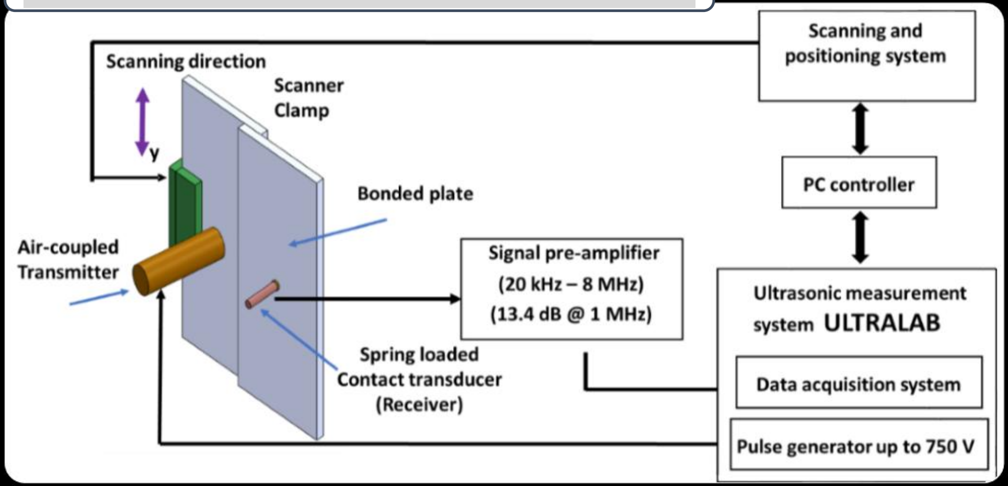
Immersion (through transmission)



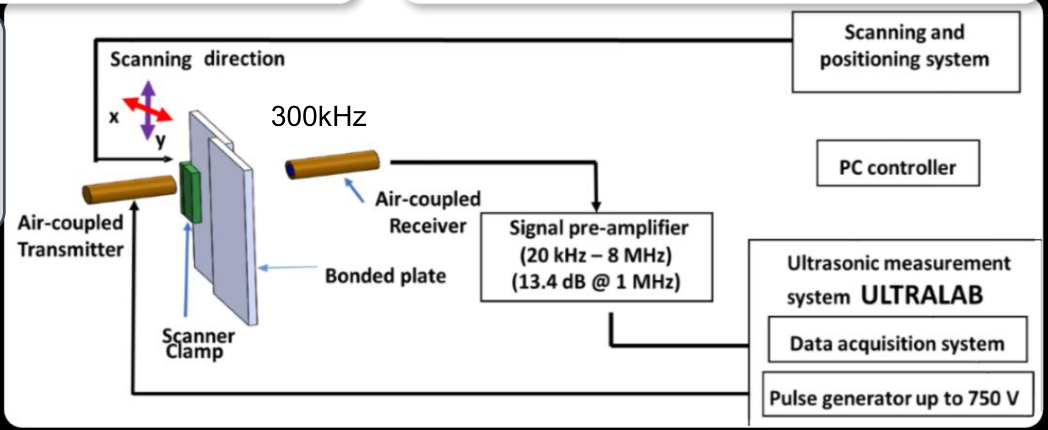
Scanning Acoustic Microscopy



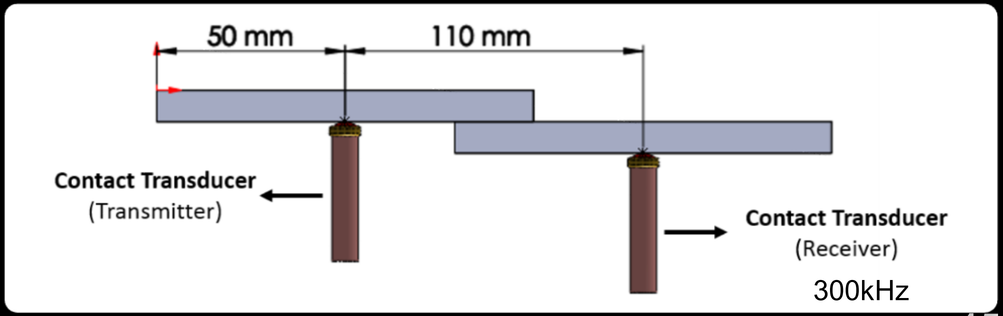
Air-coupled to contact transducer



Air-coupled through transmission



Contact to contact transducer



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Samples

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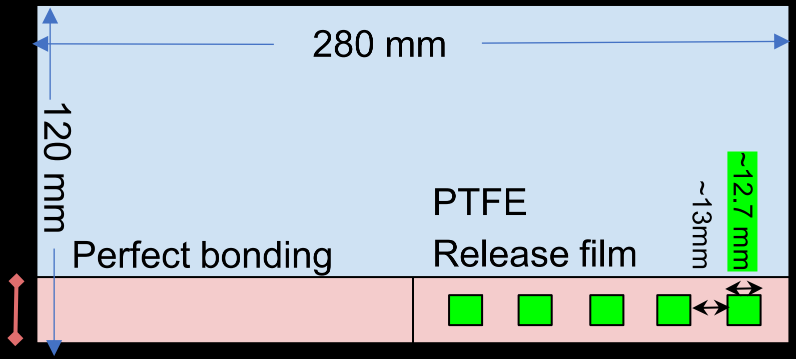
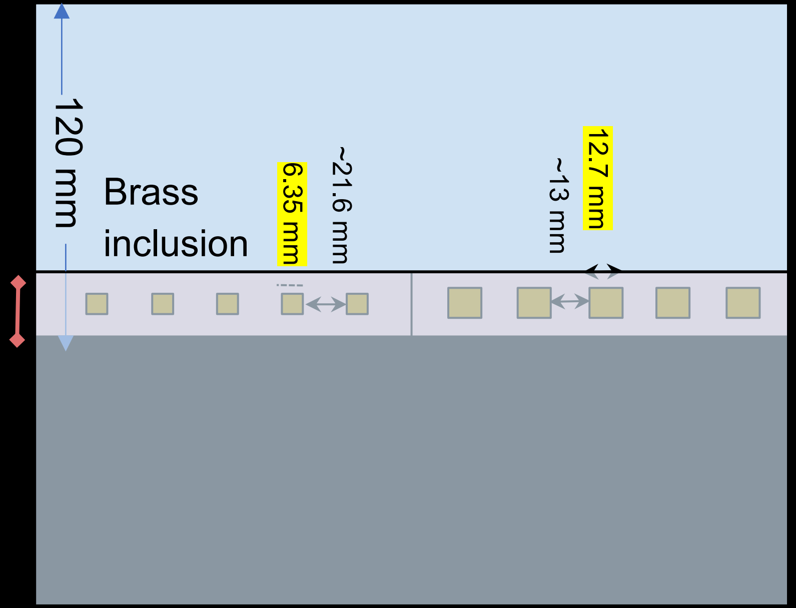
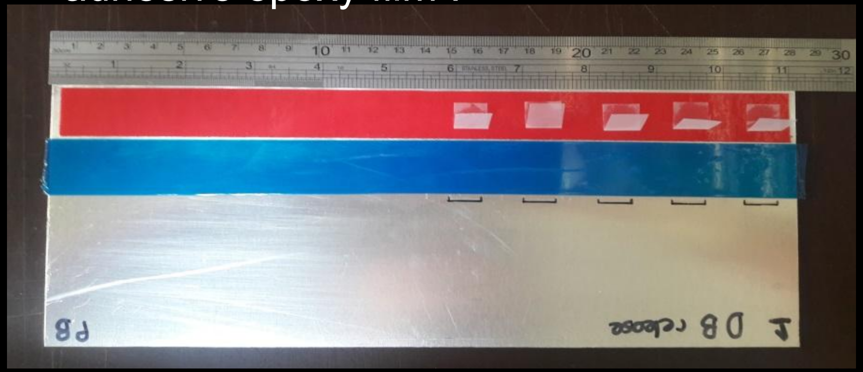
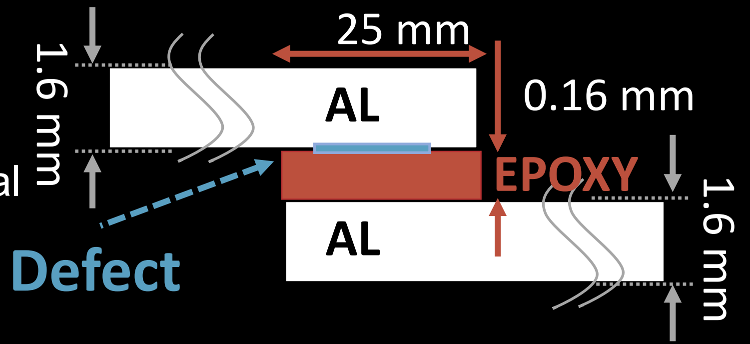




Adhesive single lap joints

Adherent type - Aluminum
Adhesive – 3M Scotch-Weld AF163 structural adhesive epoxy film :





Bonding quality:

- PB - Perfect bond
- DB – artificial disbond
- Brass film inclusion
- Weak bonds :
  - WB-RA due to release agent
  - WB-FC due to faulty curing

COTESA COMPOSITES

Bond quality evaluation: comparison of ultrasonic techniques

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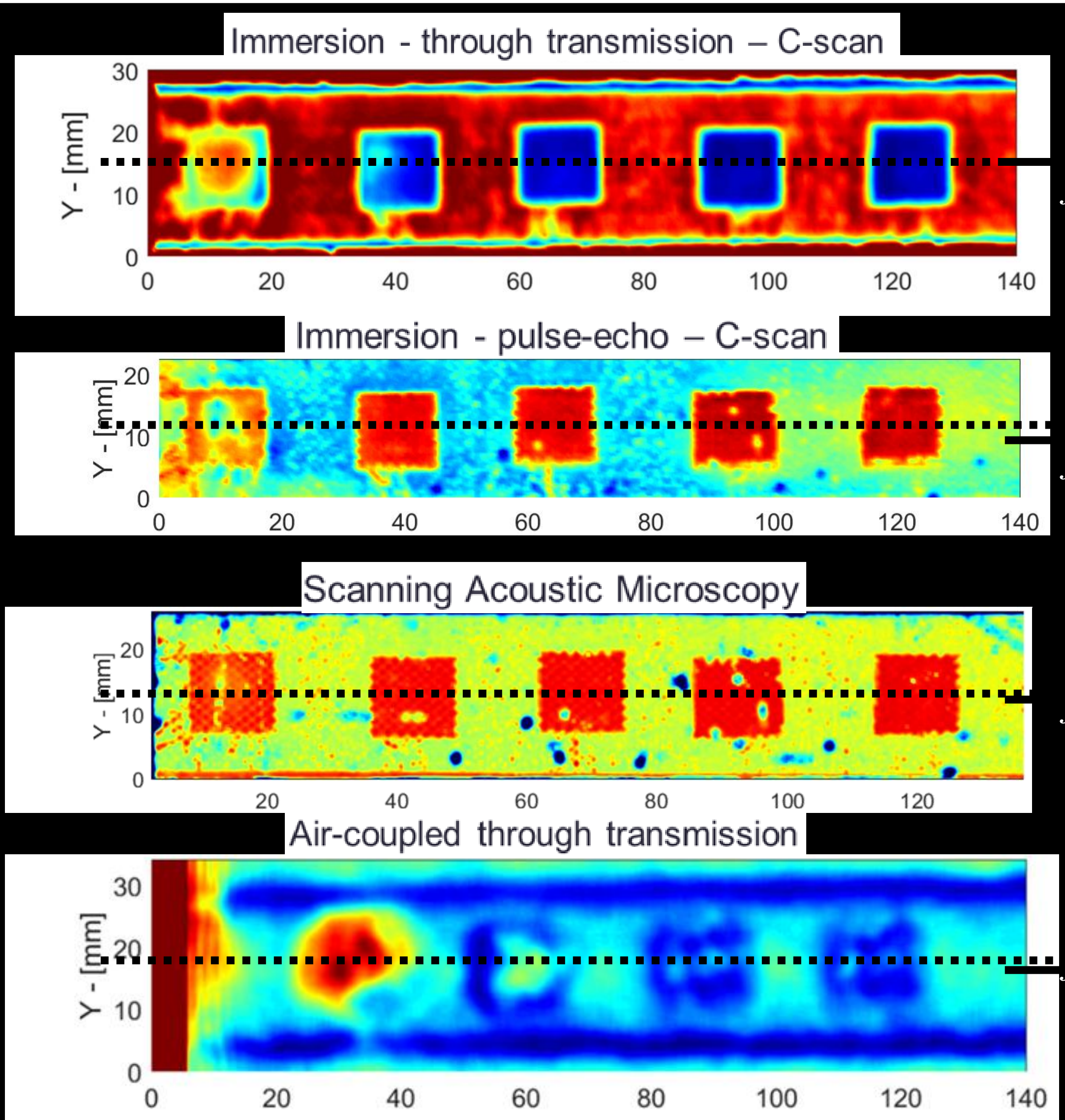


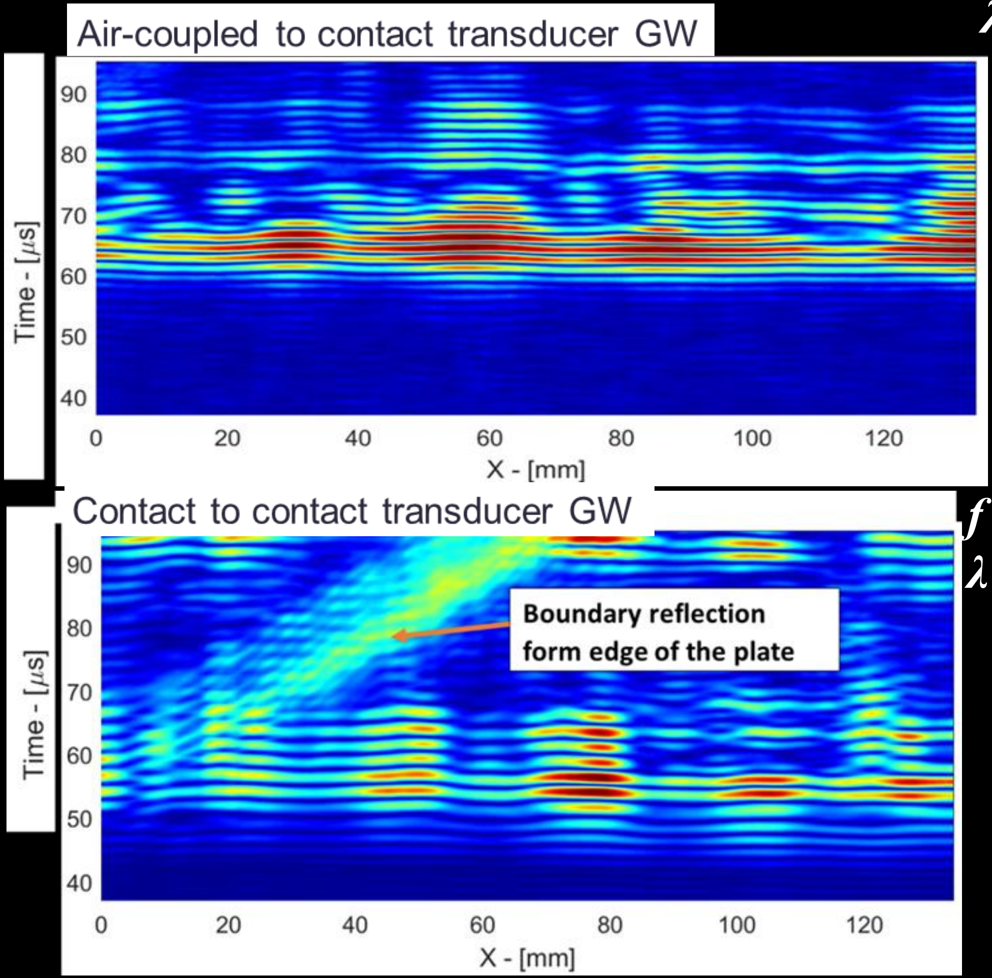
f = 10 MHz
λ = 0.15 mm

f = 10 MHz
λ = 0.15 mm

f = 50 MHz
λ = 0.03 mm

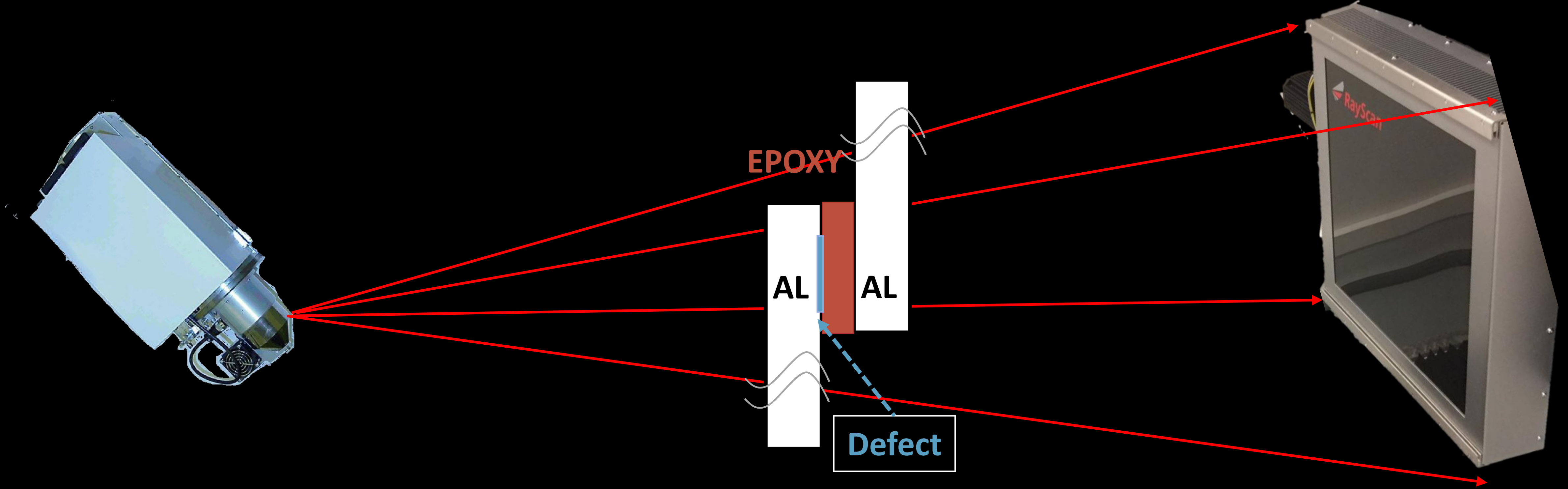
f = 300 kHz
λ = 1.14 mm

f = 300 kHz
λ = 1.14 mm

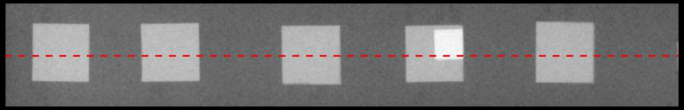


f = 300 kHz
λ = 1.14 mm

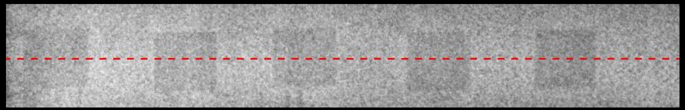
Radiography



Inclusion



Disbond



Feature extraction

Smagulova, D.; Yilmaz, B.; Jasiuniene, E.. Ultrasonic features for evaluation of adhesive joints: a comparative study of interface defects // Sensors. Basel : MDPI. ISSN 1424-8220. 2024, vol. 24, iss. 1, art. no. 176, p. 1-17. DOI: https://doi.org/10.3390/s24010176

Bonding qualities

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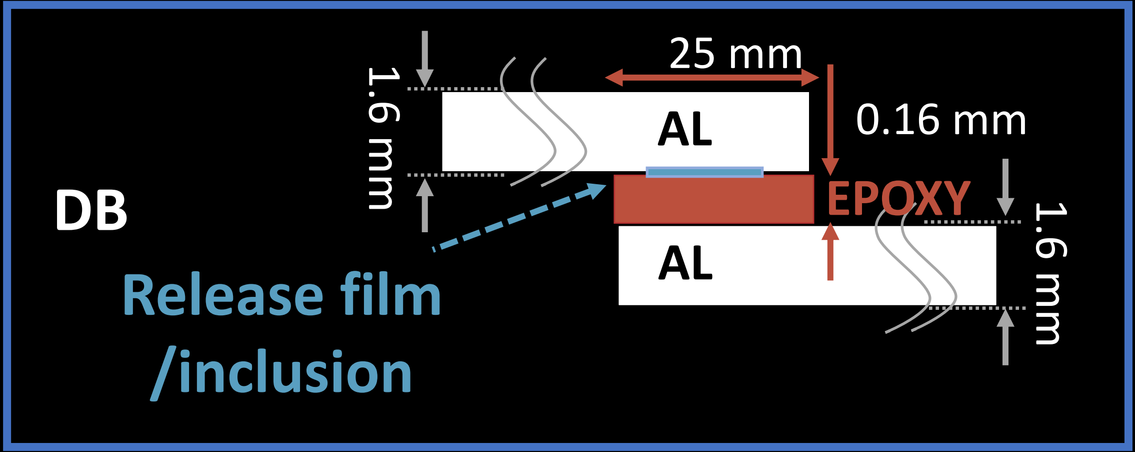
- Aluminum 2024 adherend
- 3M Scotch-Weld AF163 structural adhesive epoxy film

Bonding qualities:

- **DB**: Debonding - two-fold *Wrigtlon* 4600 release film



UT – Feature extraction

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No	Ultrasonic Feature	Mathematical Expression
1	Peak-to-peak amplitude, U_{pp}	$U_{pp} = \max(u(t)) - \min(u(t)),\ t \in t_n \div t_{n+1}$, $n = 1,2,3,4$ (interface reflections)
2	Ratio coefficients, K_1, K_2	$K_1 = \frac{U_{pp_n}}{U_{pp_{n+1}}}, \quad K_2 = \frac{U_{pp_{n+1}}}{U_{pp_n}}$
3	Attenuation, α	$\alpha = 20log_{10}\frac{U_{pp_n}}{U_{pp_{n+1}}}$
4	Maximum amplitude at frequency domain, U_{fmax}	$U_{fmax} = \max(\mathrm{FT}(u(t))),\ t \in t_n \div t_{n+1}$, FT—Fourier Transform
5	Absolute Energy, A	$A = \sum_{t_n}^{t_{n+1}} U_{p-p}{}^2$
6	Frequency value at the maximum amplitude, f_{Umax}	$f_{Umax} = \mathrm{FT}(u(t)),\ t \in t_n \div t_{n+1}$
7	Absolute time of flight difference, Δt	$\Delta t = \lvert t_{n+1} - t_n \rvert$
8	Kurtosis, k	$k = \mathrm{FT}\frac{E\,(u(t_n \div t_{n+1}) - \mu)^4}{\sigma^4}$, μ—is a mean of $(u(t_n \div t_{n+1}))$, σ is a standard deviation, E is the expected value of the quantity $(u(t_n \div t_{n+1}) - \mu)^4$

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UT – Feature extraction

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No	Ultrasonic Feature	Mathematical Expression
9	Mean value of the amplitude in frequency domain, u_{fmean}	$u_{fmean} = \sum_{i=1}^{N} \mathrm{FT}\left(\frac{u_i(t)}{N}\right)$, $t \in t_n \div t_{n+1}$, u_i—is each datum of amplitudes at selected time interval, N—is a number of observations
10	Skewness, s	$s = \mathrm{FT}\frac{E\,(u(t_n \div t_{n+1}) - \mu)^3}{\sigma^3}$ μ—is a mean of $(u(t_n \div t_{n+1}))$, σ is a standard deviation, E is the expected value of the quantity $(u(t_n \div t_{n+1}) - \mu)^3$
11	Standard deviation value in time domain, σ	$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} u_i(t) - \overline{u(t)}}$ u_i—is each data of amplitudes at selected time interval, $\overline{u(t)}$—is a mean value, N—is a number of observations
12	Standard deviation value in frequency domain, σ_f	$\sigma_f = \mathrm{FT}\cdot\sqrt{\frac{1}{N-1}\sum_{i=1}^{N} u_i(t) - \overline{u(t)}}$
13	Variation coefficient in time domain, cv	$cv = \frac{\sigma}{u_{mean}}$
14	Variation coefficient in frequency domain, cv_f	$cv_f = \mathrm{FT}\left(\frac{\sigma_f}{u_{fmean}}\right)$

Smagulova, D.; Yilmaz, B.; Jasiuniene, E.. Ultrasonic features for evaluation of adhesive joints: a comparative study of interface defects // Sensors. Basel : MDPI. ISSN 1424-8220. 2024, vol. 24, iss. 1, art. no. 176, p. 1-17. DOI: https://doi.org/10.3390/s24010176

UT – Feature extraction

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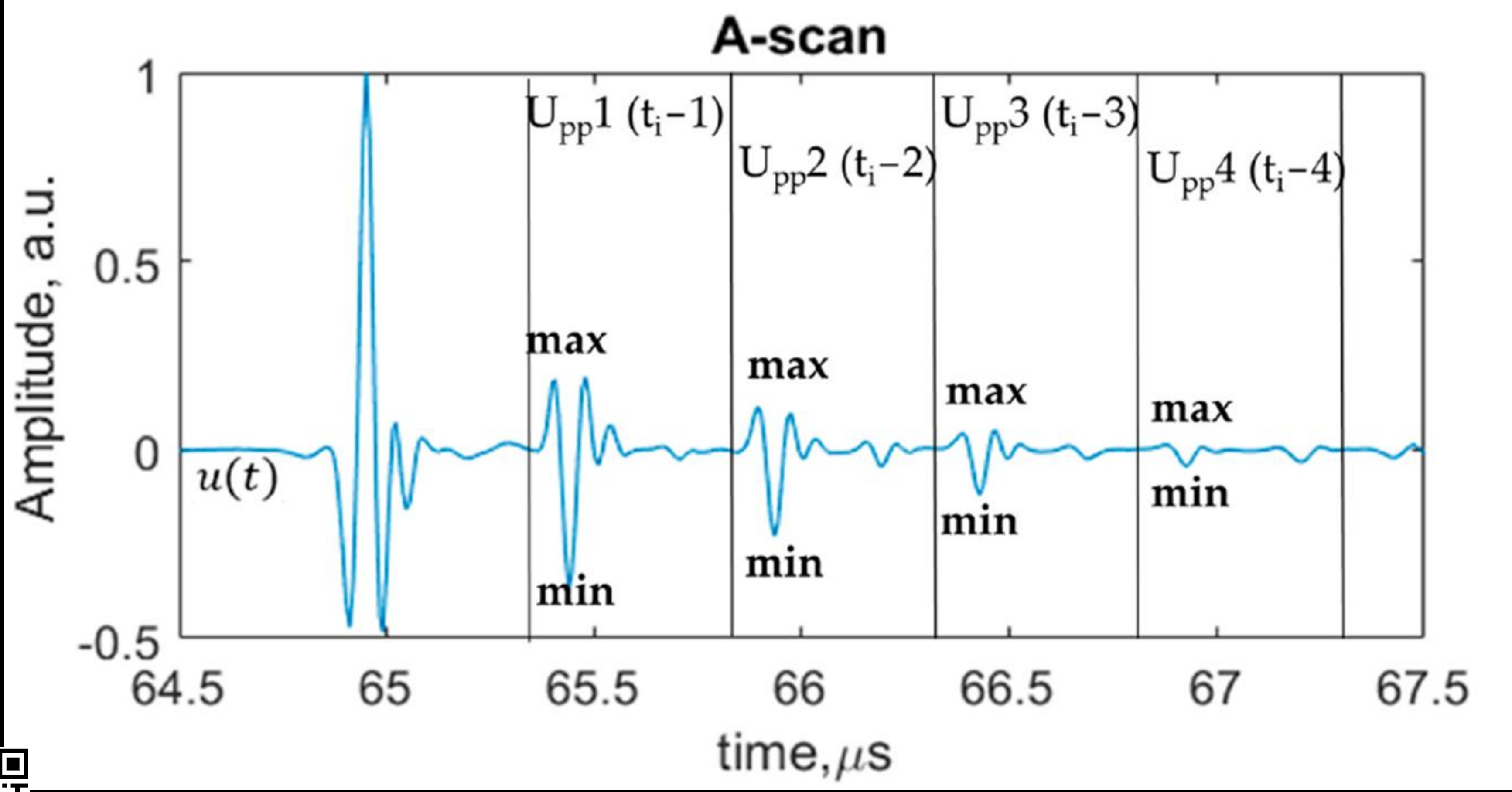
Symbol	Features	Equations
U1-U3	Peak-to-peak amplitude at interface (1st; 2nd and 3rd)	$UT_{p2p} = \log_{10}(max\,(U_T(t)) - min\,(U_T(t)))$
U4-U5	Attenuation between interface (1st and 2nd; 2nd and 3rd)	$UT_{\alpha} = -\frac{1}{t_k}\log_{10}\left(\frac{UT(t_k)}{UT(t_0)}\right)$
U6-U7	Frequency domain max amplitude at interface (1st and 2nd)	$UT_{fmax} = \log_{10} FT\left(UT(t)\right)$
U8-U9	Energy of signal at interface (1st and 2nd)	$UT_{\varepsilon} = \sum_{t_n}^{t_{n+1}} {U_{p-p}}^2$
U10	Absolute time of flight difference between 2nd and 3rd interface	$\Delta t = \lvert t_{n+1} - t_n \rvert$
U11	Mean value of the amplitude in frequency domain at 2nd interface	$u_{fmean} = \sum_{i=1}^{N} \mathrm{FT}\left(\frac{u_i(t)}{N}\right)$
U12	Standard deviation value in time domain at 2nd interface	$SD_t = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} u_i(t) - \overline{u(t)}}$
U13	Standard deviation value in frequency domain at 2nd interface	$SD_f = FT \cdot \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} u_i(t) - \overline{u(t)}}$
U14	Variation coefficient in frequency domain at 2nd interface	$VC_f = \mathrm{FT}\left(\frac{SD_f}{u_{fmean}}\right)$

UT – Feature extraction



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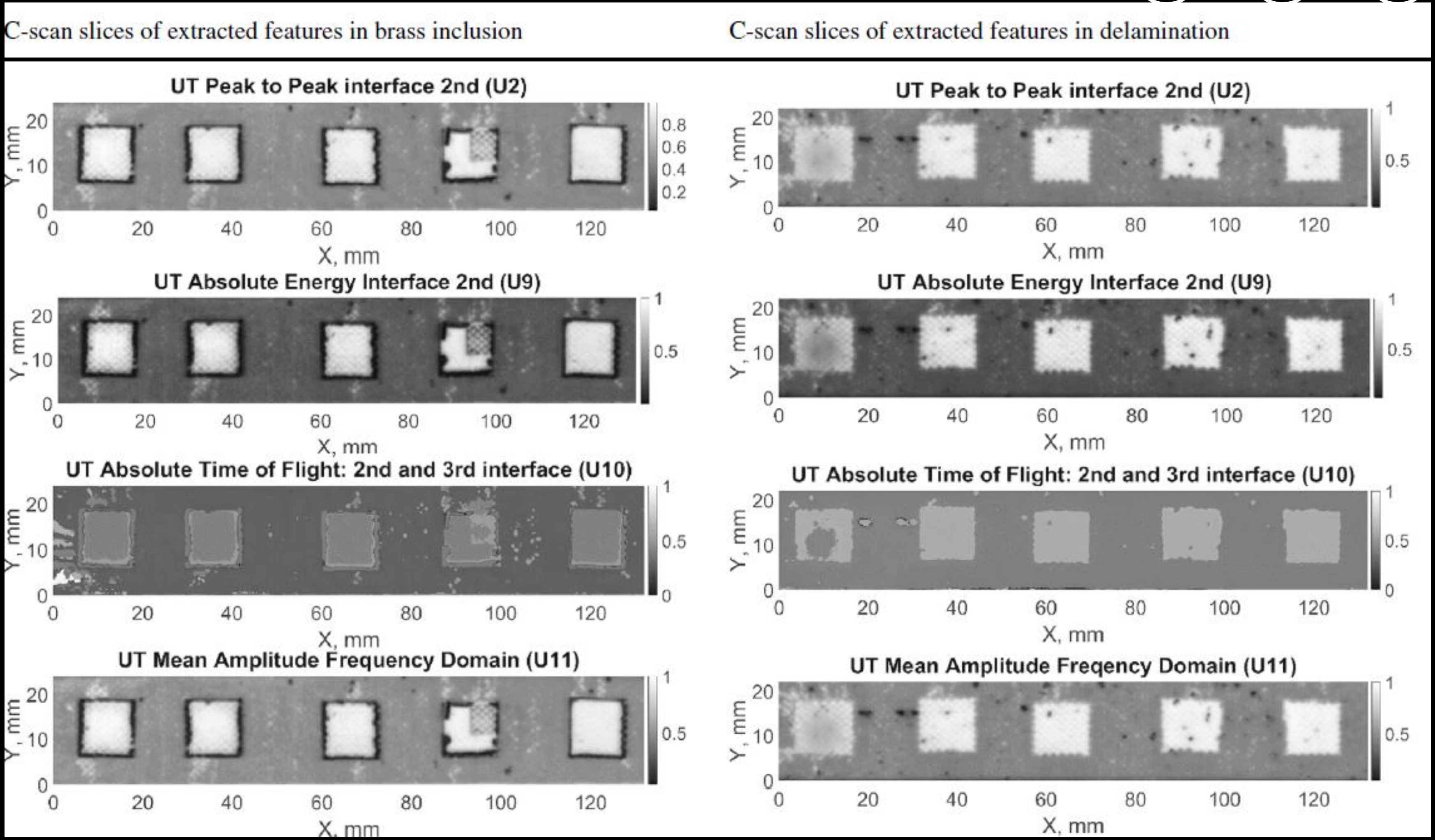

Bhat, G. A.; Smagulova, D.; Jasiūnienė, E.. Improved defect sizing in adhesive joints through feature-based data fusion // Journal of nondestructive evaluation. New York : Springer. ISSN 0195-9298. eISSN 1573-4862. 2025, vol. 44, iss. 1, art. no. 14, p. 1-16. DOI: 10.1007/s10921-024-01146-w

Performance evaluation

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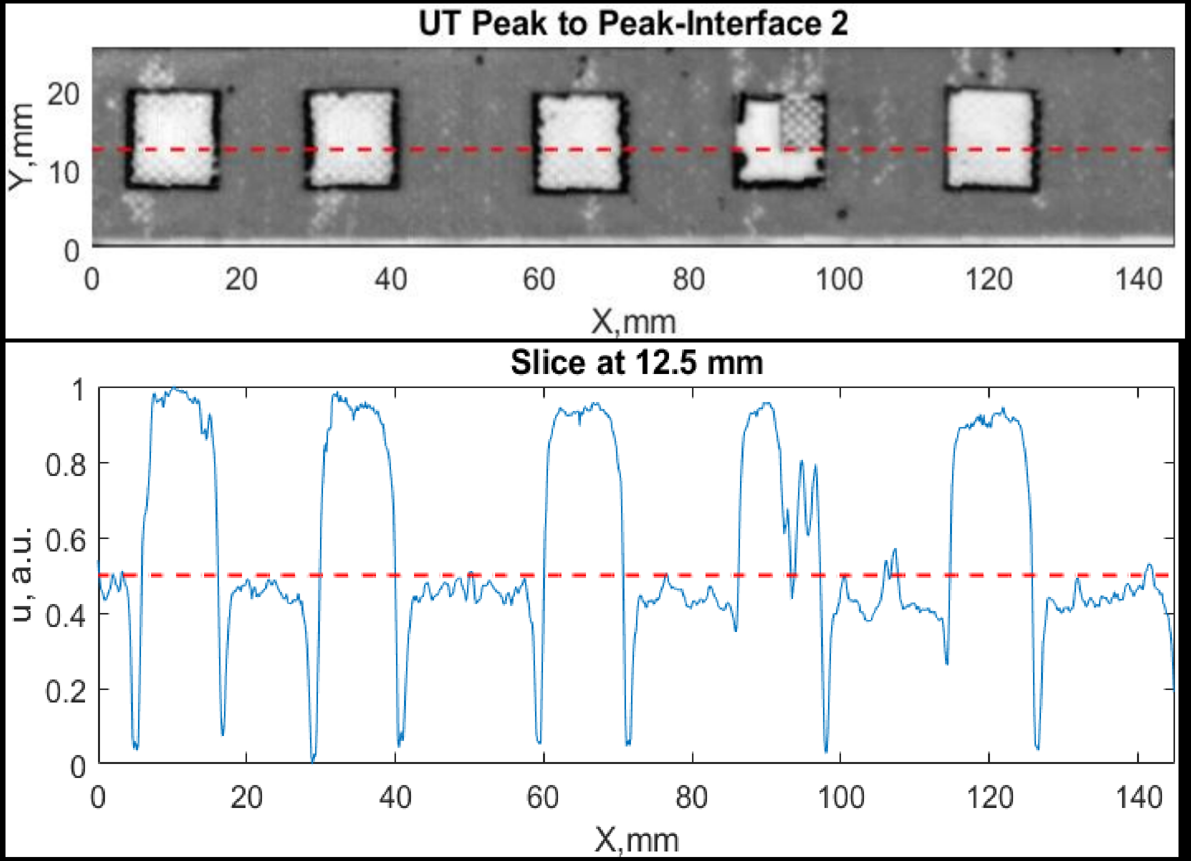
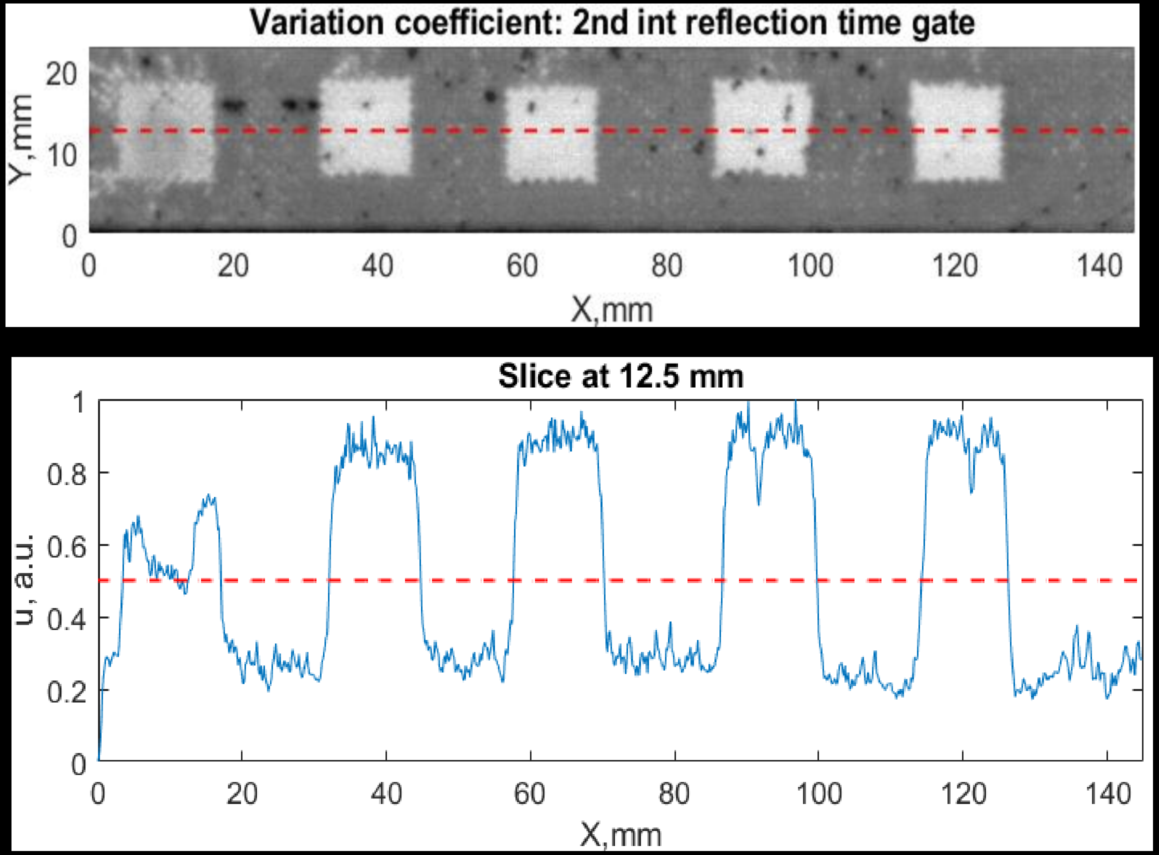
-6dB threshold sizing method

Aluminum lap joint with brass inclusions



Aluminum lap joint with delaminations



Performance evaluation

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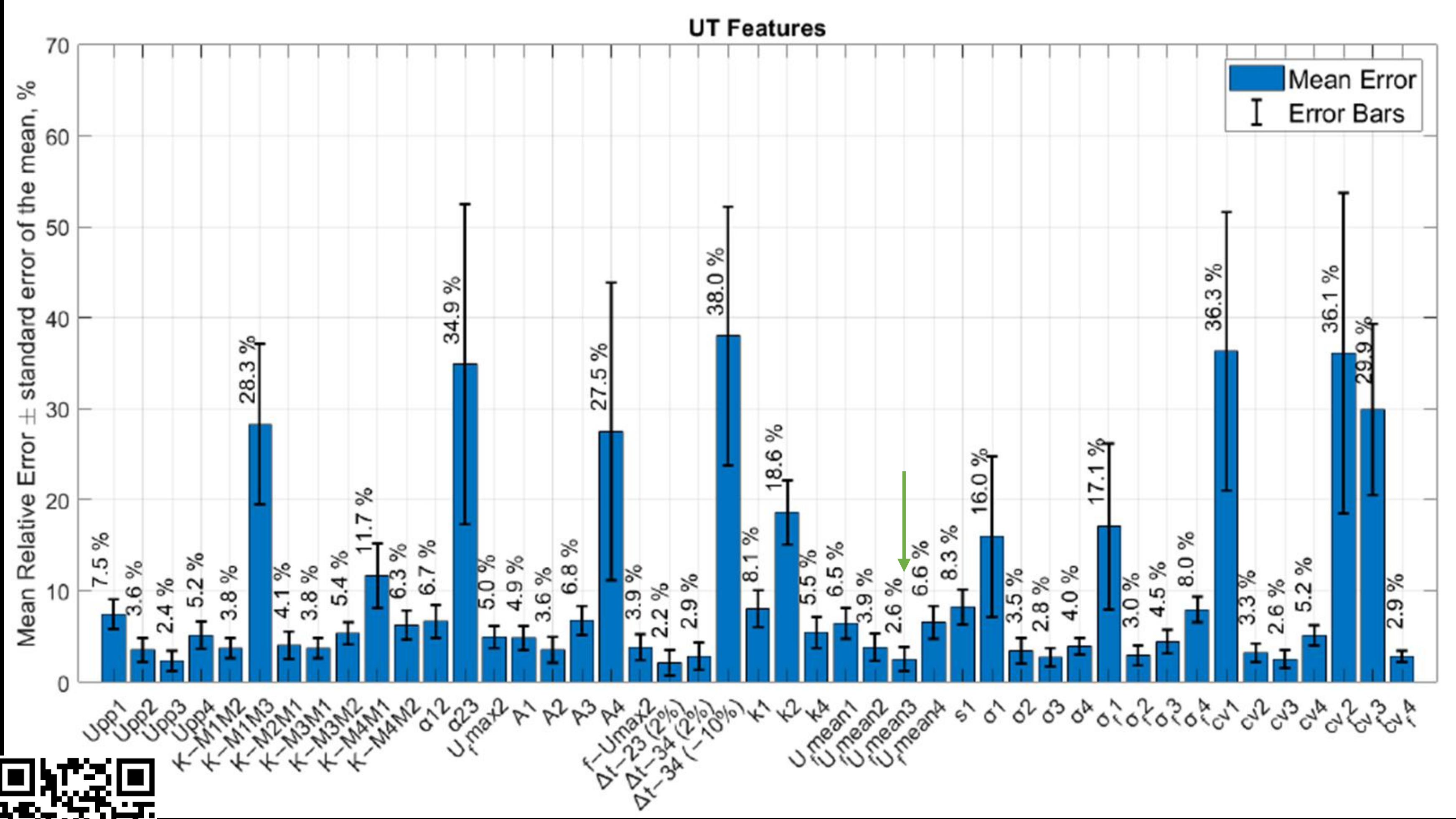

Ultrasonic features that showed highest performance:

- absolute time of flight Δt,
- standard deviation value in time and frequency domains σ and σ_f,
- variation coefficients in the time and frequency domain cv and cv_f.

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RT – Feature extraction

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Symbol	Features	Equations
X1	Amplitude	$X1(x,y) = max\ X-ray(x,y,z)$
X2	Features from Accelerated Segment Test (FAST)	$S_p \rightarrow x = \begin{cases} darker, & if\ I_p \leq (I_p - t) \\ similar, & if\ (I_p - t) \leq I_p \leq (I_p + t) \\ brighter, & if\ I_p \geq (I_p + t) \end{cases}$ $S_p \rightarrow x$ – pixel intensity transformation, I_p – intensity of central pixel evaluated for corner detection,

Data fusion

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Ultrasonic vs Radiography

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Ultrasonic:

ADVANTAGES

- ✓ Sensitive to elastic properties and density
- ✓ Good at detecting planar defects, such as lack of bonding/delamination

DISADVANTAGES

- ➢ Challenges inspecting anisotropic, materials
- ➢ Orientation sensitivity
- ➢ Challenges inspecting weak bonds

Radiography

ADVANTAGES

- ✓ Sensitive to changes in density
- ✓ Good at detecting volumetric defects
- ✓ Good at detecting inclusions

DISADVANTAGES

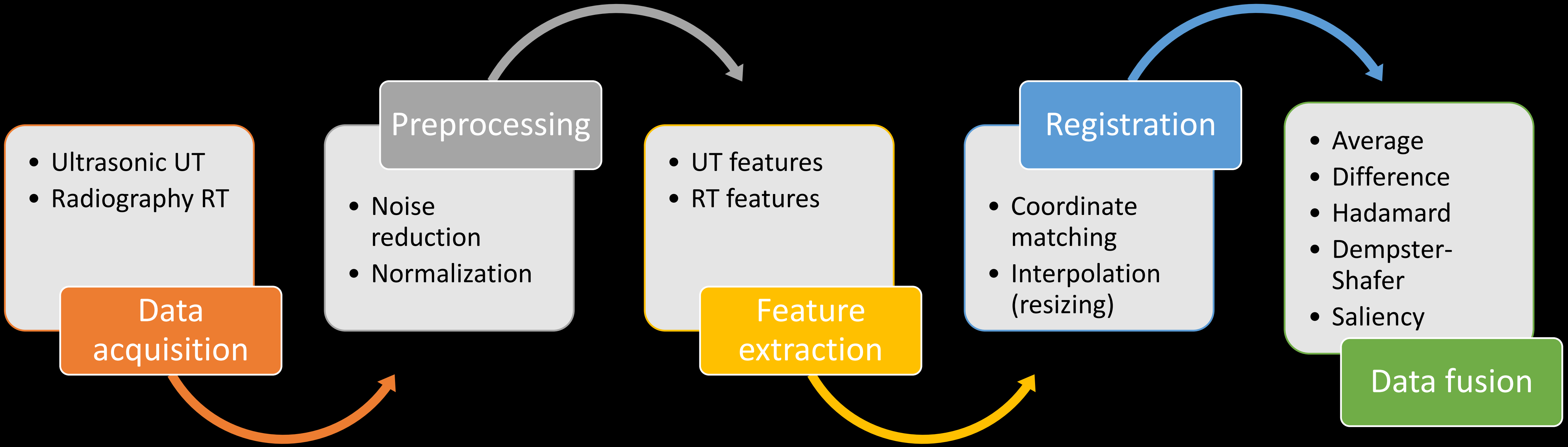
- ➢ Difficulties inspecting thin objects
- ➢ Limited performance on planar defects
- ➢ Orientation sensitivity
- ➢ Challenges inspecting weak bonds

Data fusion

Data fusion is the process of integrating and combining data from multiple sources to produce more comprehensive and accurate information.

- Improved accuracy
- Reduced uncertainty

Data fusion steps



Workflow of data fusion

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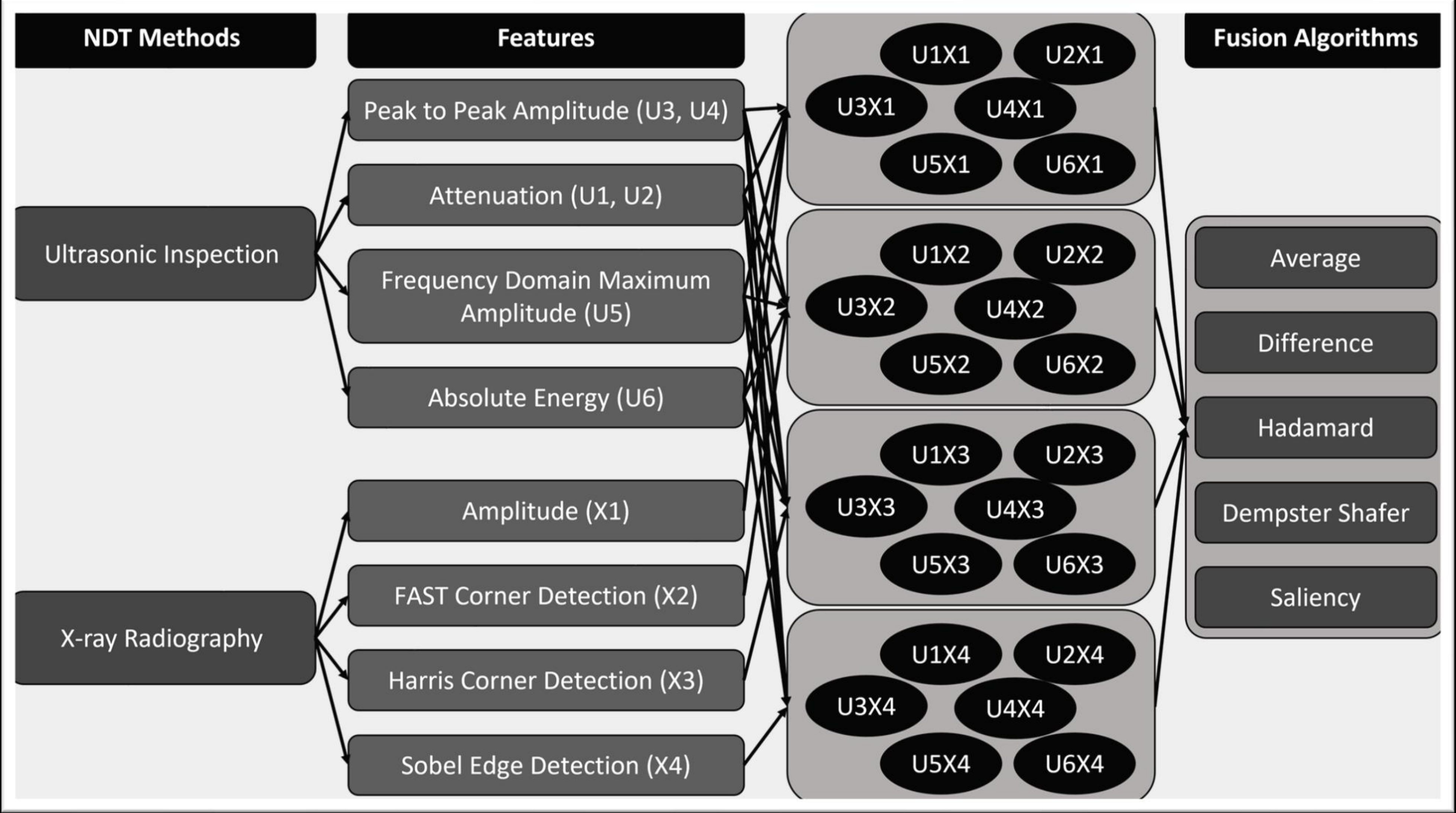

Data fusion

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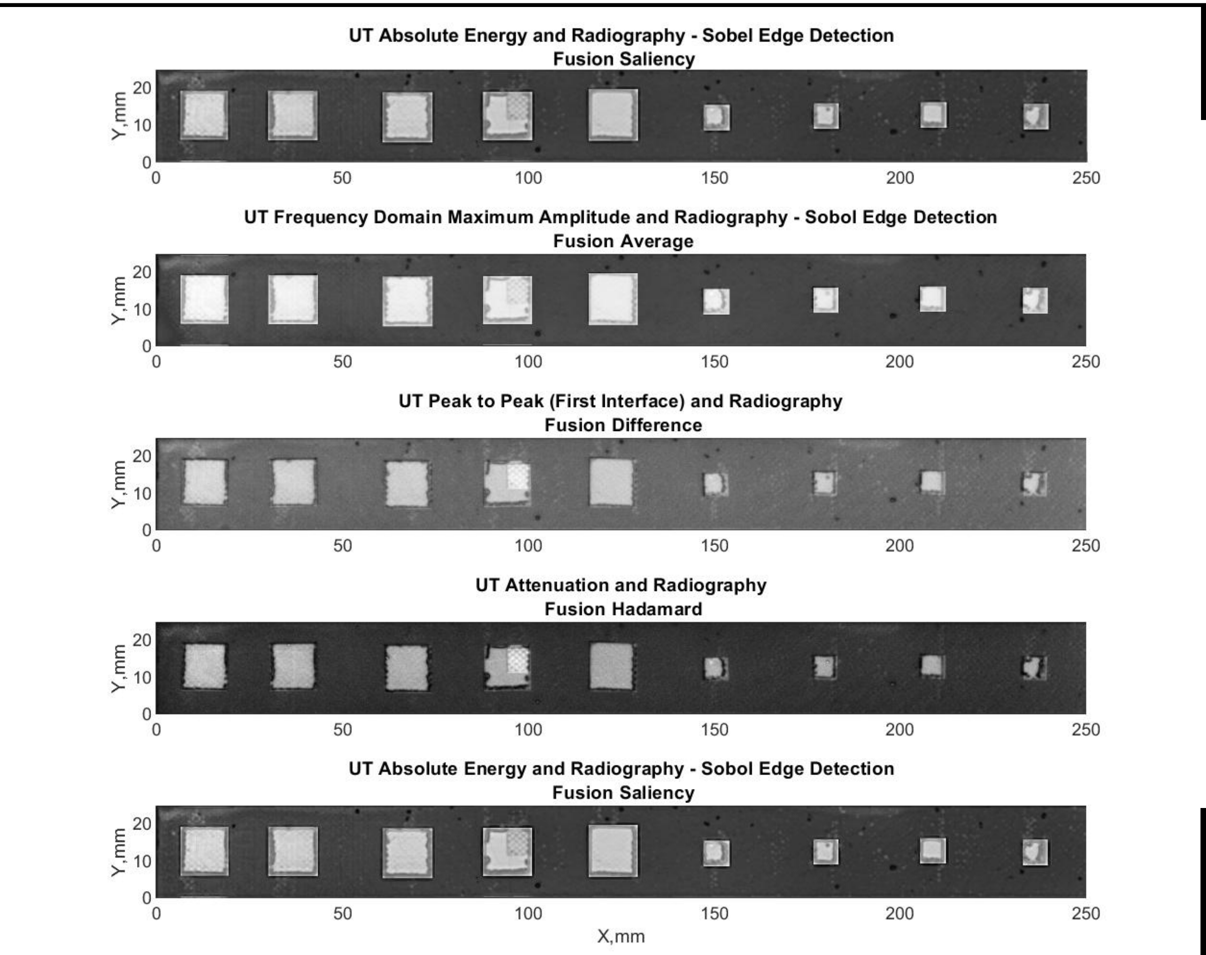

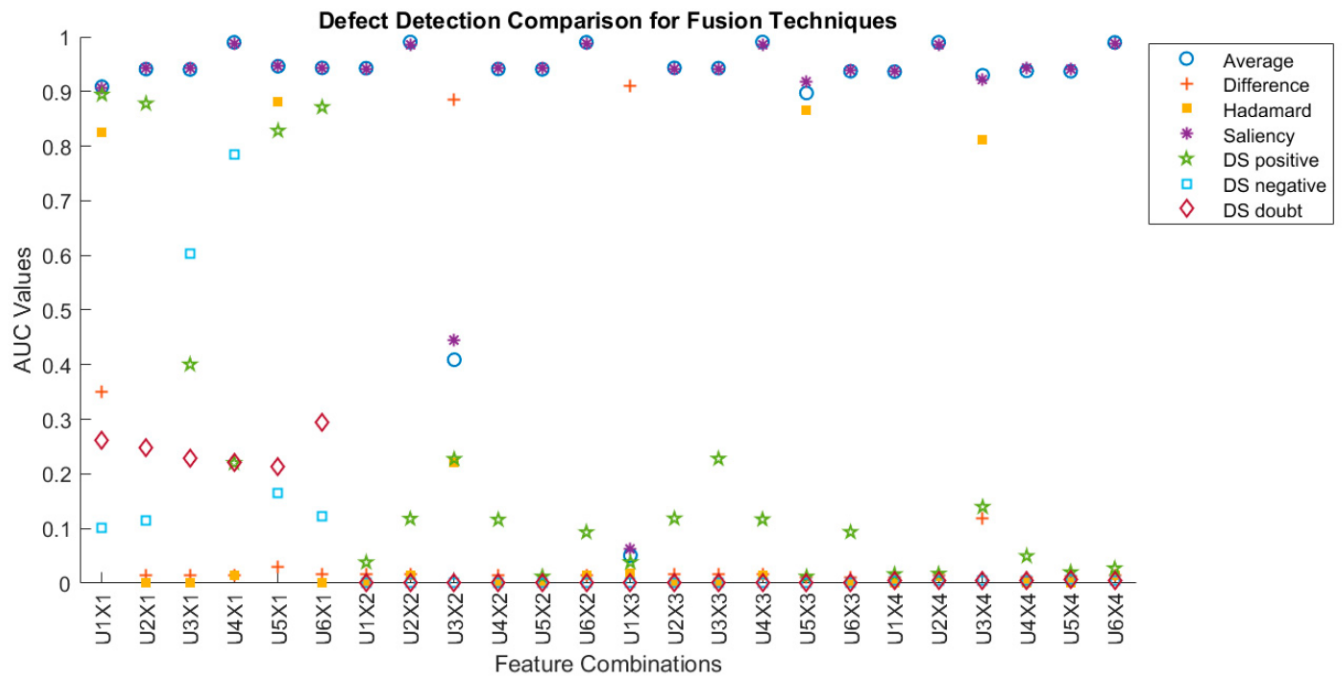

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Data fusion

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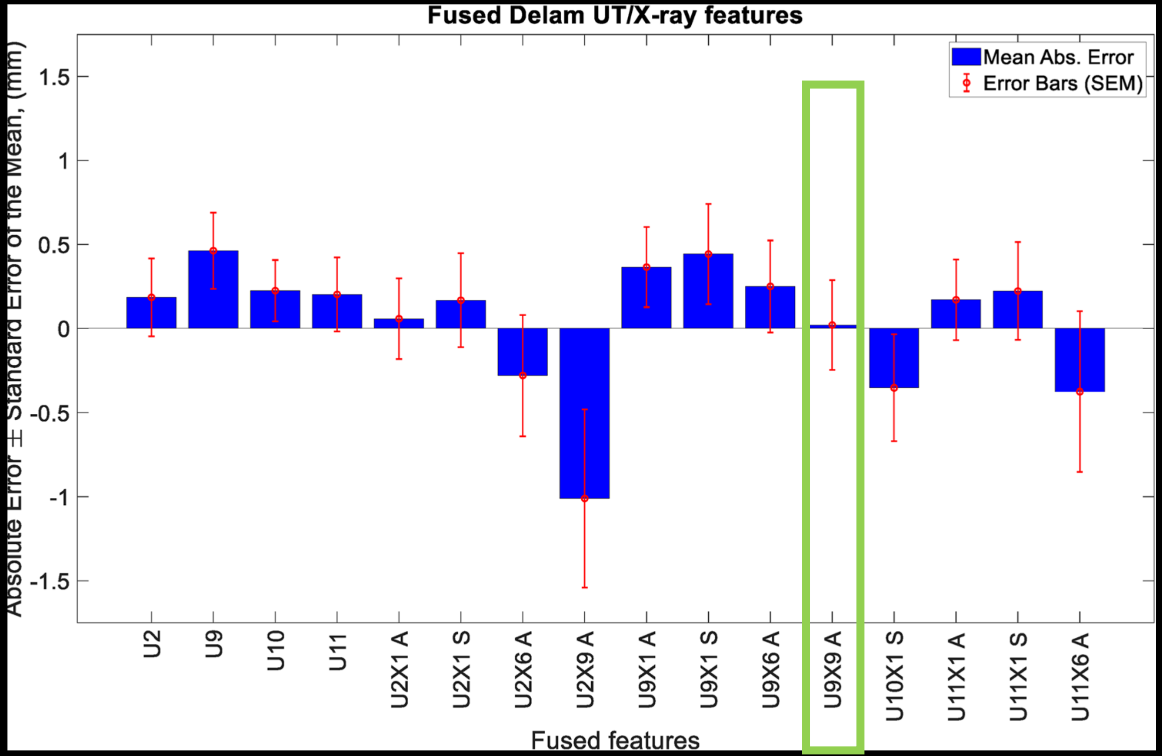

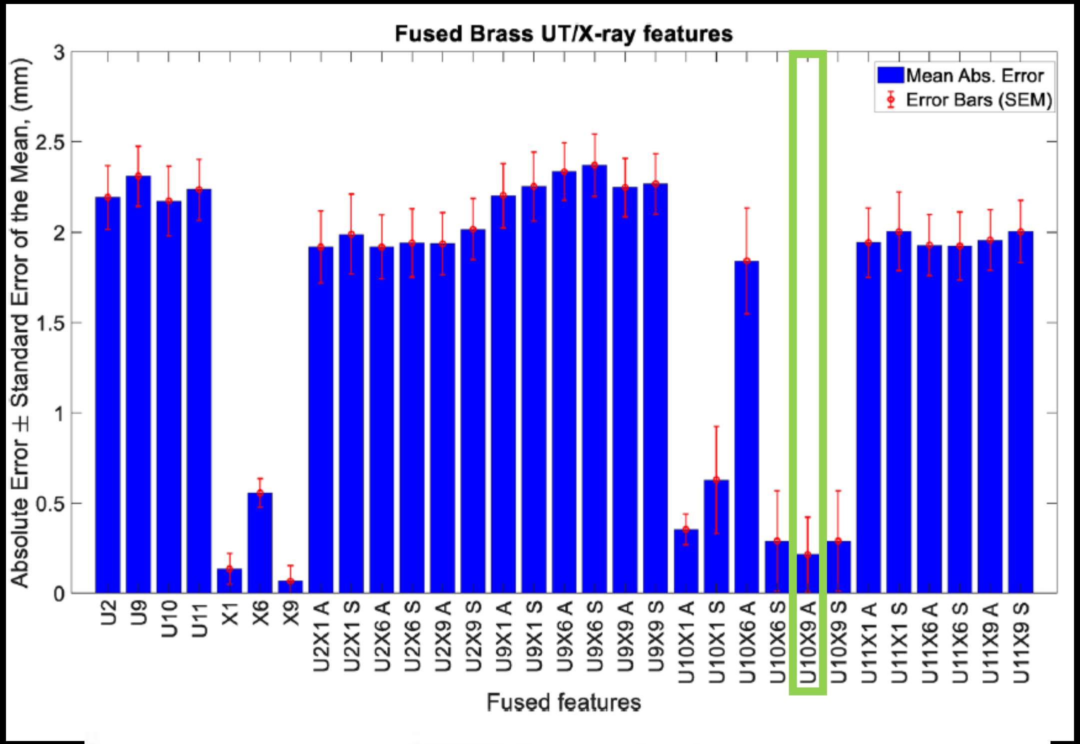

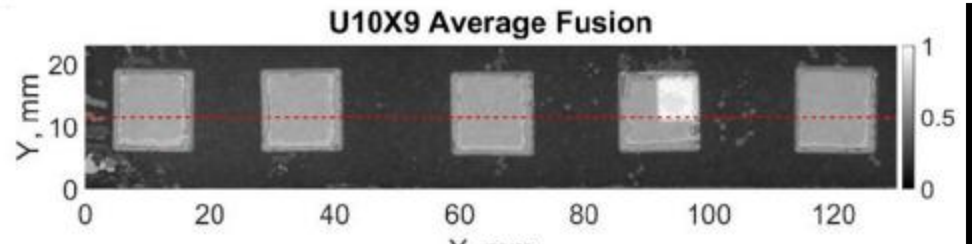

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Conclusions

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- Adhesive-bonded joints are highly advantageous for various aerospace applications;
- Reliable NDT techniques are required for the inspection of adhesive joints;
- Feature extraction enables to get more reliable results;
- Data fusion has the potential to improve the evaluation of adhesive bonds;

Acknowledgment

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Thank you for your attention

Do you have questions?

Would you like to collaborate?

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