DELAMINATION DETECTION IN A COMPOSITE PLATE USING A DUAL PIEZOELECTRIC TRANSDUCER NETWORK

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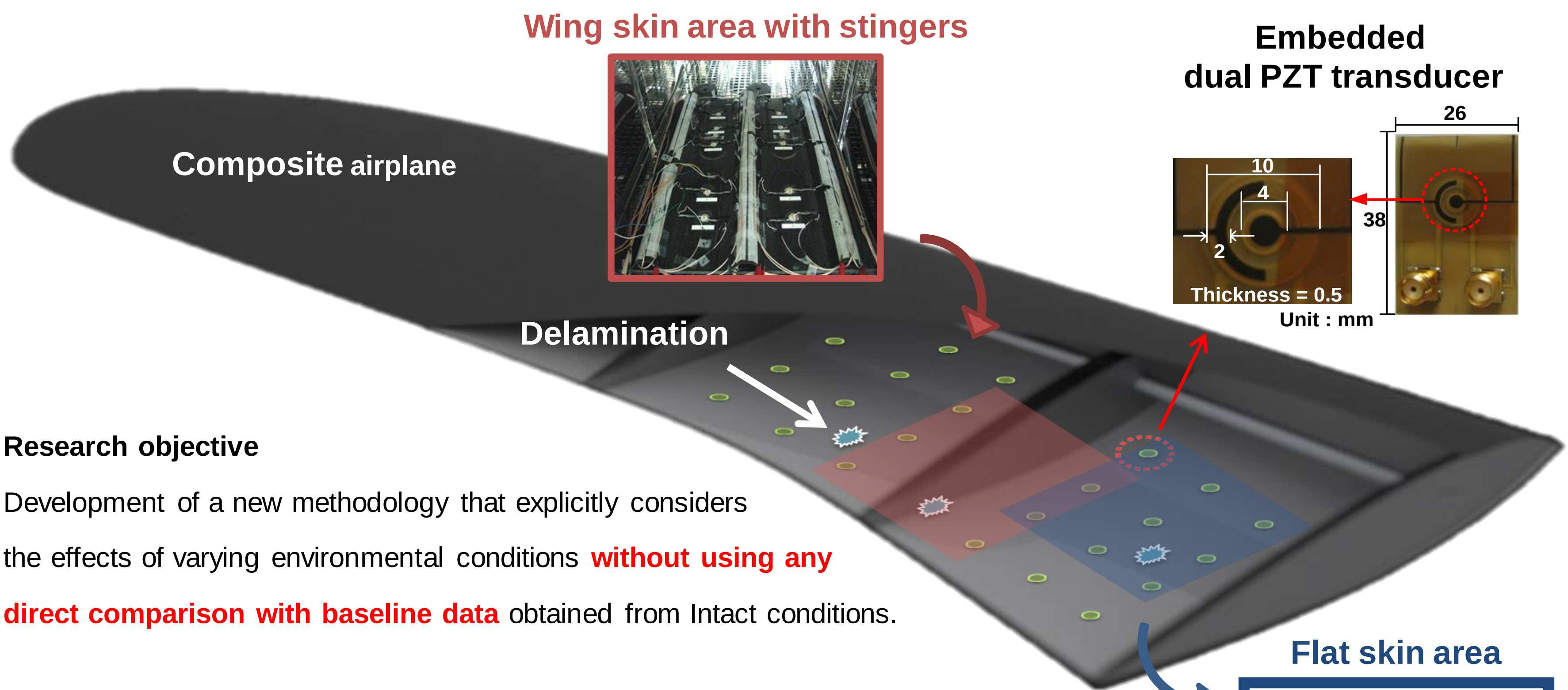


Research objective

Development of a new methodology that explicitly considers the effects of varying environmental conditions **without using any direct comparison with baseline data** obtained from Intact conditions.

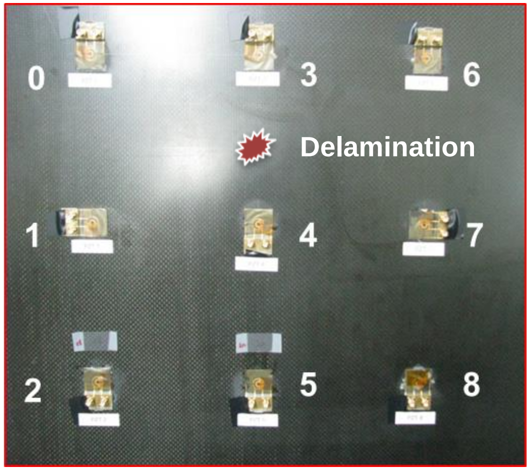
Uniqueness of the proposed technique

(1) Robust delamination diagnosis even under varying temperature using an automatically determined damage threshold

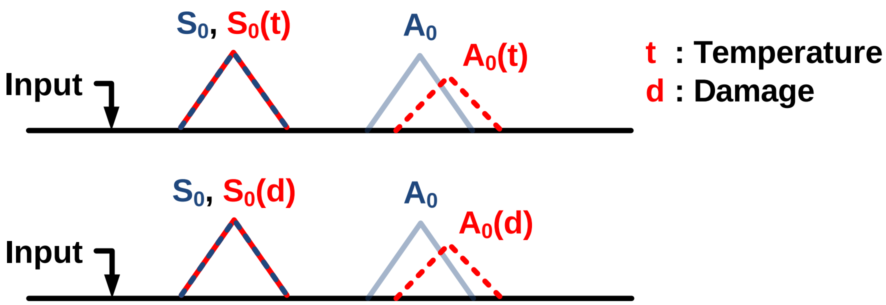
(2) Effective detection of multiple delaminations

(3) Application to complex geometric structures by applying the proposed mode extraction technique using dual PZTs

What Makes the Detection of Delamination Challenging?

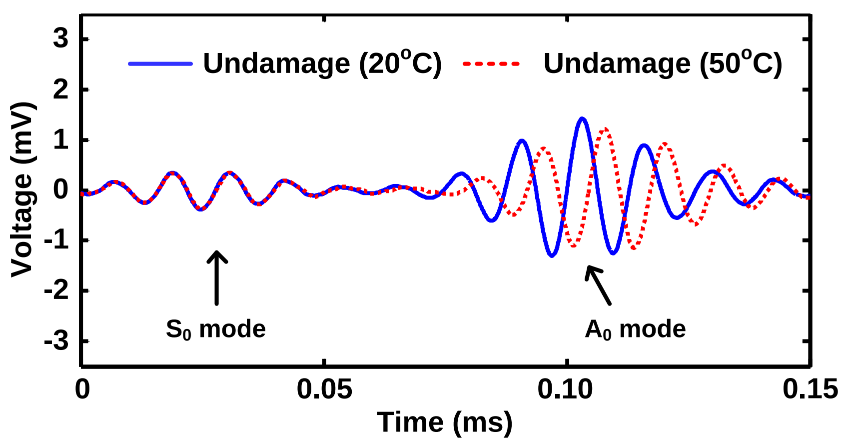


Composite specimen with PZT transducers

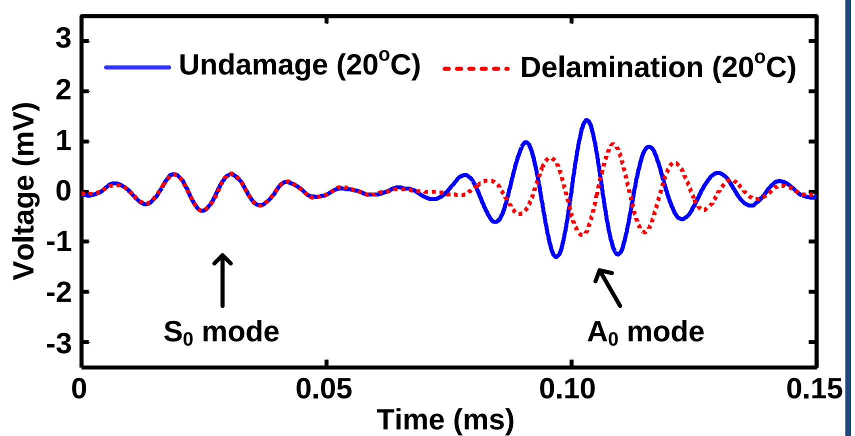


Delamination and temperature have **similar effects**

Temperature effect

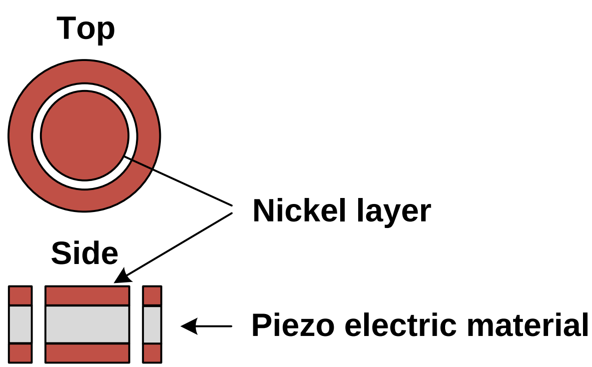


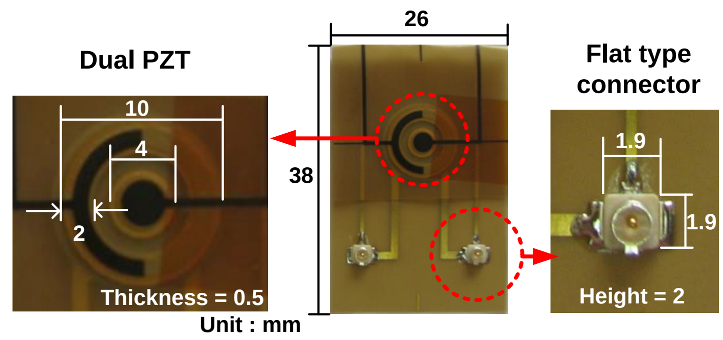
Delamination effect



Description of a Dual PZT and Signal Notations

Schematic drawing and picture of the dual PZT

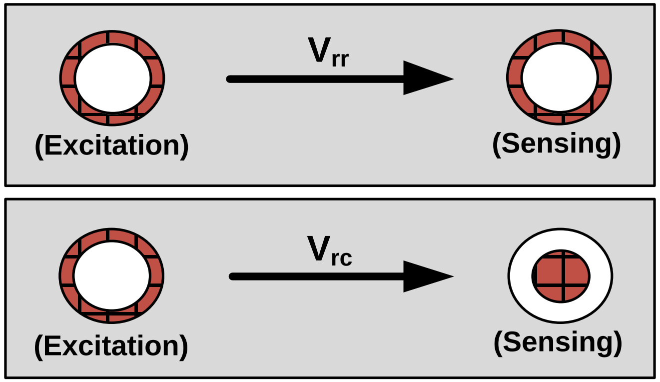




Notations of signals obtained from the dual PZTs

$$V_{ij},\ i\ and\ j = r\ and\ c$$

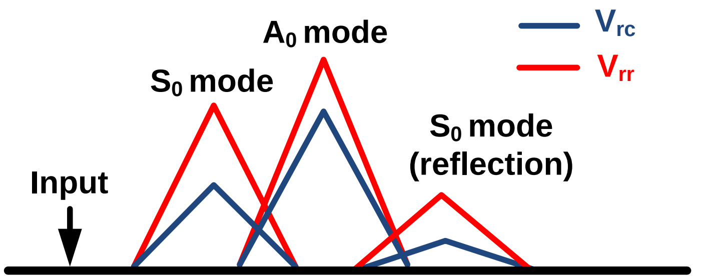
V_{rr} denotes a response measured by the ring part of the sensing PZT when the ring part of the exciting PZT is activated. Similarly, V_{rc} is measured by the circular part of the sensing PZT when the ring part of the excitation PZT is actuated.

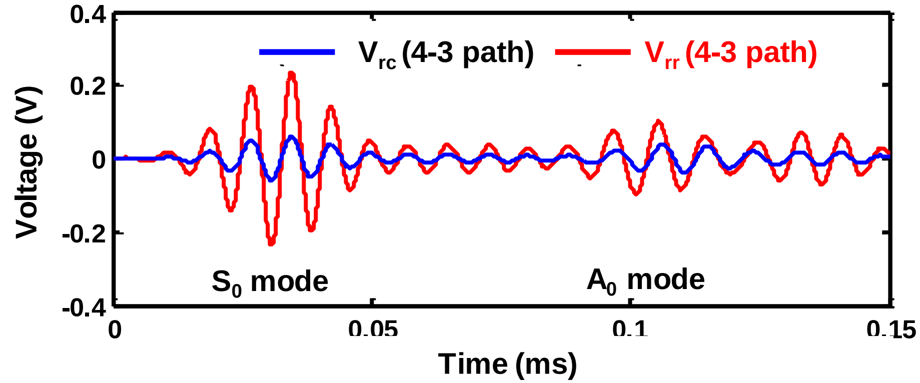


Signals obtained from dual PZTs

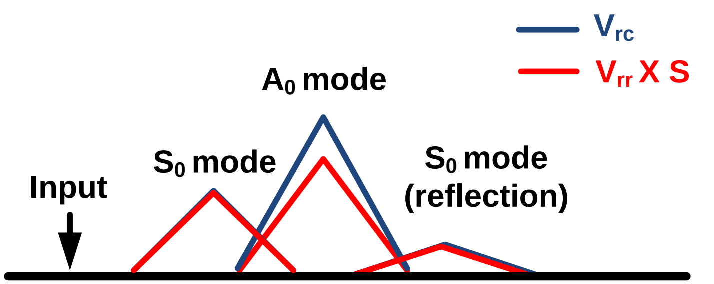
Extraction of the A_0 Mode from a Measured Signal

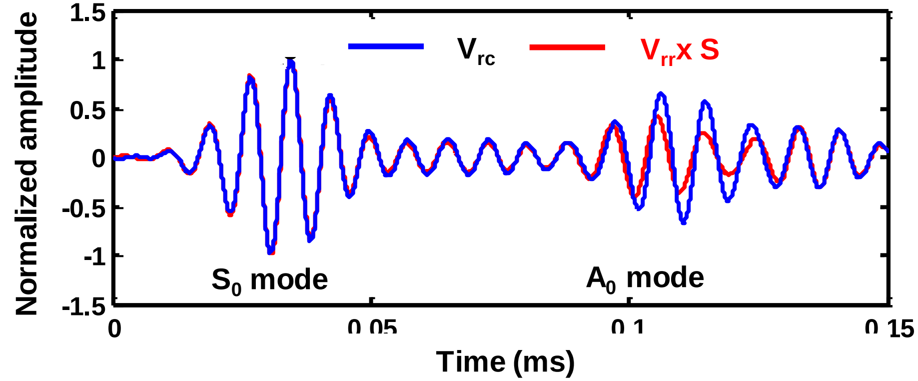
1) Signals measured different sensing size



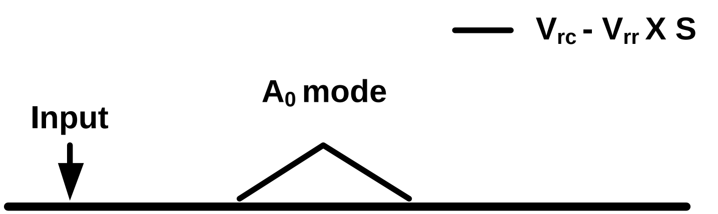


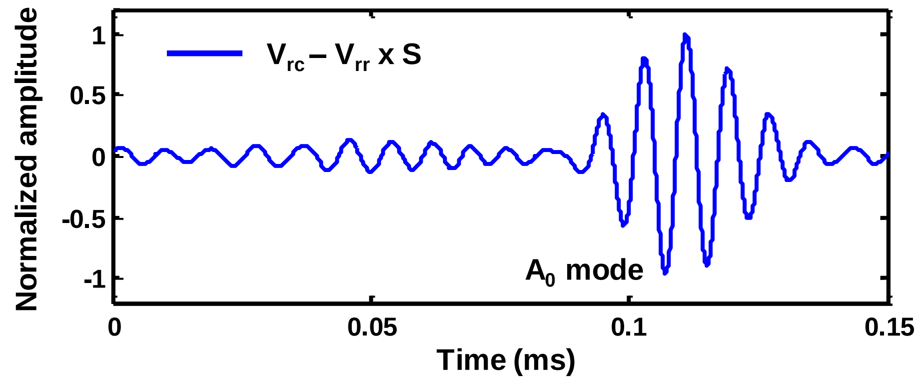
2) Matching of the amplitude of the S_0 mode





3) Extraction of the A_0 mode

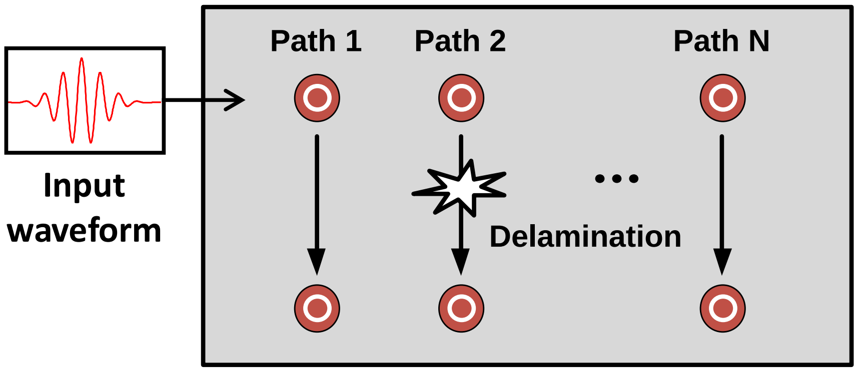




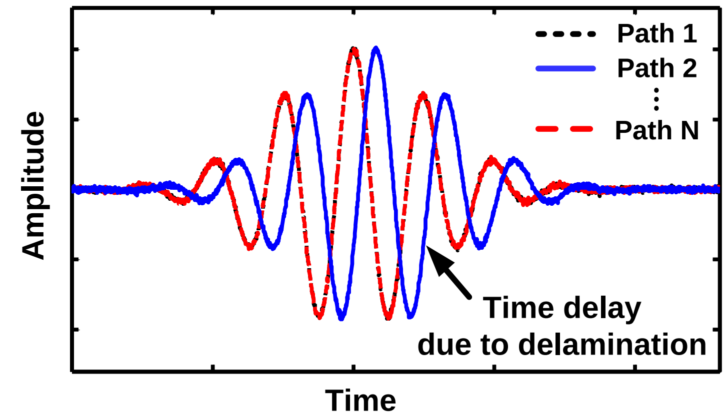
Chul min Yeum, Hoon Sohn, Jeong Beom Ihn, "Lamb wave mode decomposition using concentric ring and circular PZT Transducers," *Wave motion*, 2011

Overall Procedure of the Instantaneous Delamination Detection Technique

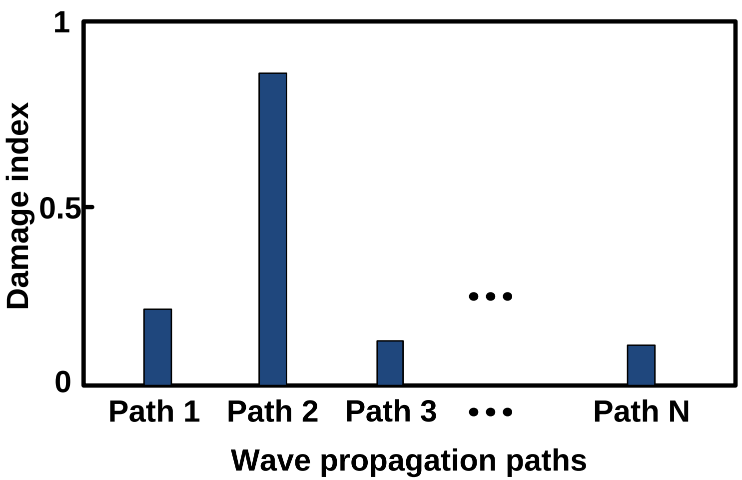
(1) Data collection from multiple paths



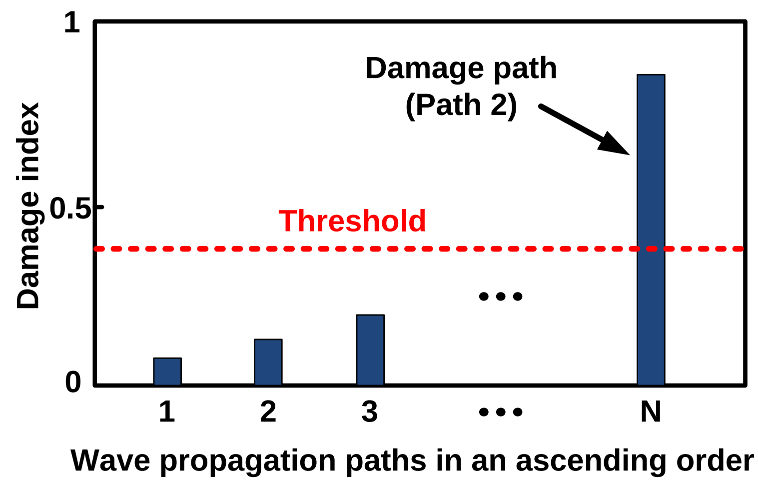
(2) Extraction of the A_0 modes from all paths



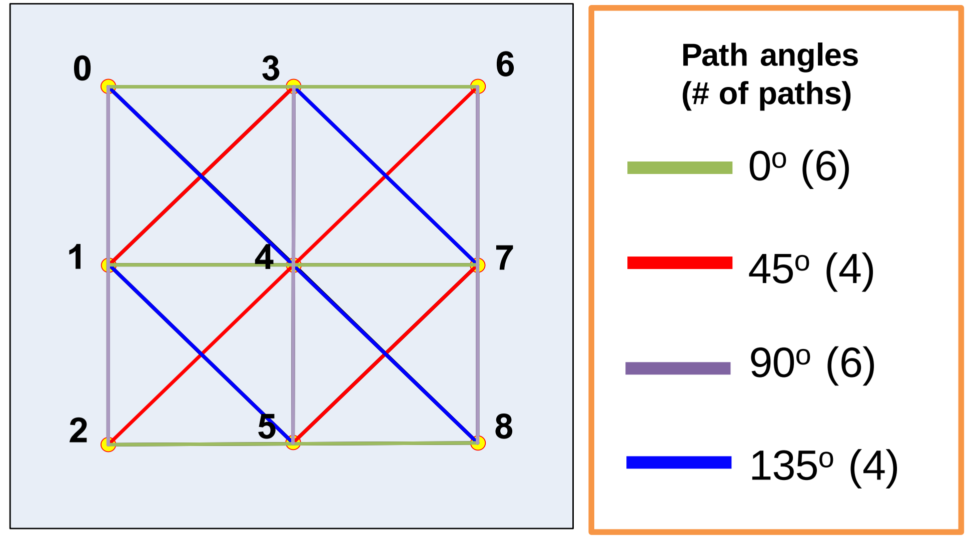
(3) Calculation of damage indexes



(4) Damage classification using outlier analysis



Correlation-based Damage Index



$$DI(i,\Omega) = \frac{1}{2}\left(1 - \frac{2}{n_d}\sum_{j}^{n_d/2} corr\left(A_0(i,\Omega), A_0(j,\Omega)\right)\right)$$

$$DI(i) = \frac{1}{N}\sum_{\Omega}^{N} DI(i,\Omega)$$

Ω is the driving frequency.

$A_0(i, \Omega)$ or $A_0(j, \Omega)$ is the A_0 mode obtained from the paths *i and* j ($1 \leq i, j \leq 20$)

The path *'j'* is selected as the undamaged paths having same angle and spacing with the path i.

'Corr ' is the cross correlation.

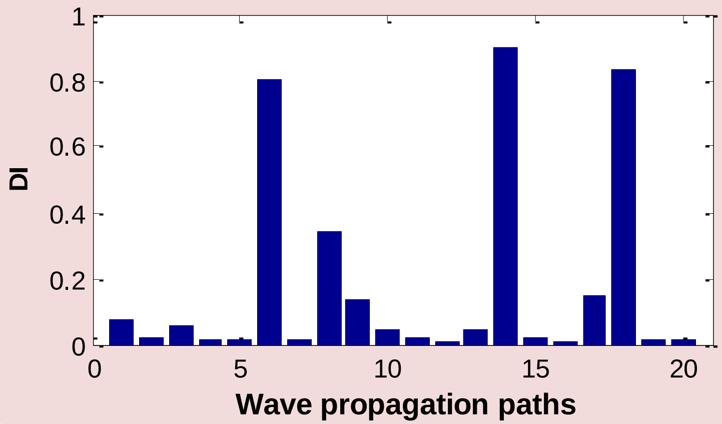
d is the angle of the path i. (*d* = 0º, 45º, 90º, and 135º)

$$0 \leq DI(i,\Omega) \leq 1$$

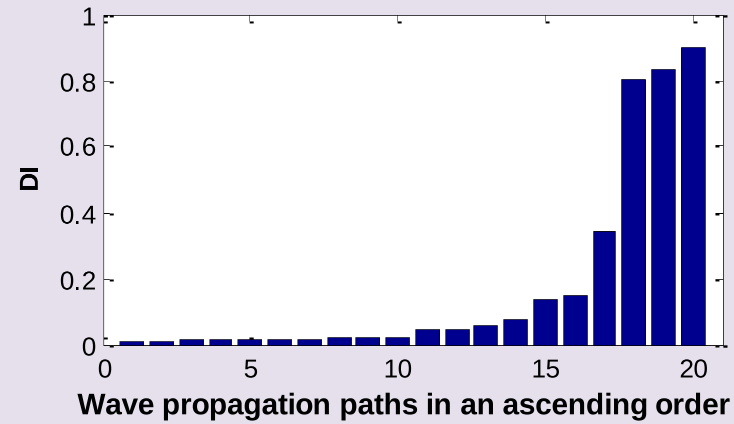
n_d is the number of paths of the *d* angle.

Instantaneous Outlier Analysis

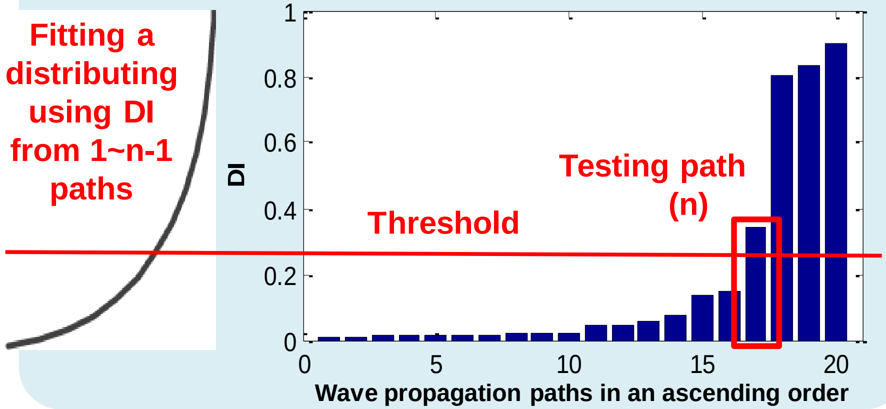
(1) Calculation of damage indexes using A_0 mode in all paths



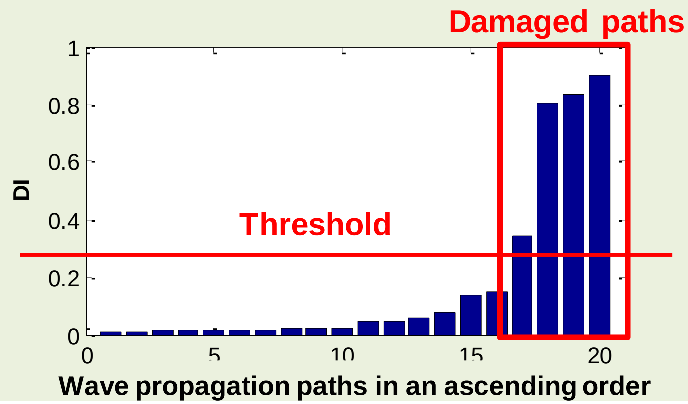
(2) Arrange all damage indexes in an ascending order



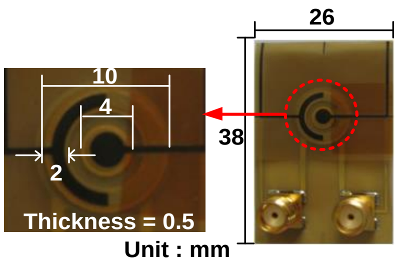
(3) Fit a parametric distribution to the n-1 smallest damage indices and compute a threshold value



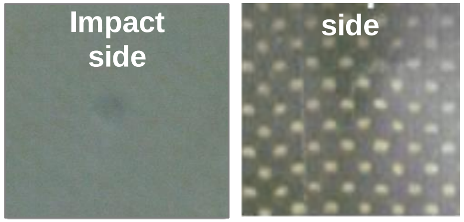
(4) If value of the n^{th} smallest damage index is larger than the threshold value, n^{th}, $n+1^{th}$ ~ N^{th} damage indices are determined to be damaged.



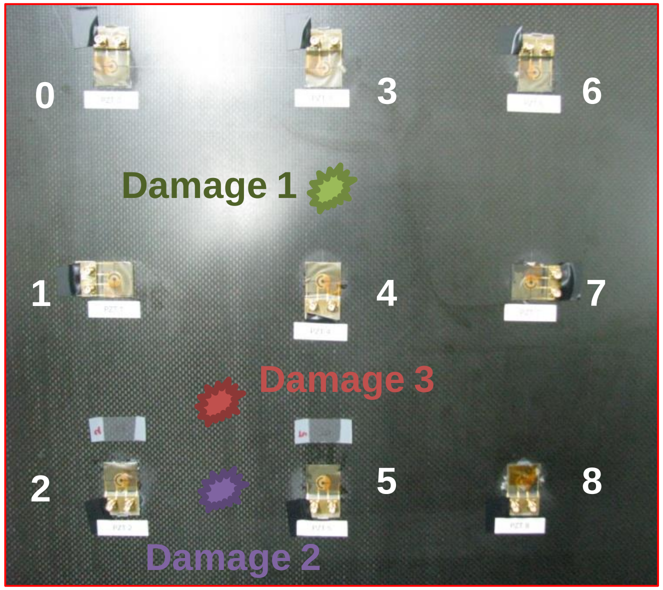
Impact-induced Delamination Damage on a Composite Specimen

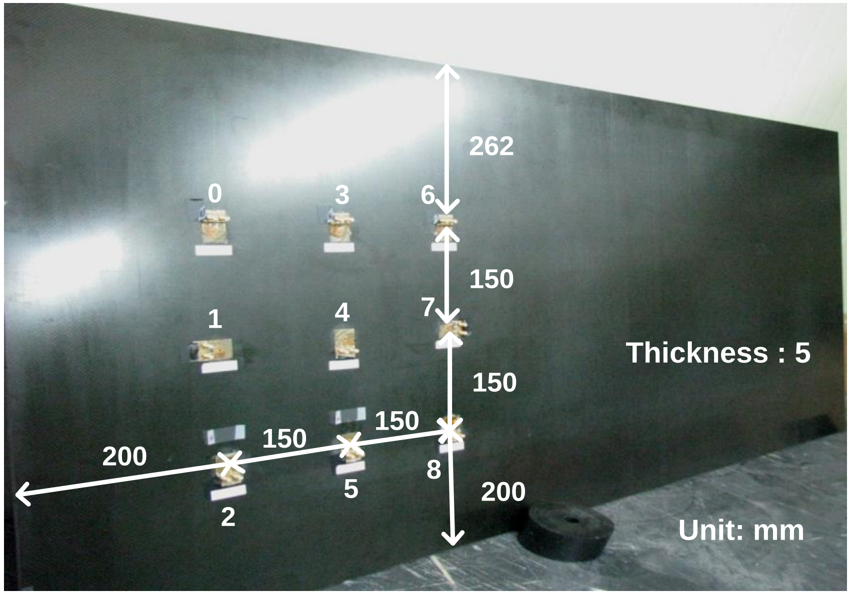


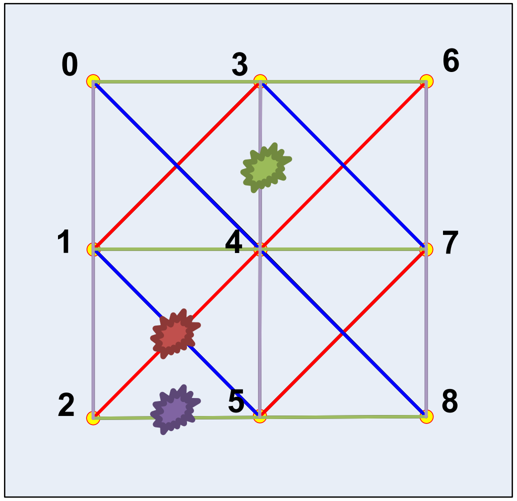
Dual PZT



Impact damage



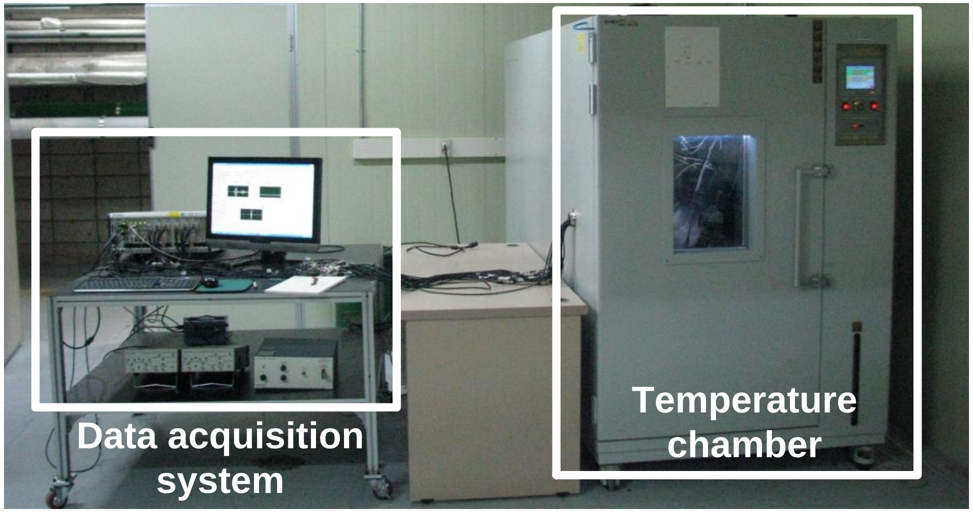


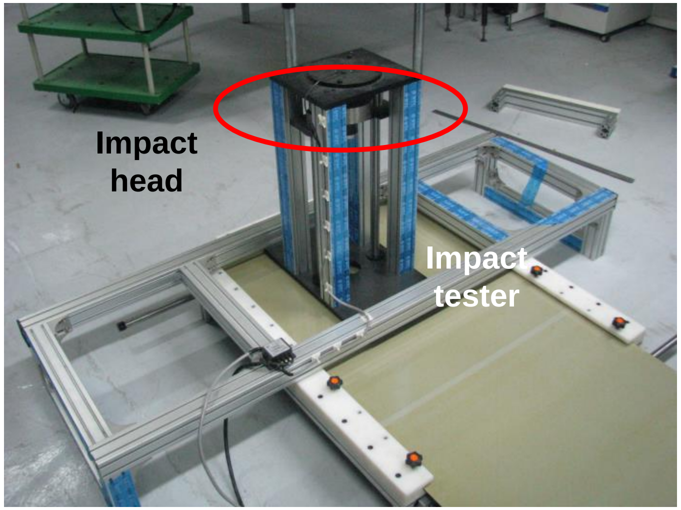


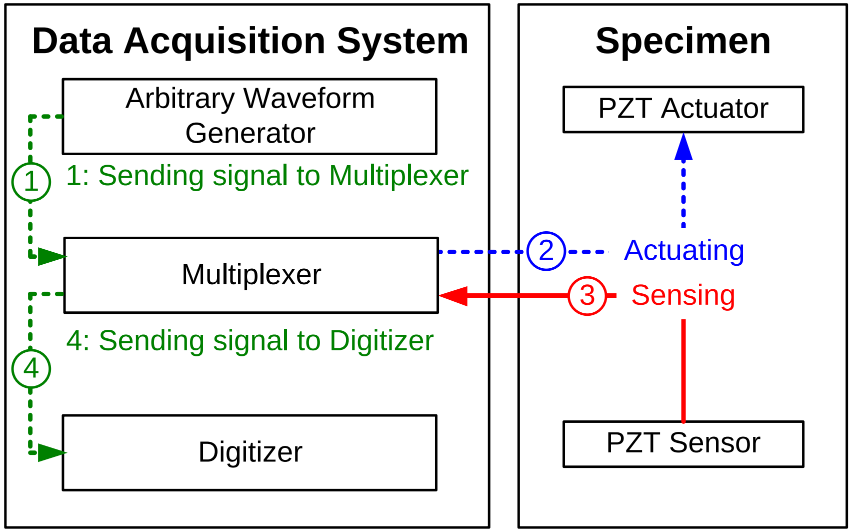
Path angles (# of paths)

- 0^{o} (6)
- 45^{o} (4)
- 90^{o} (6)
- 135^{o} (4)

Experimental Setup for Impact and Temperature Tests

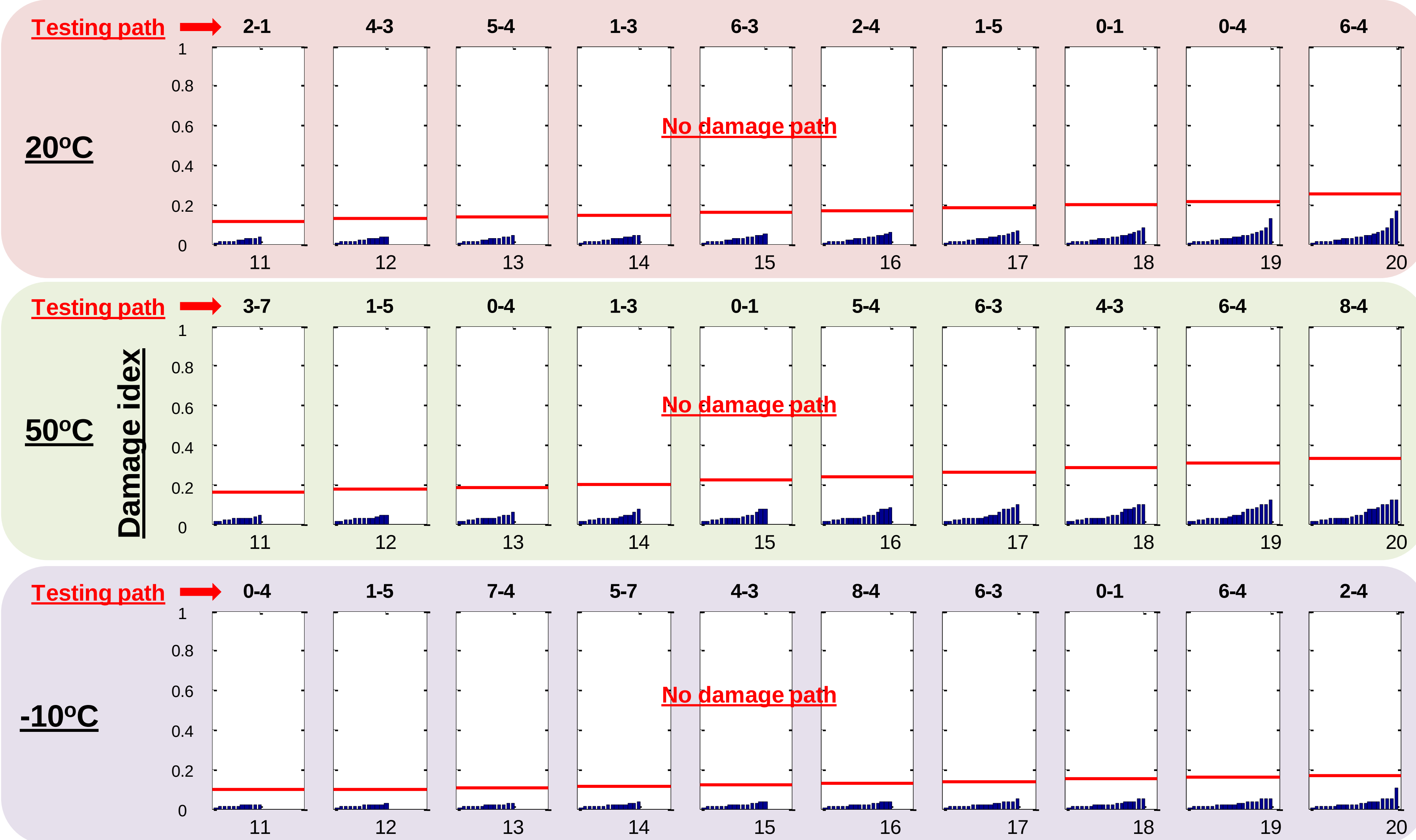






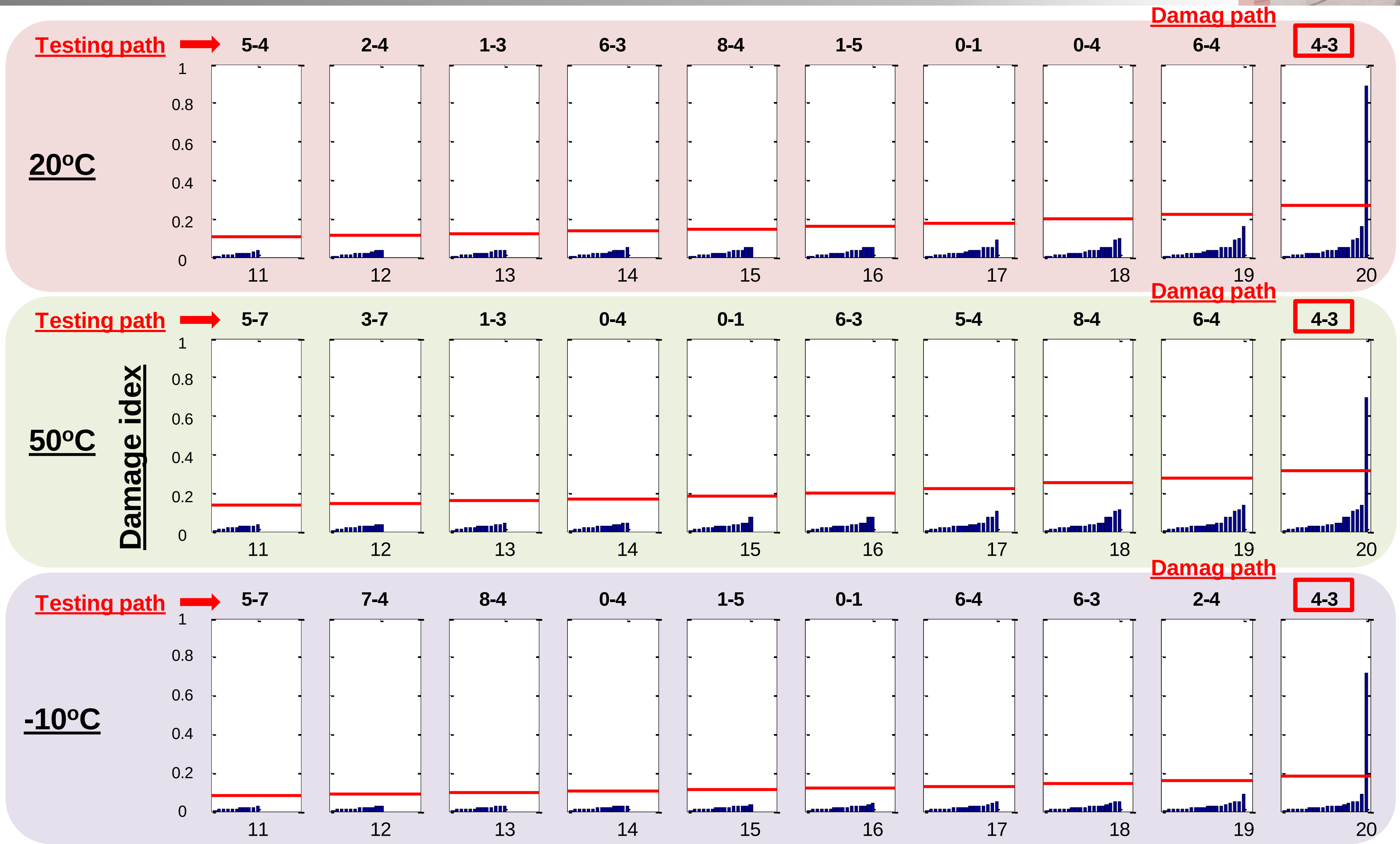
- The dimension of each PZT :
  - * 9 packaged dual PZTs
  - * PSI-5A4E type
- Input signal :
  - A tone-burst signal with ± 10 peak-to-peak voltage
  - A frequency range 80 kHz to 120 kHz with an increment of 10 kHz
- Sampling rate : 20MS/s
- Power amplifier gain : 5
- Data averaging : 120 times
- Temperature : -10, 20, 50 °C

Instantaneous Outlier Analysis (Intact)



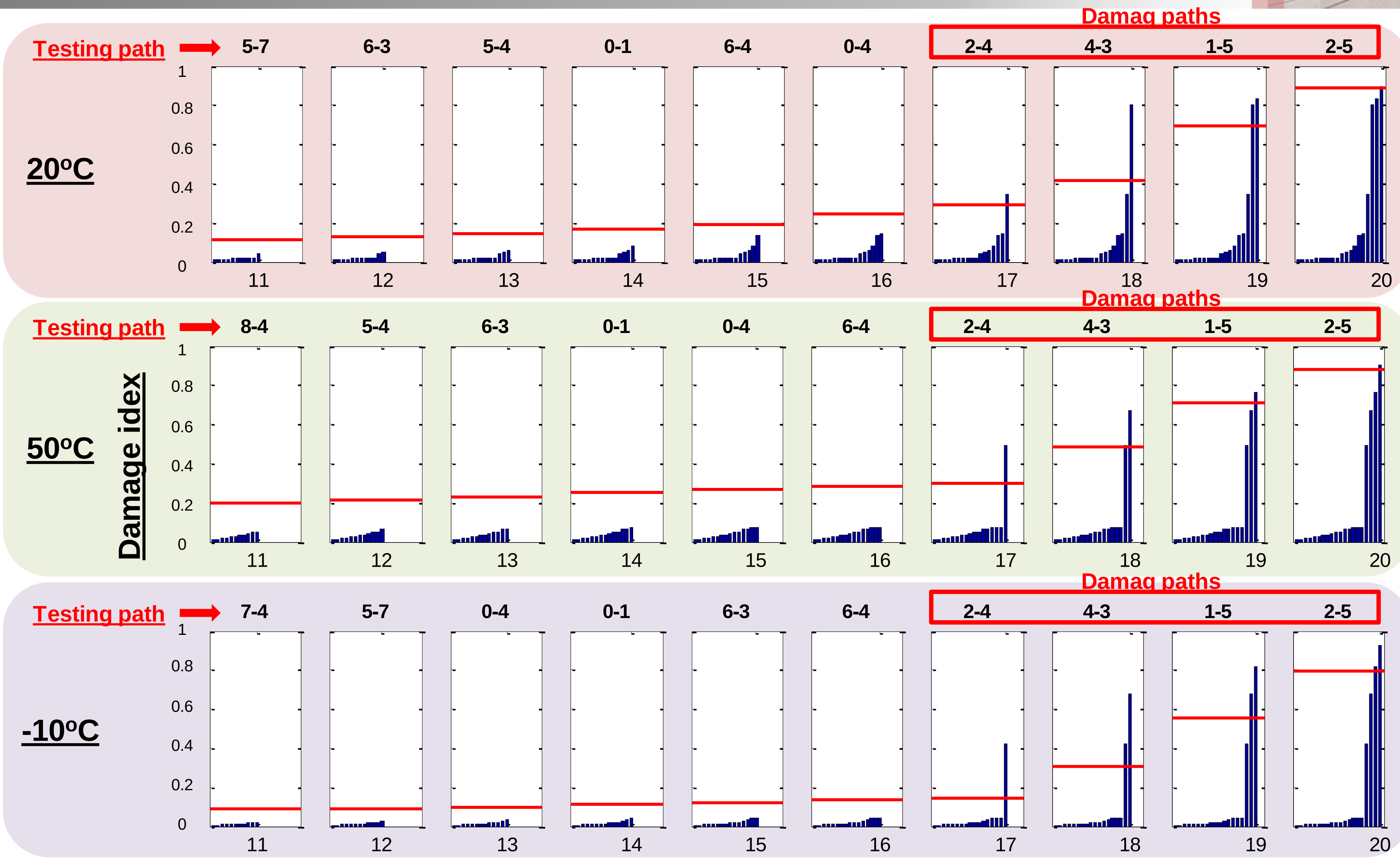
Wave propagation paths sorted in an ascending order

Instantaneous Outlier Analysis (Damage 1)



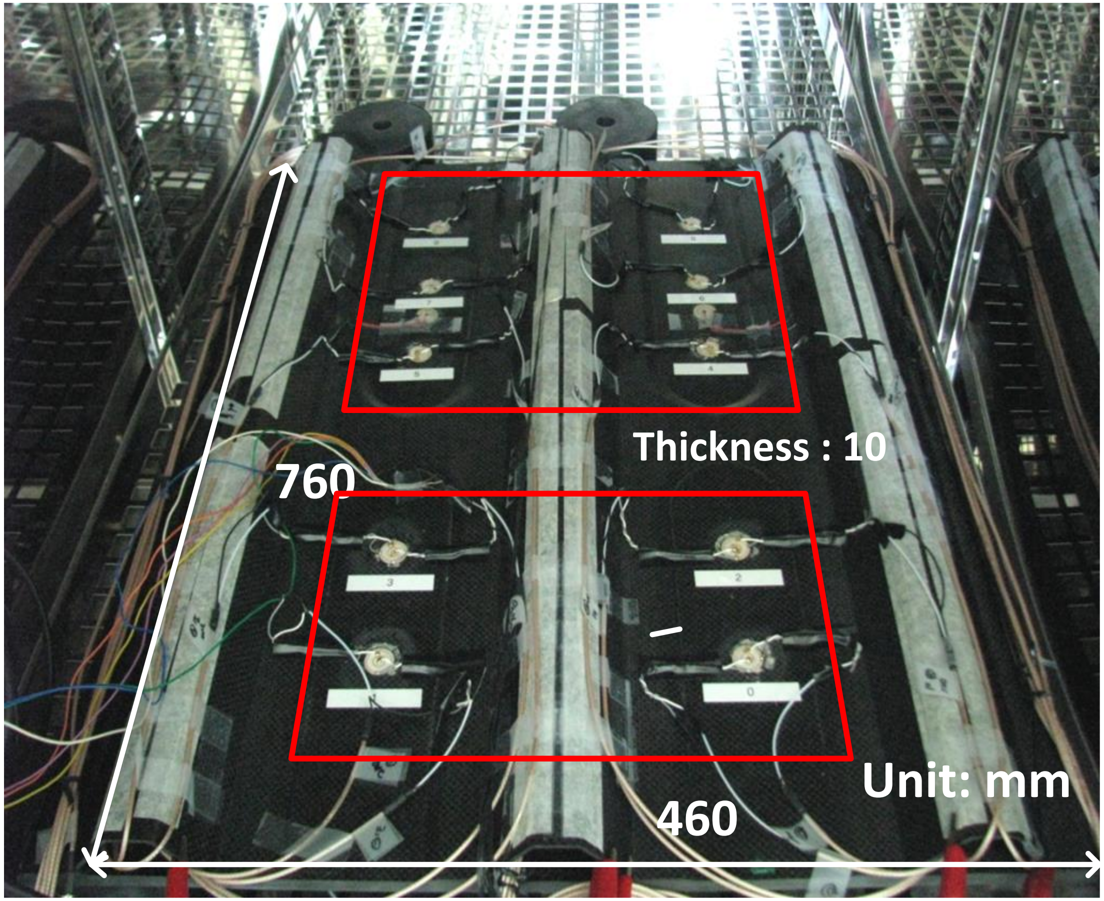
Wave propagation paths sorted in an ascending order

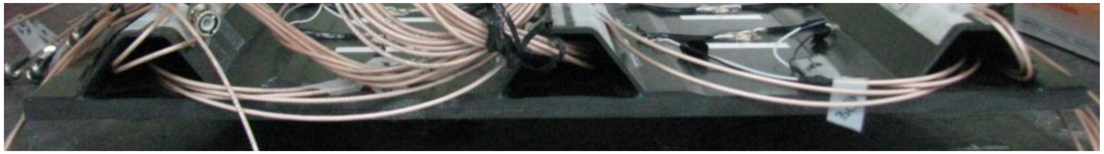
Instantaneous Outlier Analysis (Damages 1, 2 and 3)

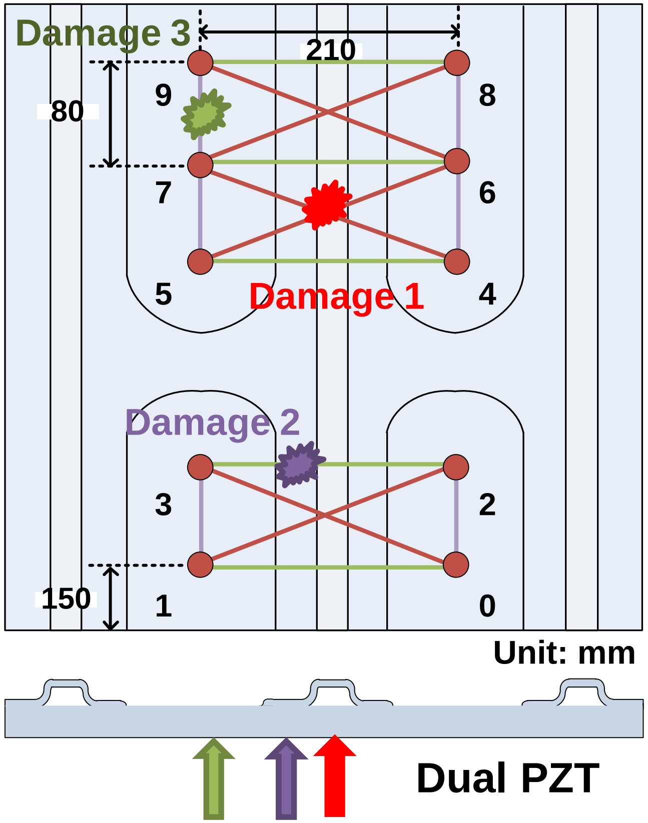


Wave propagation paths sorted in an ascending order

Impact-induced Delamination Damage



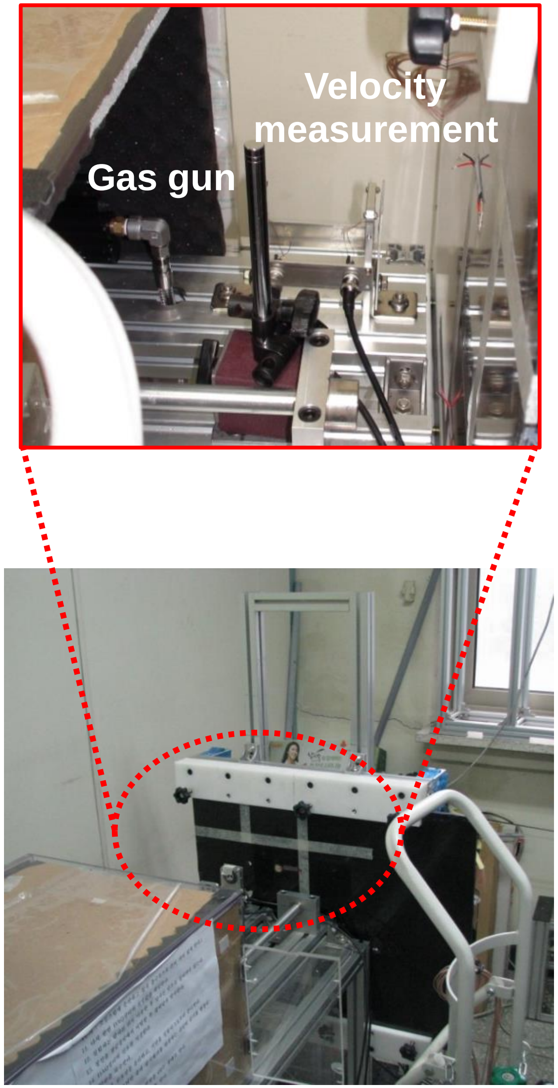


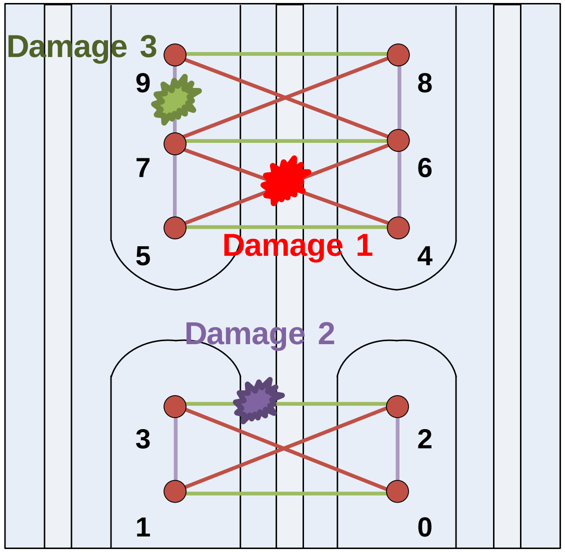


Path angles (# of paths)

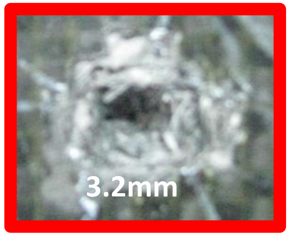
- 0º (5)
- 90º (6)
- ± 45º (6)

High Velocity Impact using a Gas Gun

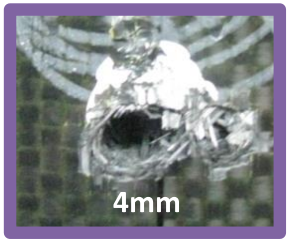




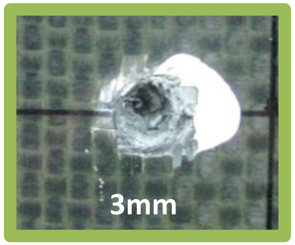
Impact energy (# of impact)



Damage 1
123J (10)

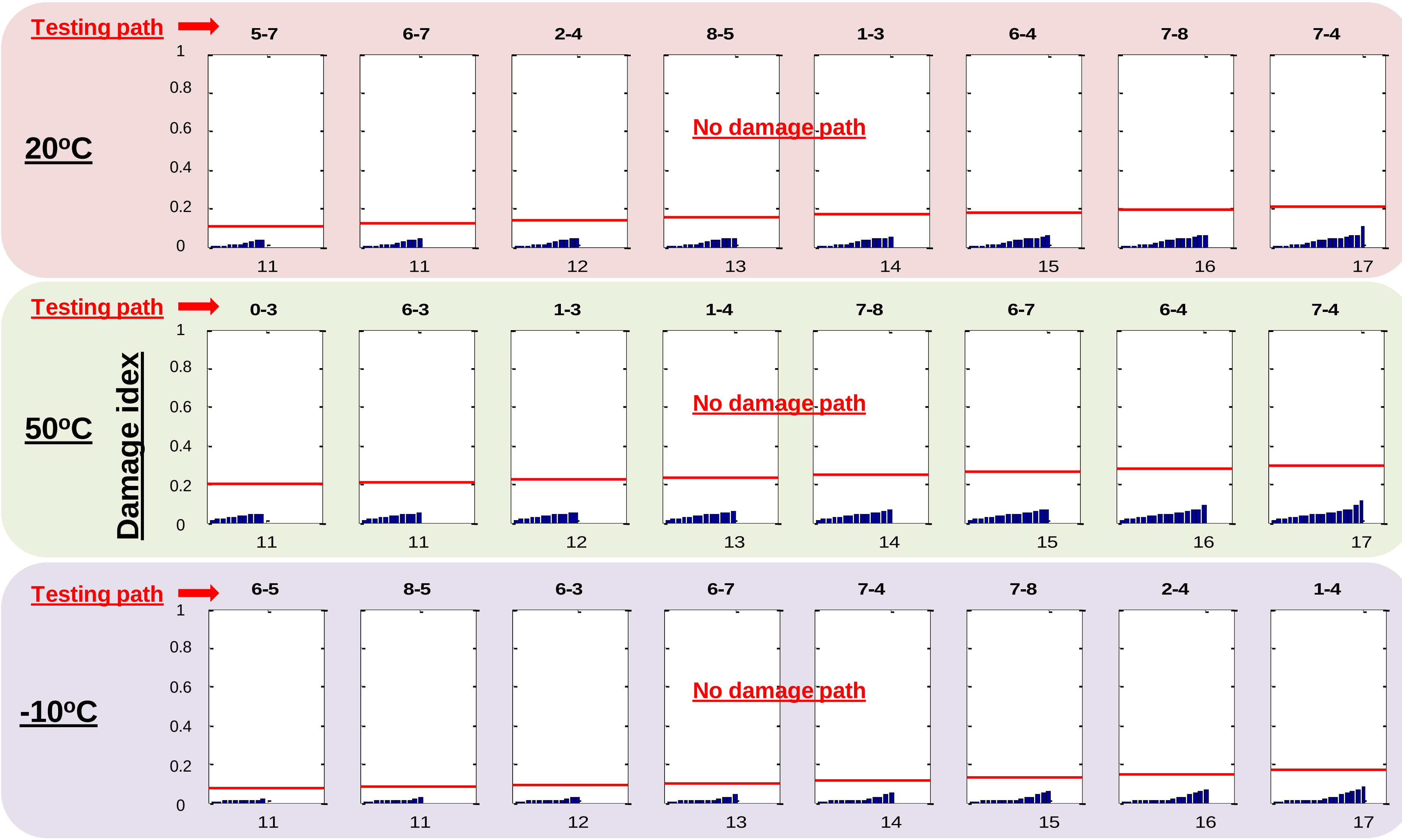


Damage 2
152J (10)



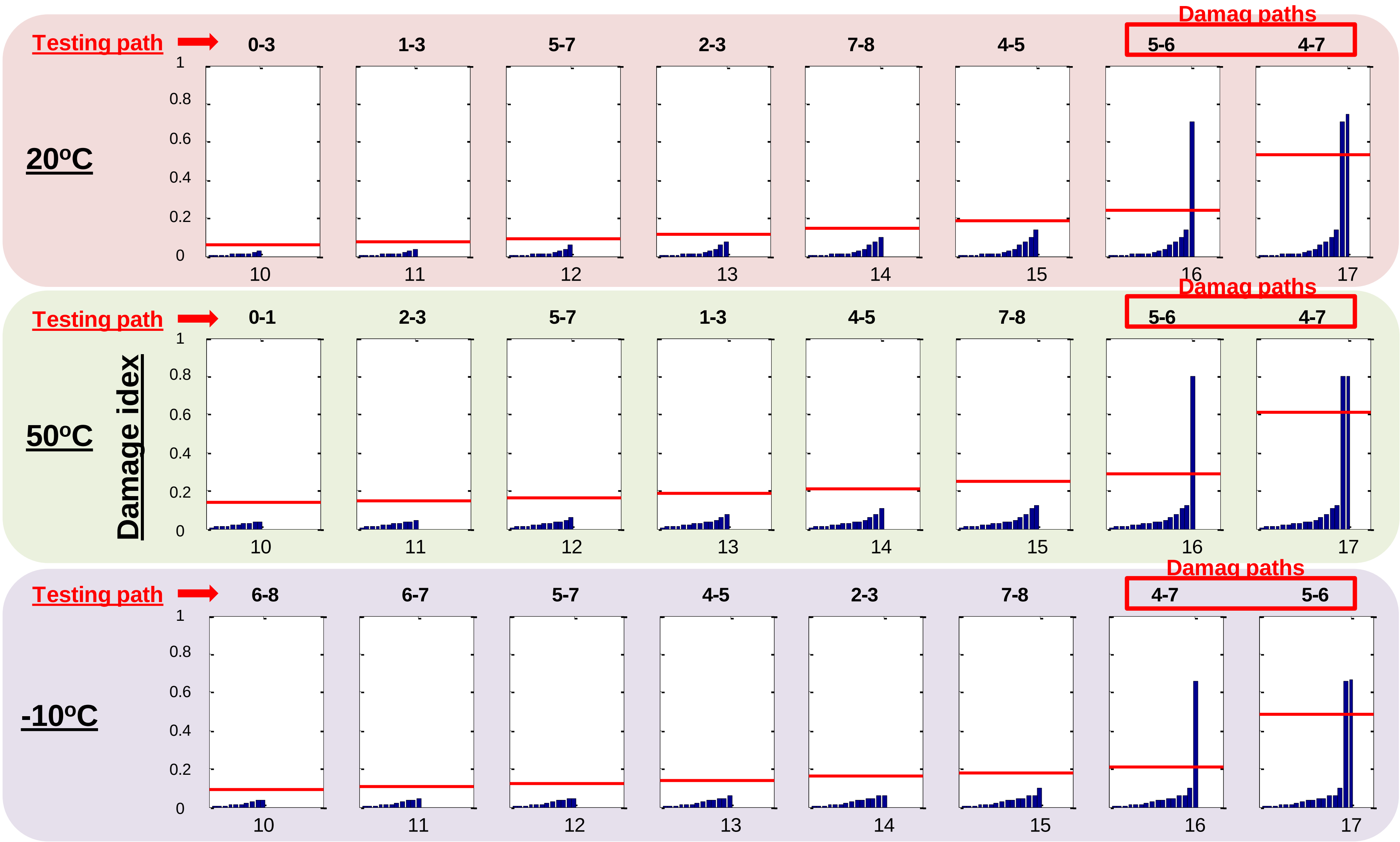
Damage 3
96J (6)

Instantaneous Outlier Analysis (Intact)



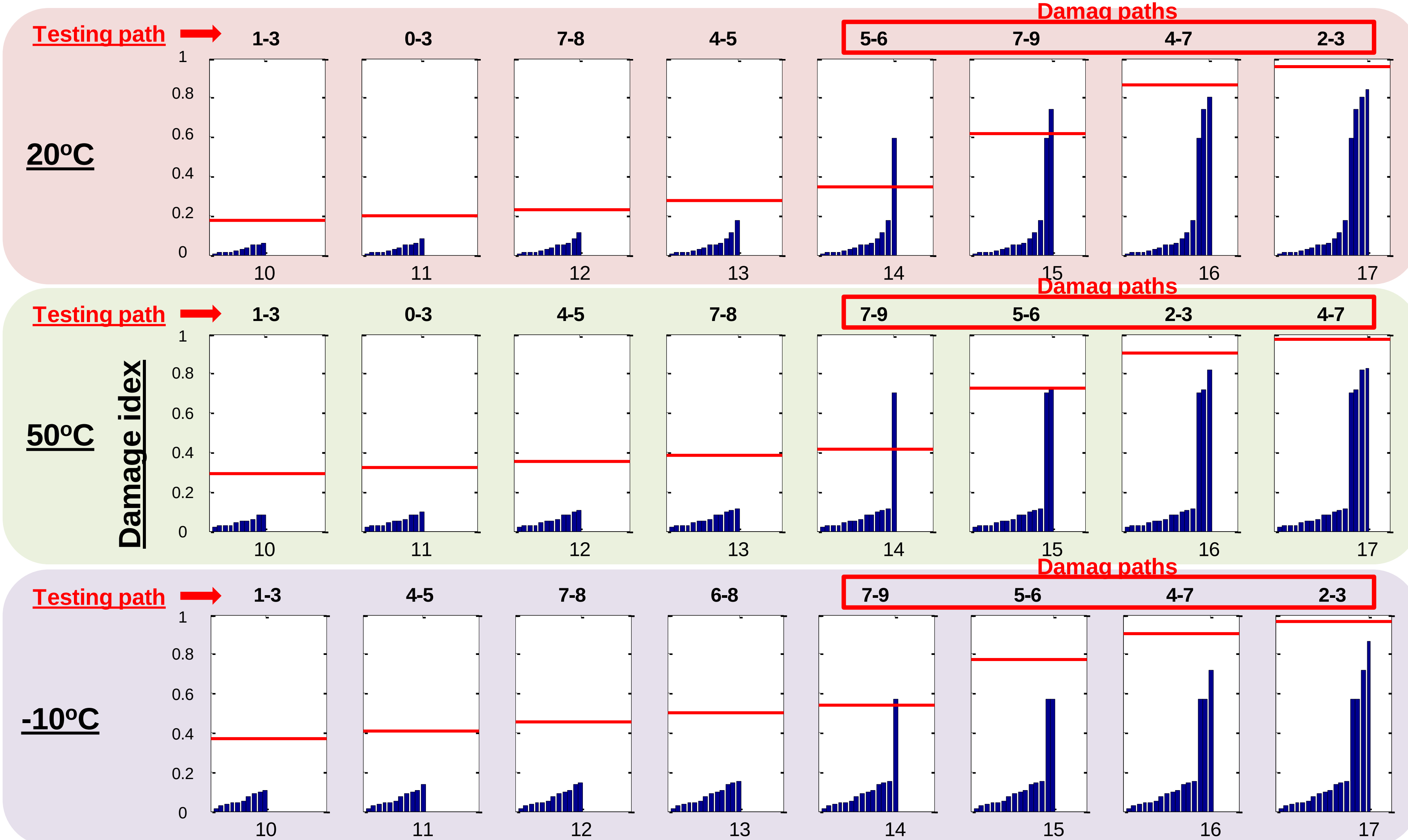
Wave propagation paths sorted in an ascending order

Instantaneous Outlier Analysis (Damage 1)



Wave propagation paths sorted in an ascending order

Instantaneous Outlier Analysis (Damages 1, 2 and 3)



Wave propagation paths sorted in an ascending order

Summary and Conclusion

- An instantaneous delamination detection technique is developed and validated using data obtained from damage states of a flat composite specimen and a specimen with stringers.

- The effectiveness of the proposed instantaneous technique is demonstrated explicitly under varying temperature and using structural components with additional structural features such as stringers.

- A fundamental Lamb wave mode (A_0 mode) was successfully extracted by the proposed mode extraction technique using a pair of dual PZTs at any desired frequency without any other special tuning.

Reference

K. H. Ip and Y. W. Mai, ”Delamination detection in smart composite beams using Lamb waves ,” Smart Mater. Struct. 13 544-51 (2004).

S. R. Anton and D. I. Inman DJ, “Reference-free damage detection using instantaneous baseline measurements,” AIAA. **47,** 1952-64 (2009).

C. T. Ng and M. Veidt, “A Lamb-wave-based technique for damage detection in composite laminates,” Smart. Mater. Struct. 18, 074006 (2009).

J. B. Ihn and F. K. Chang, “Pitch-catch active sensing methods in structural health monitoring,” Smart Mater. Struct. 7 5–19 (2008).

D. Wang, L. Ye and Z. Su, ”Probability of the presence of damage estimated from an active sensor network in a composite panel of multiple stiffeners,” Compos. Sci. Technol. 69 2054-63 (2009)

G. Petculescu, S. Krishnaswamy and J. D. Achenbach, ” Group delay measurements using modally selective Lamb wave transducers for detection and sizing of delaminations in composites,” Smart Mater. Struct. 17 015007 (2008).

S. B. Kim, and H. Sohn, “Instantaneous reference-free crack detection based on polarization characteristics of piezoelectric materials,” Smart Mater. Struct. 16, 2375-2387 (2007).

H. Sohn, S. J. Lee, “Lamb wave tuning curve calibration for surface-bonded piezoelectric transducers,” Smart Mater. Struct. 19, 015007 (2010).

A. Raghavan and C. E. S. Cesnik, “Modeling of piezoelectric-based Lamb-wave generation and sensing for structural health monitoring,” SPIE. 5391 (2004)

Z. Su, L. Ye, and Y. Lu, “Guided Lamb waves for identification of damage in composite structures: A review,” J. Sound Vib. 295, 753–780 (2006).

Backup

Correlation-based Damage Index

Damage index (*DI*)

$$DI(i,\Omega)=\frac{1}{2}\left(1-\frac{2}{n_d}\sum_{j}^{n_d/2} corr(A_0(i,\Omega),A_0(j,\Omega))\right)$$

$$DI(i)=\frac{1}{N}\sum_{\Omega}^{N} DI(i,\Omega)$$

Ω is the driving frequency.

$A_0(i,\Omega)$ or $A_0(j,\Omega)$ is the A_0 mode obtained from the paths *i and* j ($1\le i, j \le 20$)

The path *'j'* is selected as the undamaged paths having same angle and spacing with the path i.

'Corr ' is the cross correlation.

d is the angle of the path i. (*d* = 0º, 45º, 90º, and 135º)

$$0\le DI(i,\Omega)\le 1$$

n_d is the number of paths of the *d* angle.

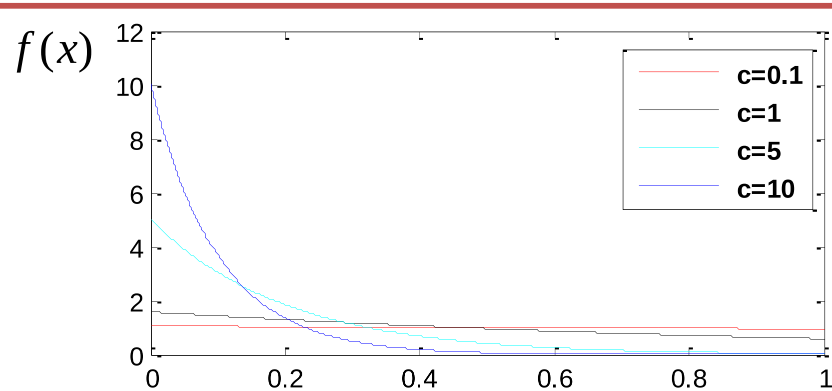
Truncated exponential distribution

- Probability density function

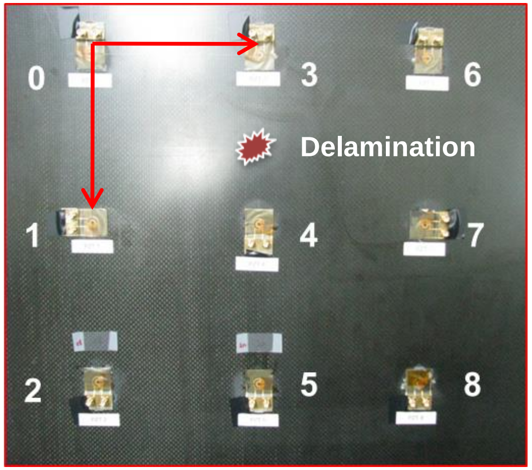
$$f(x\,|\,c)=ce^{-cx}(1-e^{-cx_0})^{-1},\quad (0<x\le 1)$$

- Estimation of a parameter *c*

$$\bar{x}/x_0=1/cx_0-1/(e^{cx_0}-1)$$

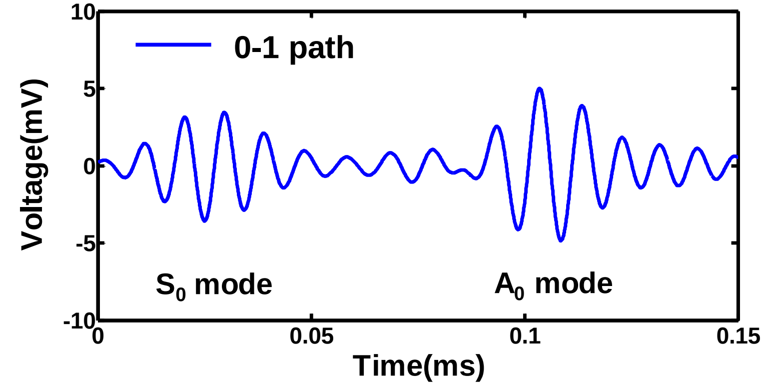


Lamb Wave Propagation Characteristics on a Multilayer Composite Material



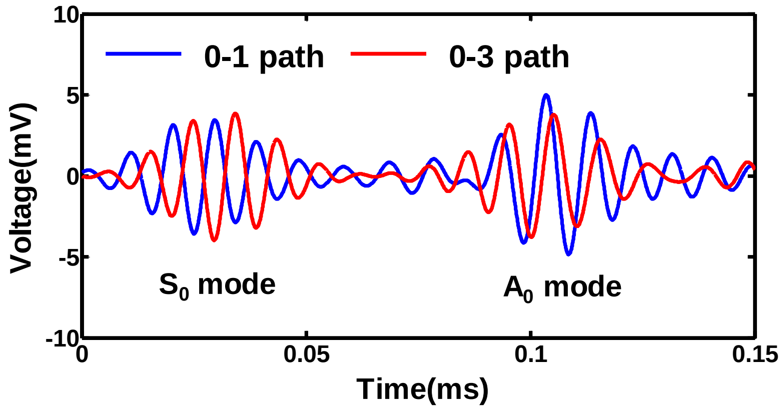
Composite specimen with PZT transducers

- **Fast S_0 mode and slow A_0 mode**



$V_{S0} \approx 5572m/s$ and $V_{A0} \approx 1460m/s$

- **Anisotropic nature of a composite material**



'0-1' and ' 0-3' paths have same spacings.

- **High attenuation of Lamb waves**