Structural Health Monitoring

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Structural health monitoring (SHM)

A structural Health Monitoring System (HMS) can be defined as a tool to continuously observe the degradation of Aircraft, Aerospace, Mechanical and Civil structures in service, with minimum manual intervention

The system should

- **evaluate changes in critical structural parameters from baseline**
- **assess structural integrity**
- **recommend maintenance strategy**

An autonomous SHM system

Motivation

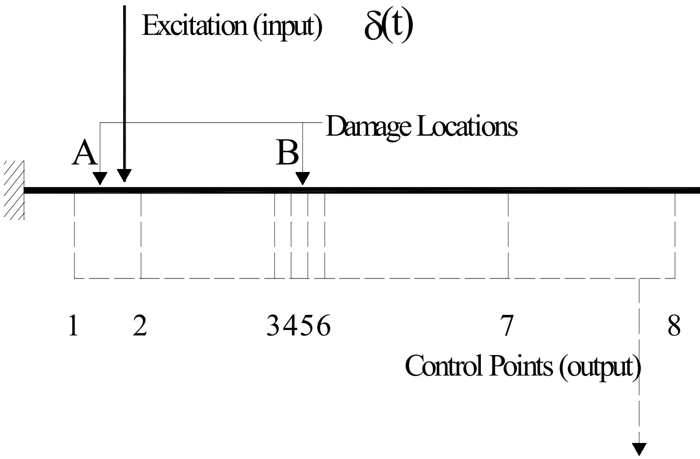
- Hidden flaws caused by aging, service loads or manufacturing processes, if left undetected, can lead to catastrophic failure of a structure.
- Conventional inspections/maintenance on regular basis are costly and often unnecessary.
- On-board autonomous health monitoring systems integrated into the design will increase the safety and reduce the maintenance cost significantly

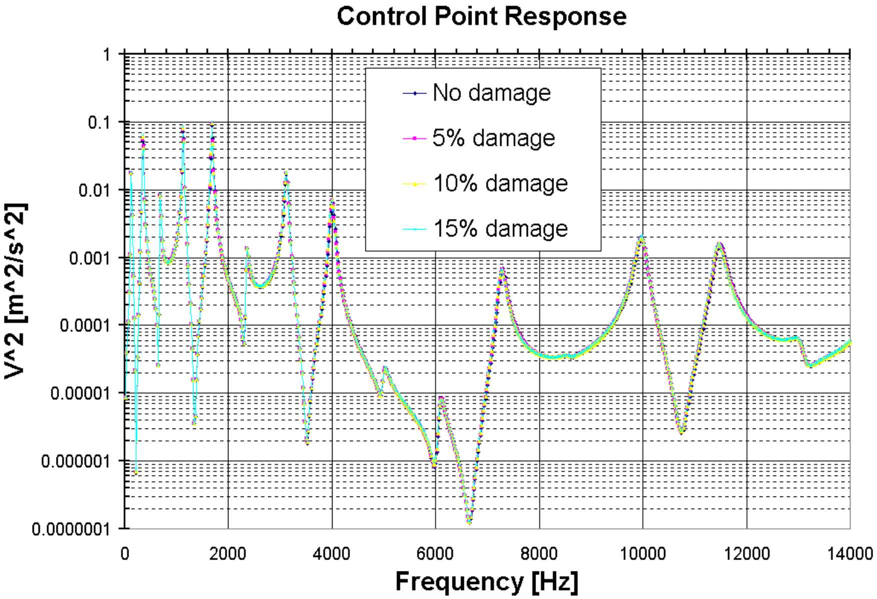
Major features of the proposed SHM system

- **Analysis of data recorded by a network of distributed sensors in critical areas of structure.**
- **Low frequency narrowband sensors to record modal response**
- **High frequency broadband sensors to record motion due to wave propagation**
- **Analysis of recorded data using a damage index approach**
- **The procedure can be automated requiring minimum operator intervention**

Effects of damage on the modal response of a beam

Aluminum beam





Damage was simulated by progressively reducing the area moment of inertia to 15 % in steps of 5 % in one element of the beam, which constitutes 2% of its entire volume.

Frequency response function (FRF) as velocity square at control point #6 on the beam produced by load, *δ(t)*. Damage location A

- **The simulated flaw appears to have very small effects on the modal response of beam.**
- **It would be difficult if not impossible to use the modal properties directly to identify damage in the beam.**

Effects of damage on the modal response of a beam (cont.)

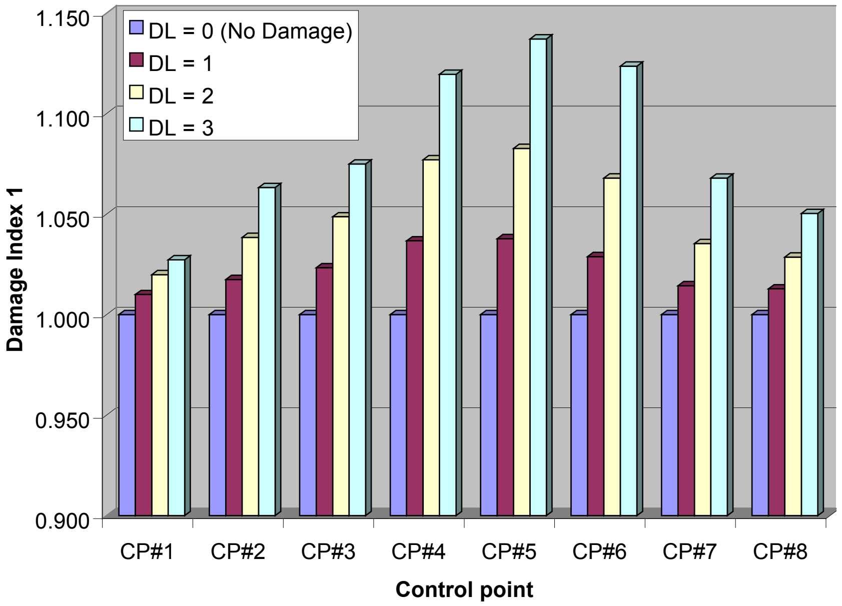
Damage index 1:

$$(\mathrm{D})_{i,DL} = \frac{\{V_i^2\}_{DL}^T * \{V_i^2\}_{DL}}{\{V_i^2\}_{DL=0}^T * \{V_i^2\}_{DL=0}}$$

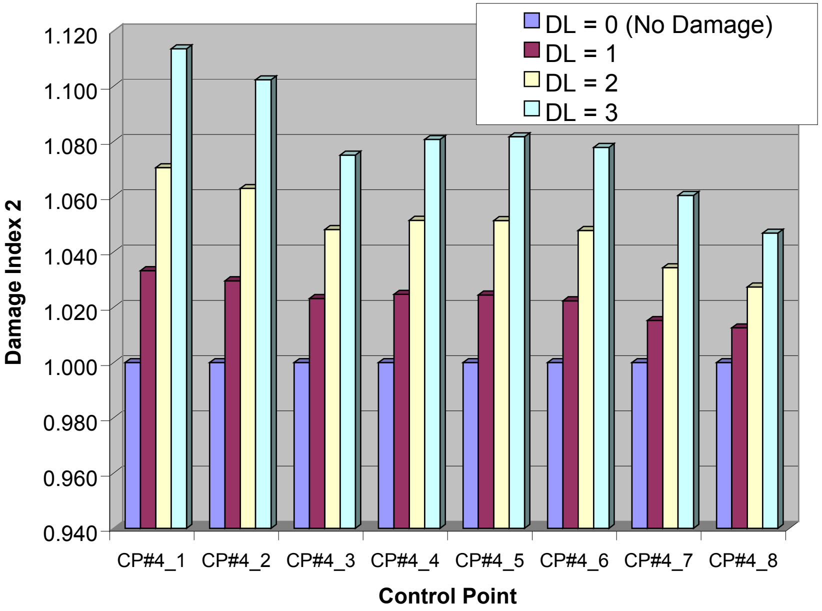
Damage index 2:

$$(\mathrm{D})_{i,j,DL} = \frac{\{V_i^2\}_{DL}^T * \{V_j^2\}_{DL}}{\{V_i^2\}_{DL=0}^T * \{V_j^2\}_{DL=0}}$$

DL is the damage level (*0 - 3*) and $\{V_i^2\}_{DL}$ is the velocity-squared response vector (700 elements consisting *f = 0 – 14 kHz* at steps of *20 Hz*) at node # *i* at damage level *DL*.



Damage location B. Damage index 1

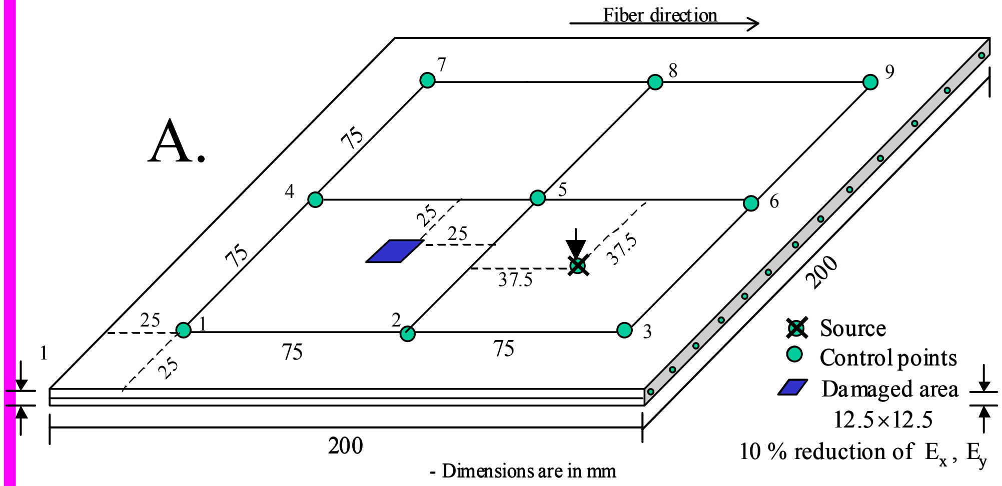


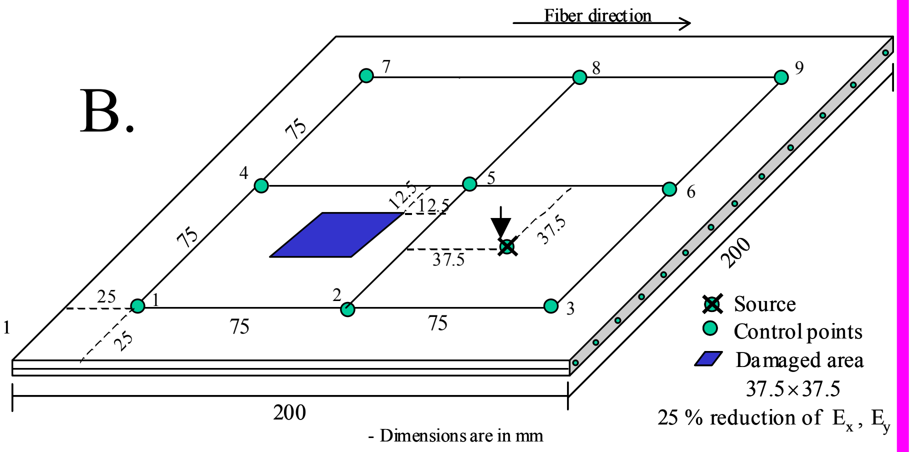
Damage location A. Damage index 2 showing correlation of CP #4 with others

Damage indices increase with the level of damage, and more importantly, the increase is pronounced at control points closer to the damage location.

Effects of damage on the modal response of a plate

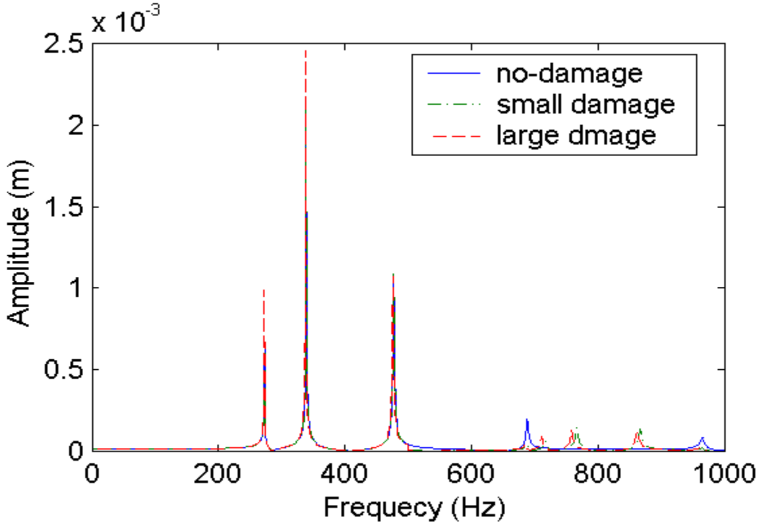
Fixed ended unidirectional graphite/epoxy composite plate





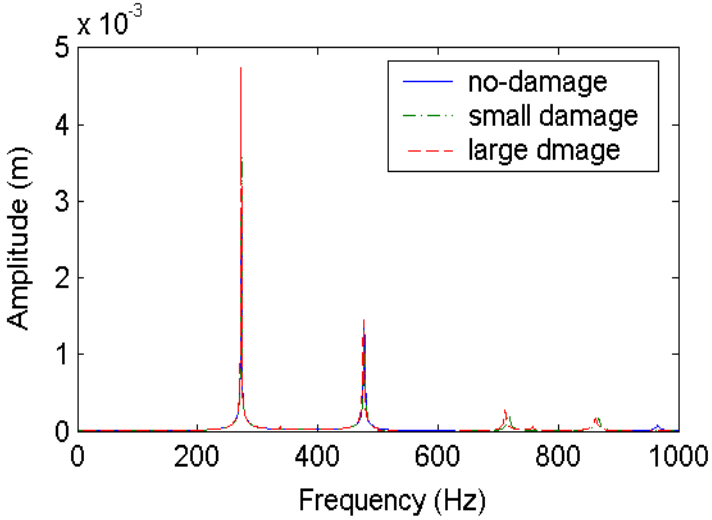
A. Simulated damage over a small area

B. Simulated damage over a large area



FRFs

Point 2 (left)
and
Point 5 (right)

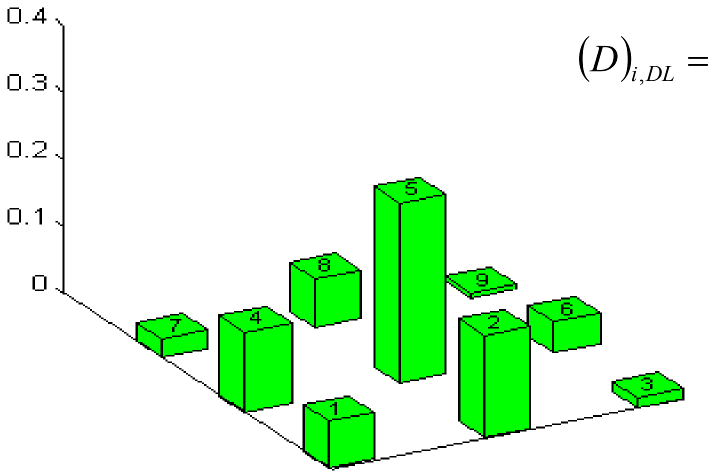


Effects of damage on the modal response of a plate (cont.)

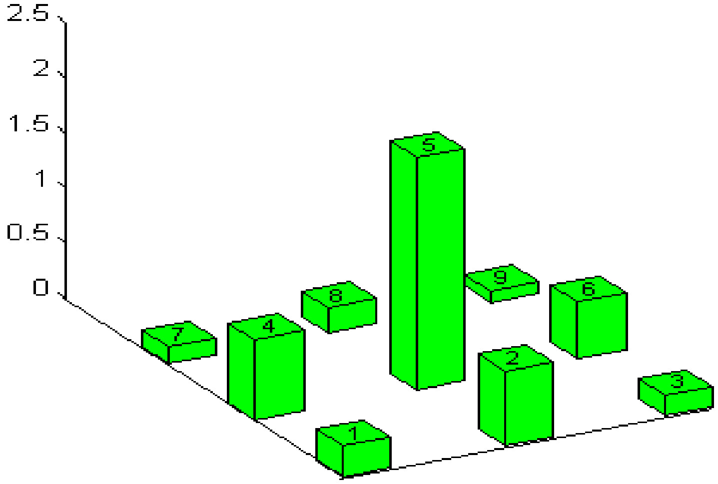
The damage index approach

Damage index

$$(D)_{i,DL} = \left| 1 - \frac{\{R_i\}_{DL}^{T} * \{R_i\}_{DL}}{\{R_i\}_{DL=0}^{T} * \{R_i\}_{DL=0}} \right|$$



A. Damage index for small damage



B. Damage index for large damage

- ➢ **Damage indices increase with level of damage**
- ➢ **Indices are high at control points closer to the damage**
- ➢ **Major damage within the structure can easily be identified from the high values of the indices**

Damage identification using wave propagation approach

Pre-impact wave propagation test

A network of PZT transducers (sources and receivers) are located on the surface of the plate. The elastic waves generated by the source are acquired by receivers, pre-processed in an ultrasonic date acquisition system and stored in the computer for analysis.

Impact test

Impact test is performed using an instrumented drop weight test frame Instron/Dynatup 8250.

Post-impact wave propagation test

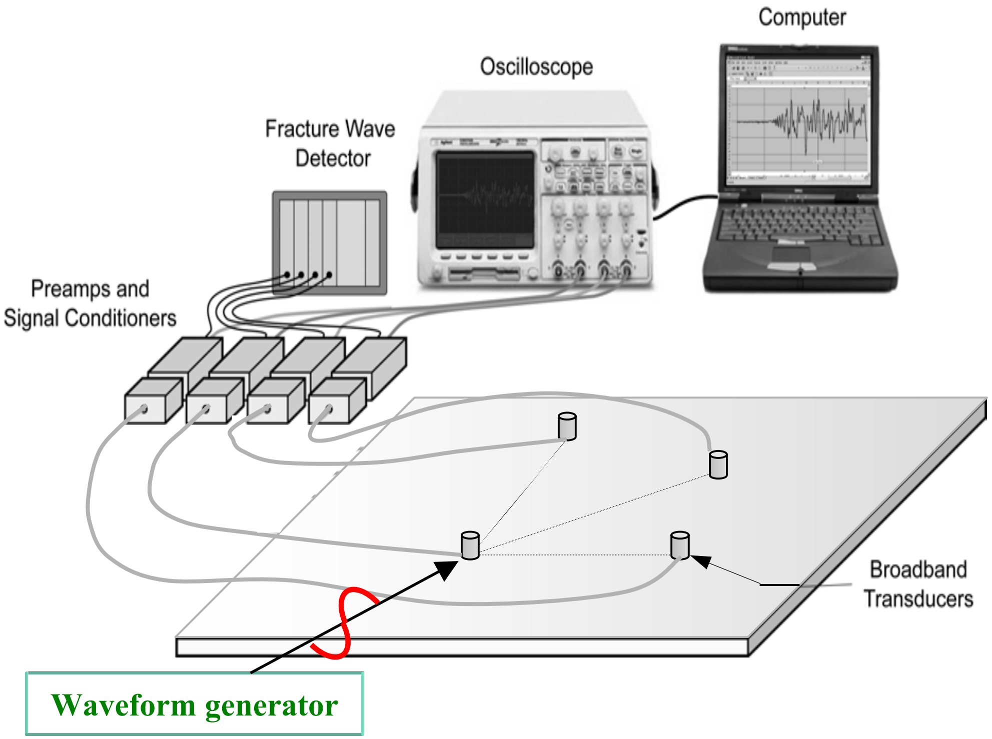
After the plate has been impacted, wave propagation tests are repeated using the same transducer configuration as in the pre-impact tests.

Evaluation of damage index

$$(D1)_i = \left| 1 - \frac{\left\{F_i\right\}^T_{post-impact} * \left\{F_i\right\}_{post-impact}}{\left\{F_i\right\}^T_{pre-impact} * \left\{F_i\right\}_{pre-impact}} \right|$$

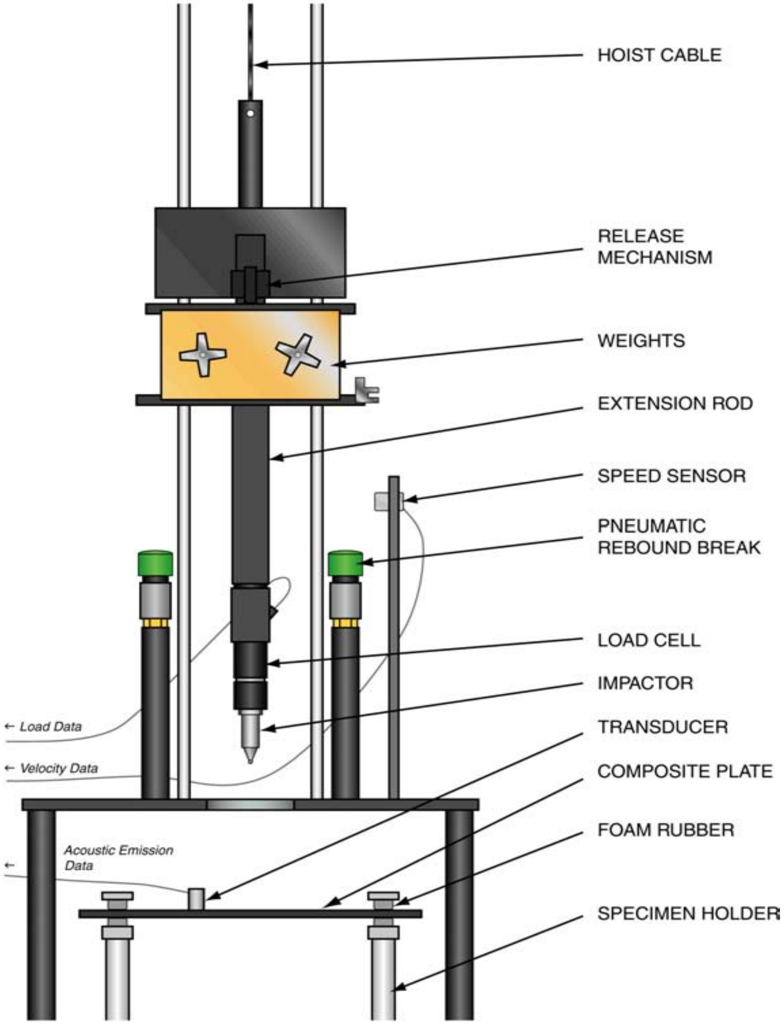
F_i = response vector

The wave propagation and impact experiments



Any one of the transducers can be used as a source to send specific signal using waveform generator

Data acquisition system for the ultrasonic wave propagation test

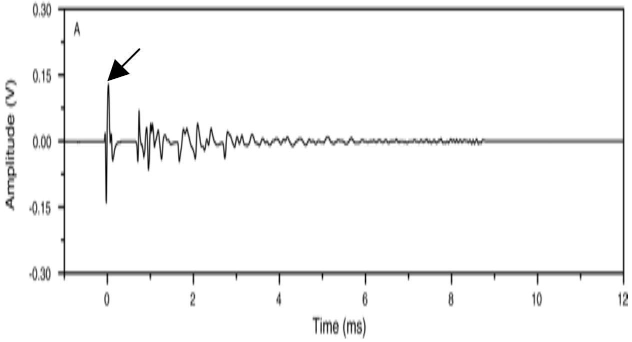


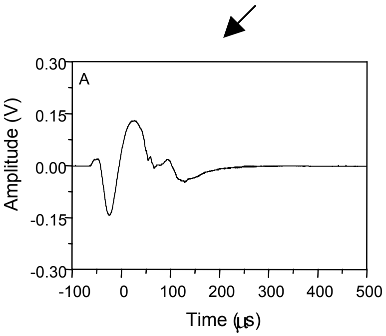
Schematics of the Dynatup 8250 for impact test

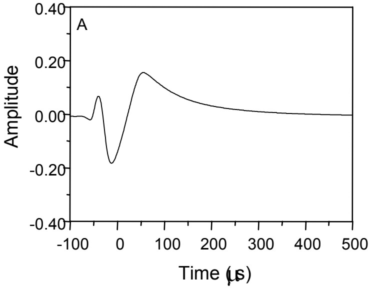
Damage identification in a composite plate

Acoustic emission (AE) waves from low velocity impact

14 lb (no damage)

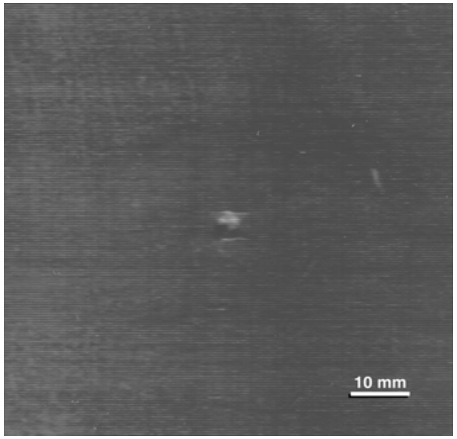




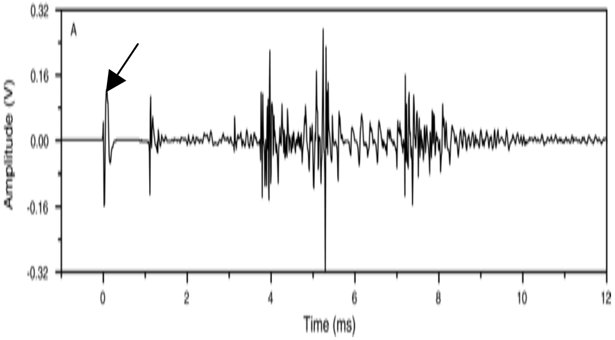


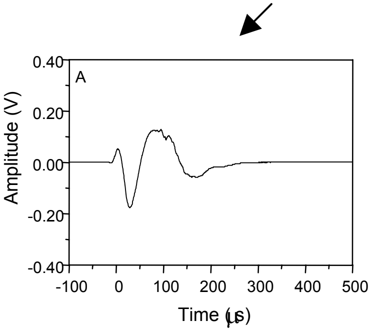
Theory

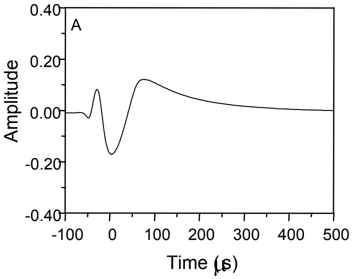
External appearance (61 lb)



61 lb (delamination)

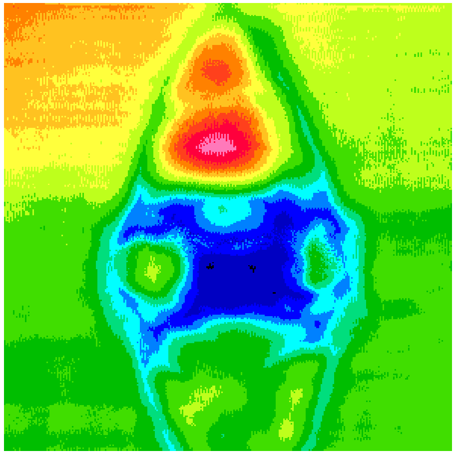






Theory

Ultrasonic C-scan (61 lb)

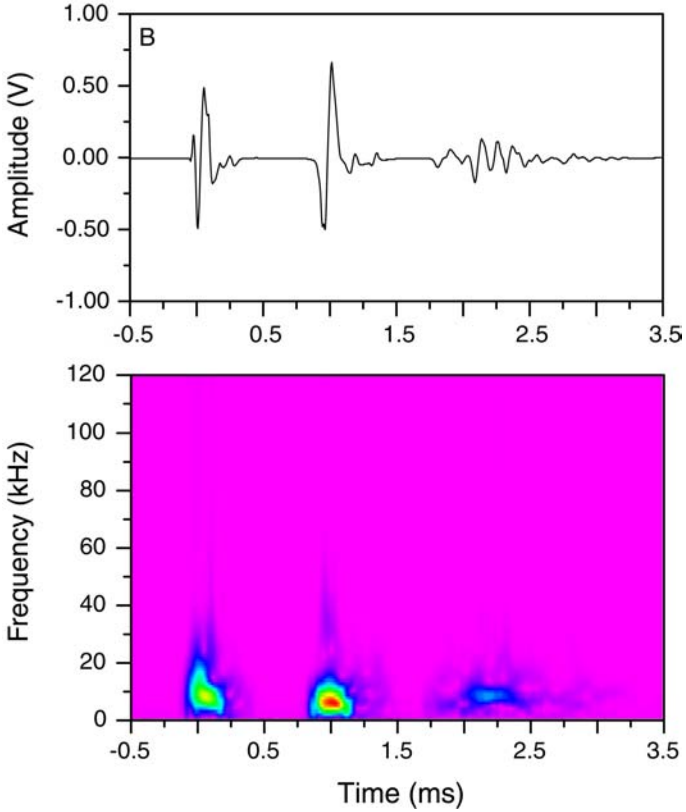


Waveforms recorded on $[0/90]_{8s}$ cross-ply graphite epoxy composite plates. Impactor was dropped from a height of 225 mm.

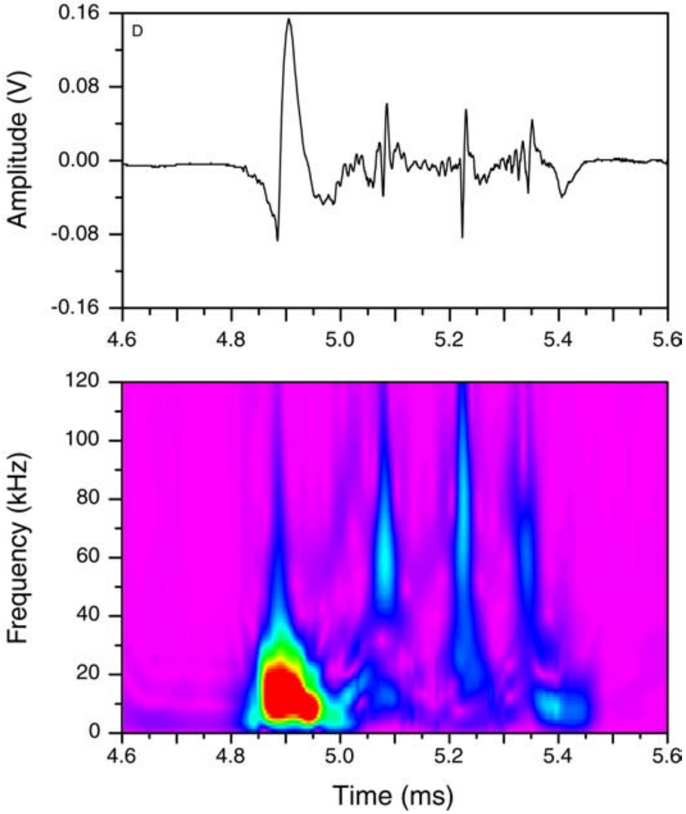
Damage identification in a composite plate (cont.)

Wavelet transforms of AE waves

No damage



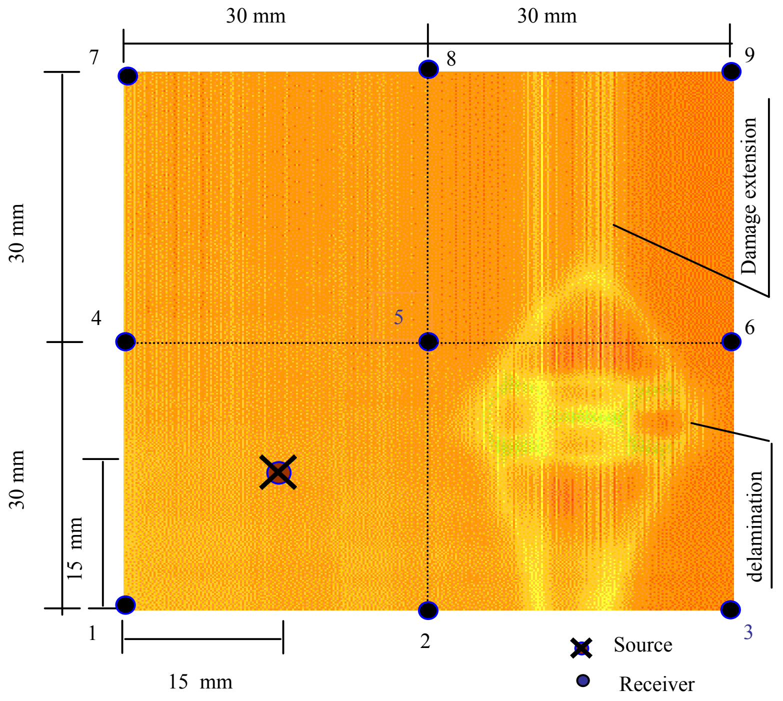
Damage



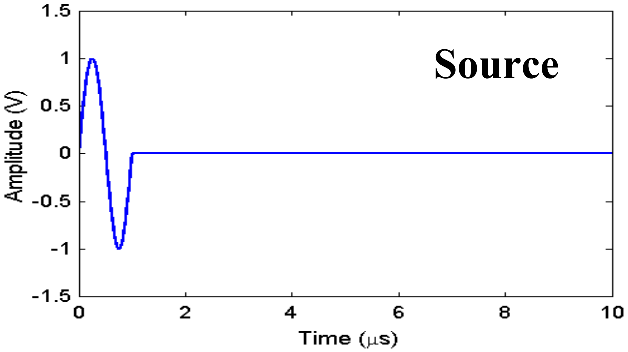
Damage identification in a composite plate (cont.)

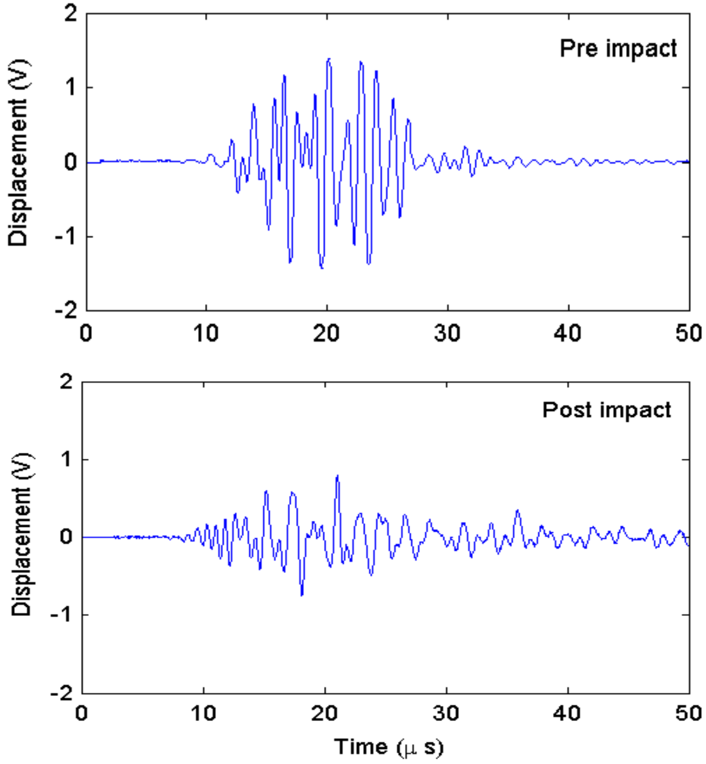
Typical recorded waveforms

4.2 mm thick $[0/90]_{8s}$ graphite/epoxy plate



Ultrasonic C-scan of the damaged plate showing the hidden defects. Sources, receivers and damaged area

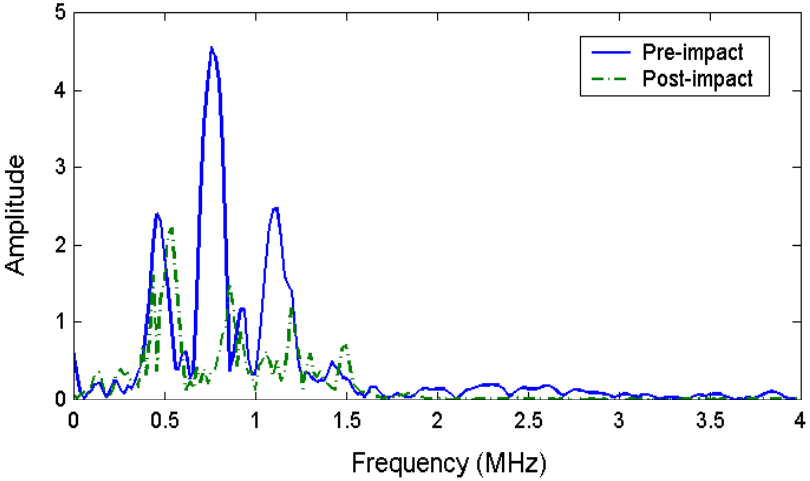




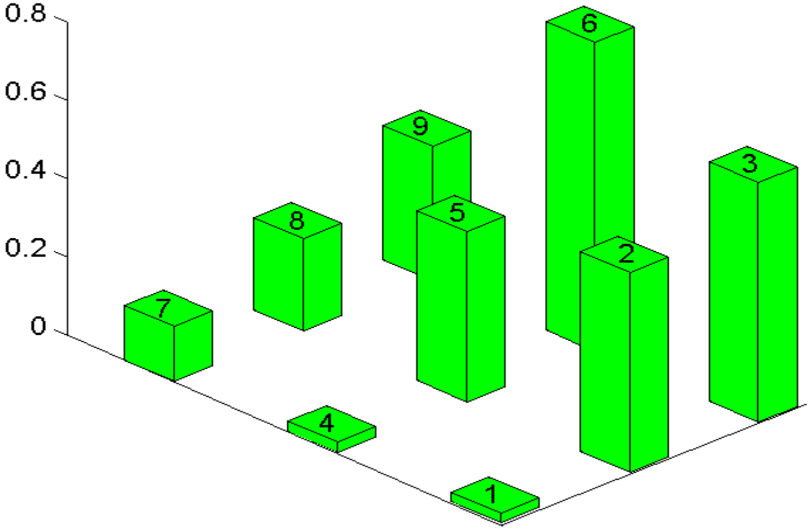
Recorded signals at receiver #6

Damage identification in a composite plate (cont.)

The damage index approach



Frequency spectra of the recorded signals at #6



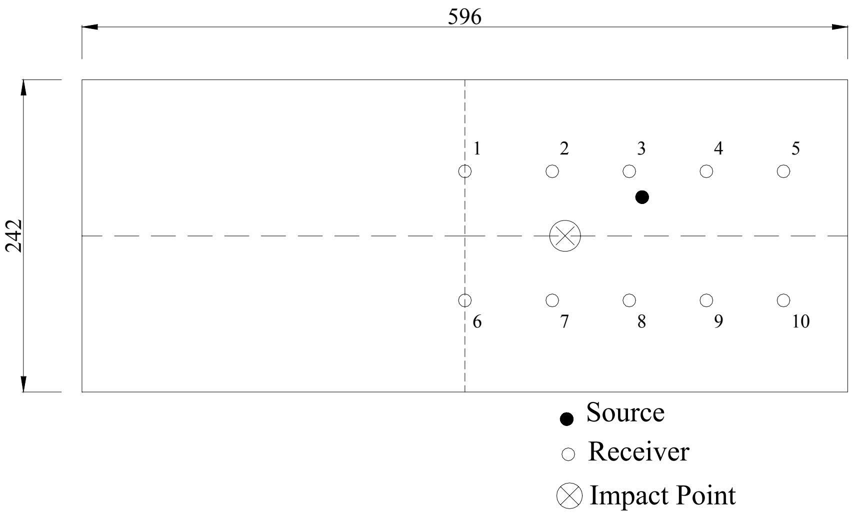
Damage index at the control points

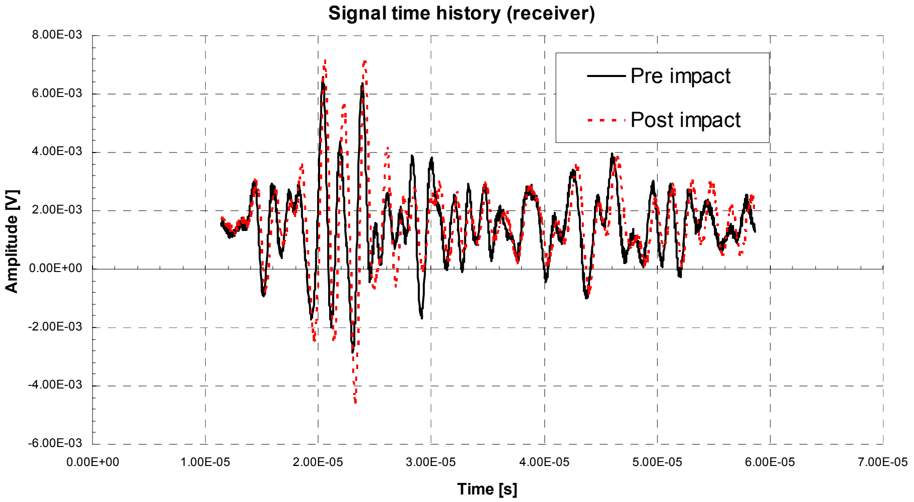
- ➢ **Delamination modifies the elastic waves propagating between the source and the receivers.**

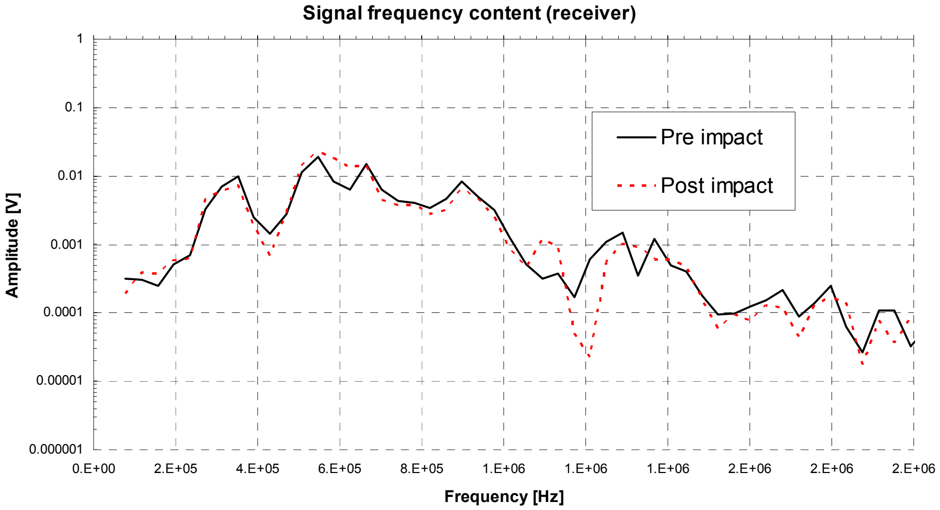
- ➢ **The influence is pronounced at points 3 and 6, near damage – and can be localized successfully**

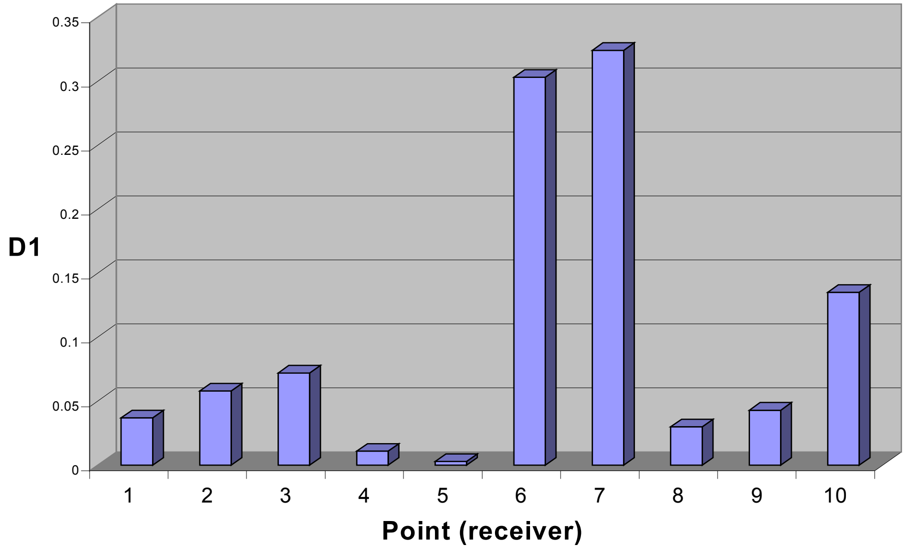
Damage identification in a composite plate (contd.)

Typical recorded signal and its frequency spectrum; damage indices

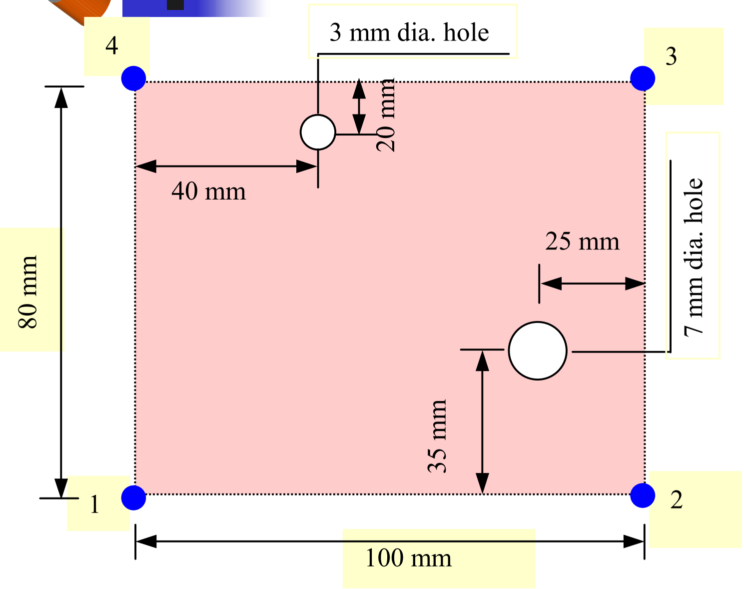






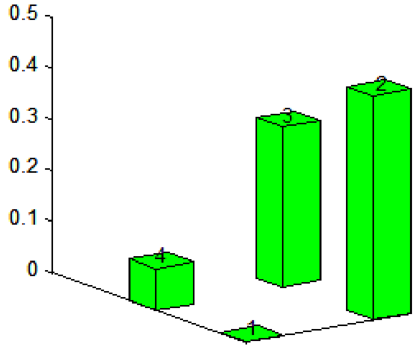


Damage identification in a composite plate (cont.)

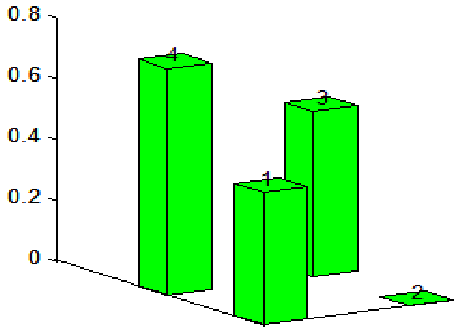


Any one of the transducers is used as a source and the others receive the signals.

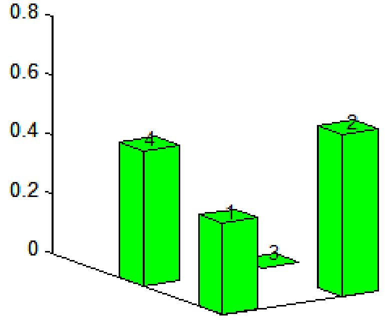
- Damage index set S_i; *i* is the source location.
- Sets S_1, S_3 and S_4 show the highest index at the control point 2, which is closer to the 7 mm dia. hole.
- For set S_2, the damage index is highest at control point 4, since the hole falls in the path of the waves from 2 to 4.
- Some insight about the presence of the smaller hole can be obtained when indices at locations 3 and 4 are considered from set S_4 and S_3, respectively.
- Onset of damage within a region can be predicted with some confidence.



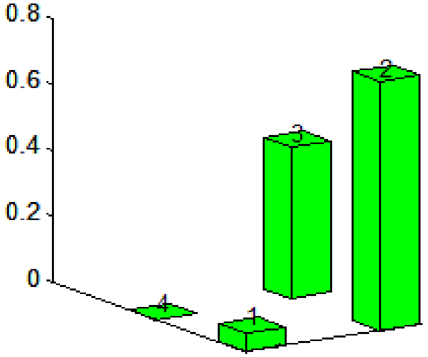
S_1



S_2



S_3



S_4

Concluding remarks

- The approach outlined here can be used for the characterization of materials degradation and the development of health monitoring systems for aircraft, aerospace and other advanced structures.
- For complex structures under realistic service conditions, the vibrational data are expected to provide information on the existence and the general location of major defects only (e.g., widespread damage).
- The wave based approach yields more detailed information on the location and nature of small hidden defects.
- The computer assisted automatic analysis of data should improve the reliability and practical applicability of the detection system to defects-critical structures.