UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
INTERNATIONALLY RECOGNIZED EXCELLENCE

OFFICE OF NAVAL RESEARCH

VIBRATION NONDESTRUCTIVE INSPECTION OF LARGE-SCALE COMPOSITE STRUCTURES

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UD-CCM

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Report Documentation Page

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

History

1D GSM w/ MS (Colin)

Steel beam

Composite beam

1999

/ MS

Composite panels, hull structure, & bridge

FEA &

/ MS

Commercial Accel.

2000

1D GSM w/ ODS (USNA)

2D GSM & 1D GFM w/ ODS

Quasi-2D GSM (USNA)

2001

uasi-2D GFM

Munition

Strain gage

Fiber optic s

Wireless sensing

SSM

Piezo-electric actuators

Automatic health monitoring

Overview

2D GSM

- Theory in 1D vs. 2D
- Statistical treatment
- Results from FEA and lab tests

Application to CIRTM Corner Structure for Director's Room

- Types of sensors (Accelerometers, Strain gages)
- Effect of frequency range
- Method of excitation (Multi-spots, One spot)

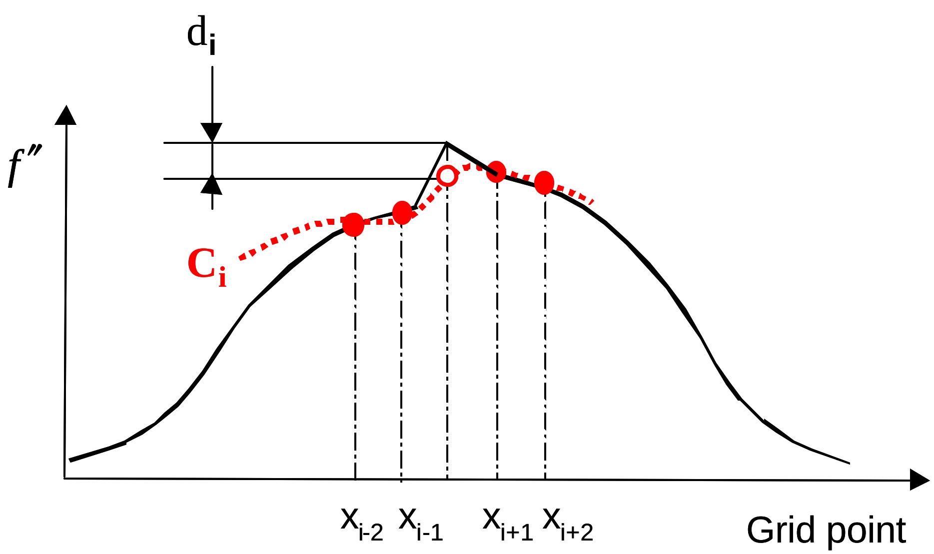
Application to Composite Bridge (Bridge 1-351)

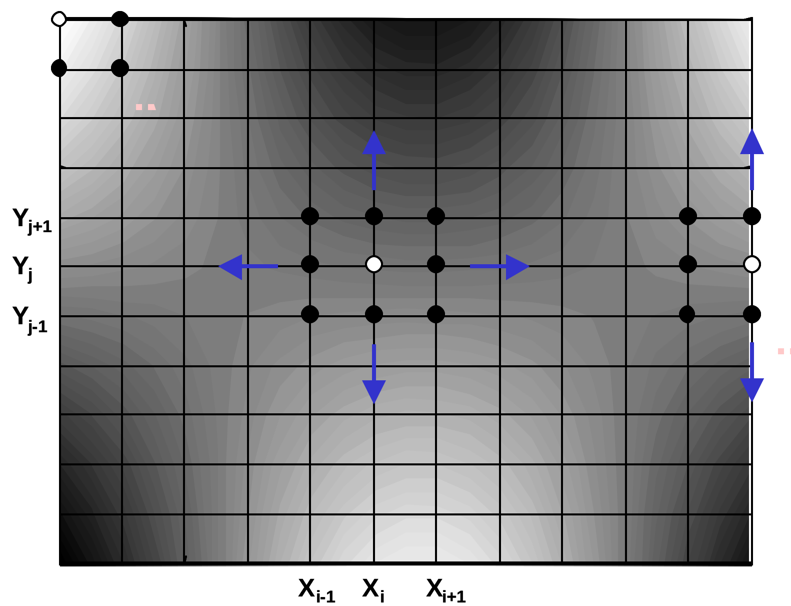
- 2D GSM results from data obtained year 1999~2002
- Testing plan for year 2003

Conclusion/Future Work

Gapped Smoothing Method (1-D vs. 2-D)

1-D GSM | **2-D GSM**





$$\nabla^2 y_{i,j} = \mathbf{g}_{i,j}{}^T \mathbf{?}_{i,j}$$

$$\mathbf{g}_{i,j}{}^T = [1, x_i, y_j],\ \mathbf{?}_{i,j}{}^T = [a_o, a_1, a_2]$$

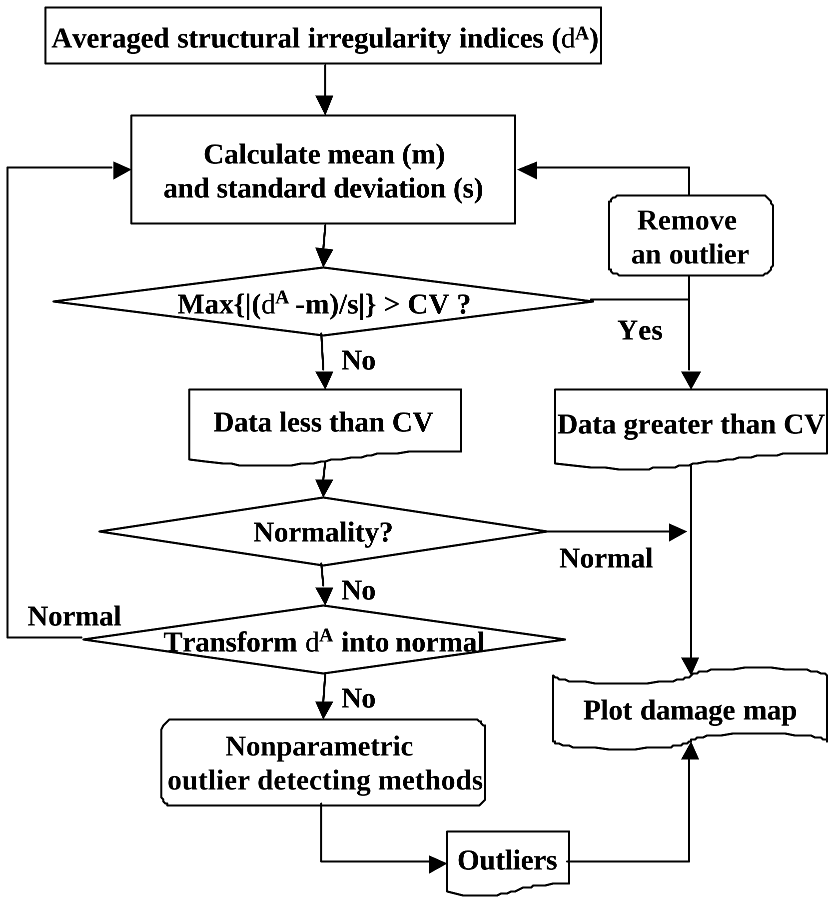
Structural Irregularity Index

=Curvature Shape – Smoothed curvature shape

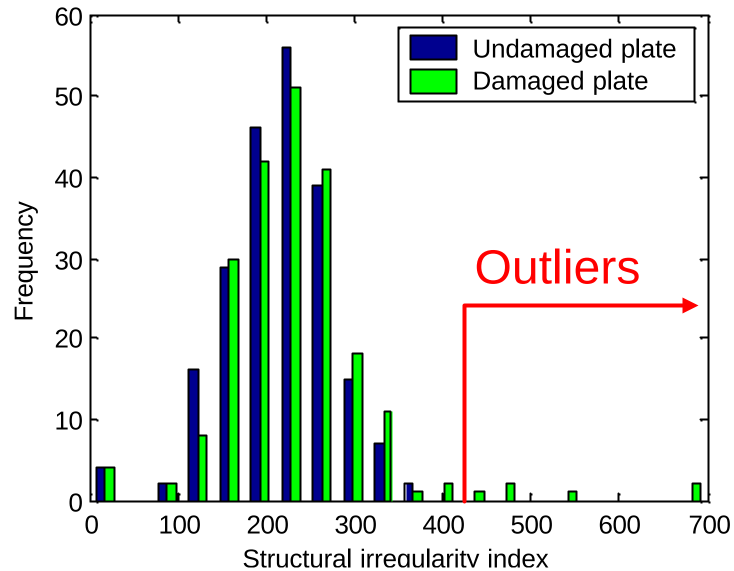
Statistical Treatment

Objective: Filter out noise to obtain only the area of damage with a confidence level CL

Flow chart for outliers detection



Histogram of structural irregularity indices



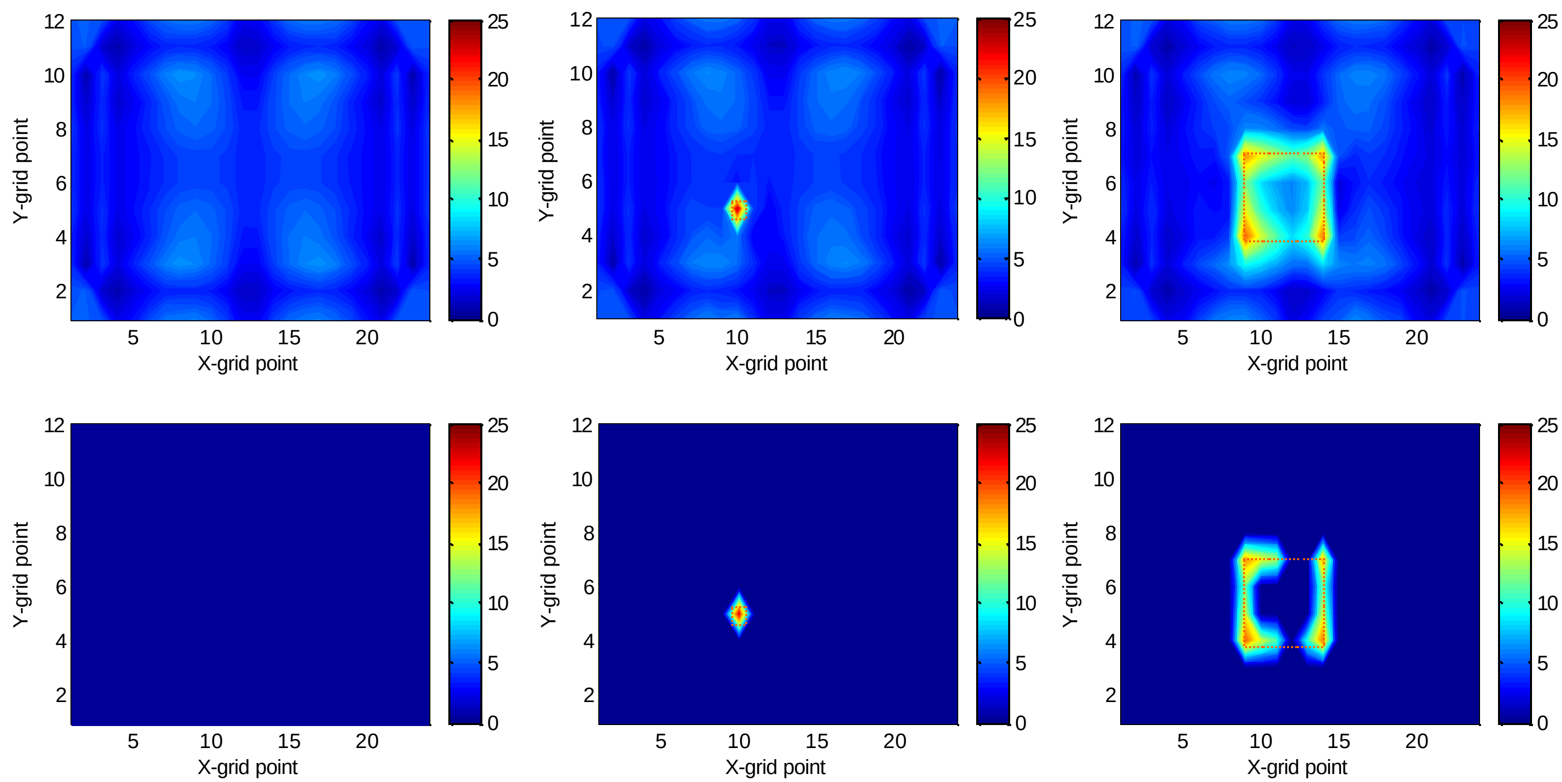
Grubb's outlier detection method

$$CV = \frac{t \cdot (n-1)}{\sqrt{n \cdot (n-2+t^2)}}$$

FEA Results
(Large vs. Small Damage)

SII

SII after Statistical Filtering (95% CL)



No damage

Modulus reduction in small area

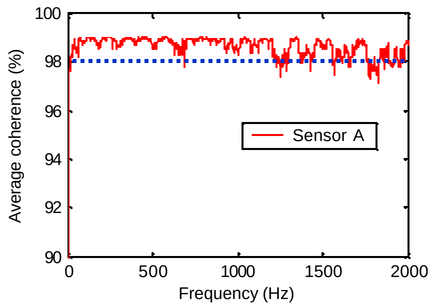
Modulus reduction in large area

- Statistical filter removes data when there is no damage
- Algorithm detects only perimeter of damage area

Lab Testing: (Composite Plate - Multiple Damage Locations)

Definition of SII ? $|\Delta f''|$ vs. $(\Delta f'')^2$

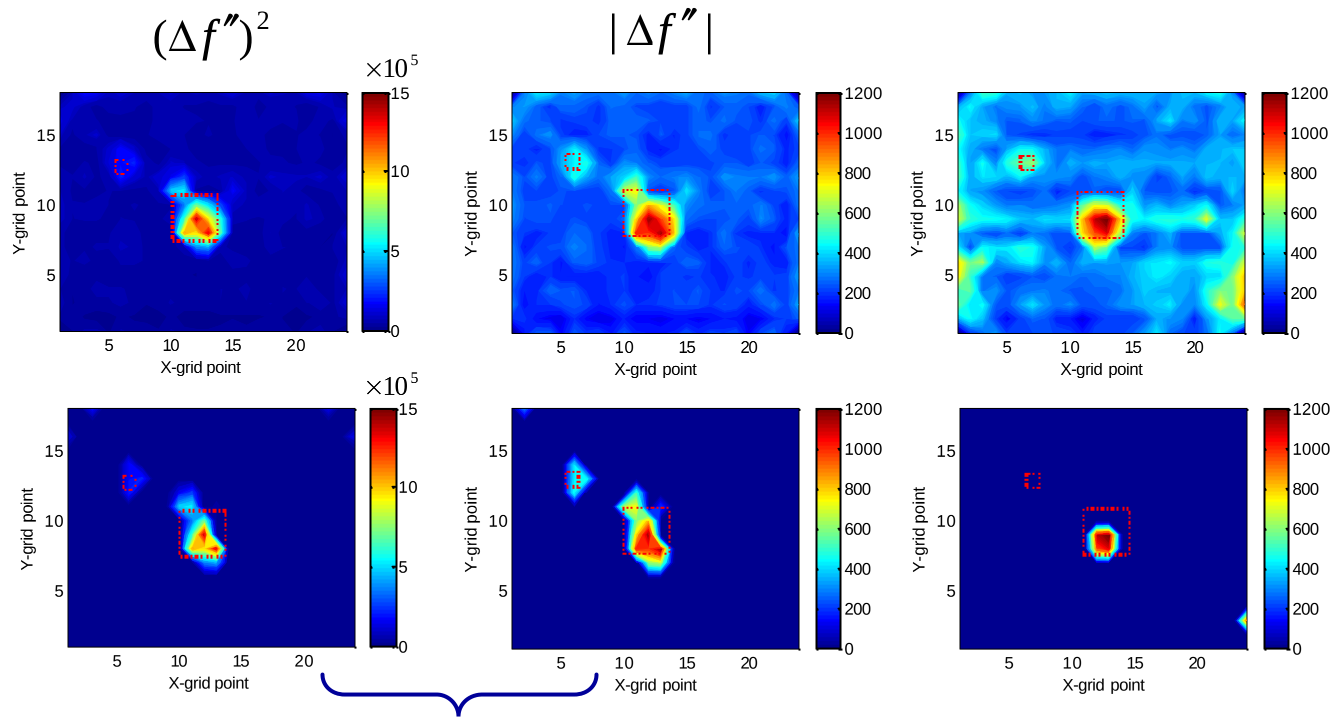
Coherence function



Frequency range: **100~2kHz**

SII

SII after Statistical Filtering (95% CL)

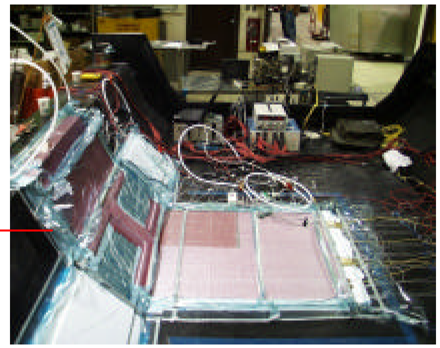


Two delamination with ODS data

Two delamination with MS data

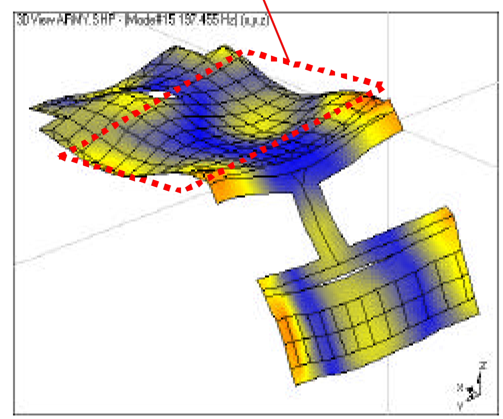
- Squaring suppresses noise as well as secondary damage
- Noise can be filtered out by statistical treatment

Lab Testing
(Composite Hull Structure)



VARTM Manufacturing process

The data used

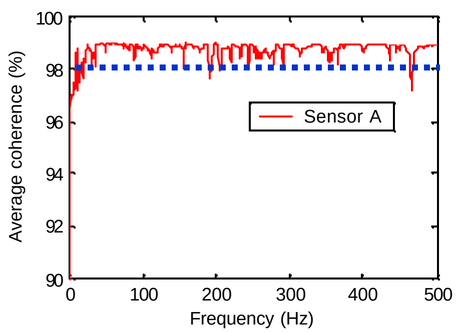


Dry spot

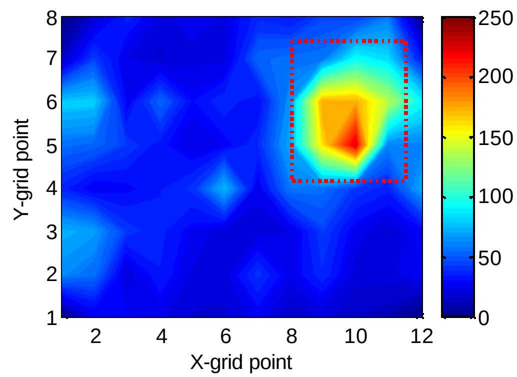
Inside surface **Outside surface**

Lab Testing Results (Composite Hull Structure)

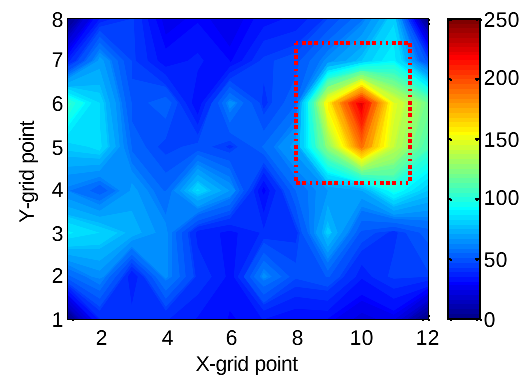
Coherence function

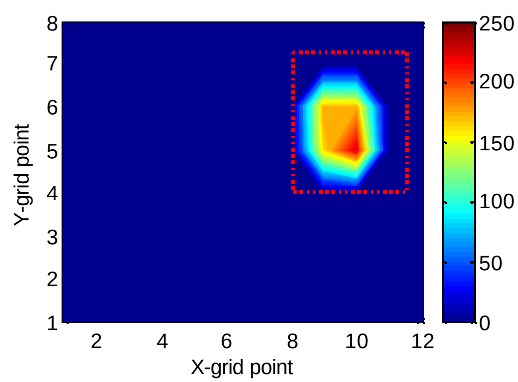


Frequency: 50~500Hz

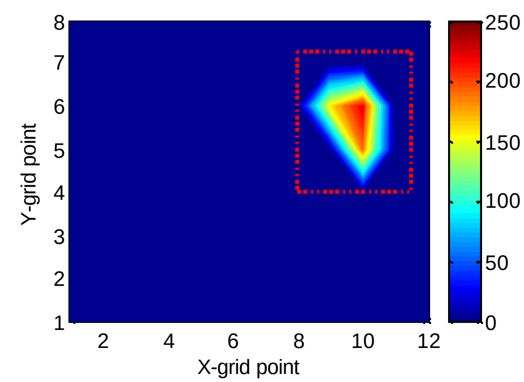


SII





SII after Statistical Filtering (95% CL)



Dry spot area with ODS data

Dry spot area with MS data

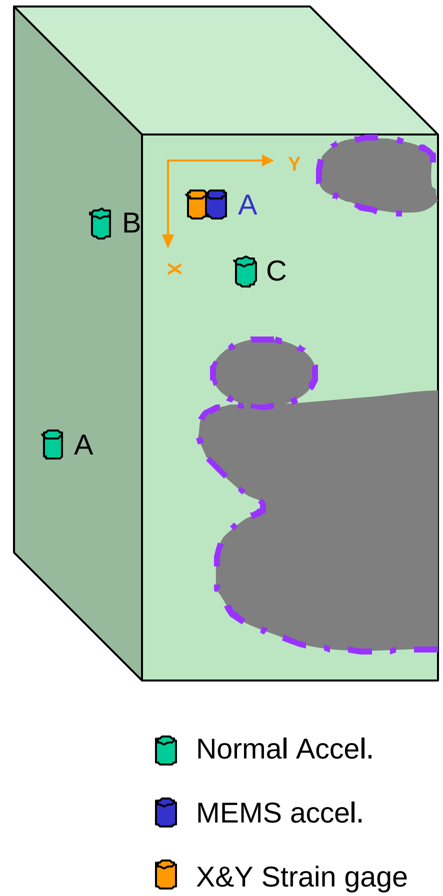
- Both ODS and MS data detected the dry spot
- Using ODS data shows less noise

Large-Scale CIRTM Structure

Objective:

Apply NDI techniques to large-scale composite structure

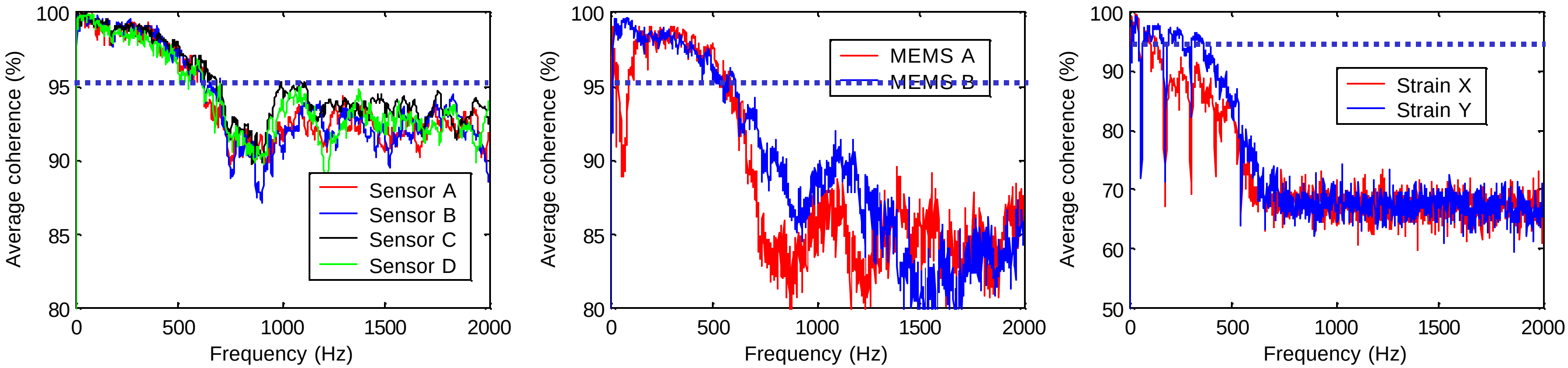
Study on effects of sensor type and location of sensors



Fabricated by

Coherence for CIRTM Structure

Coherence functions



Commercial accelerometers — **20Hz~600Hz**

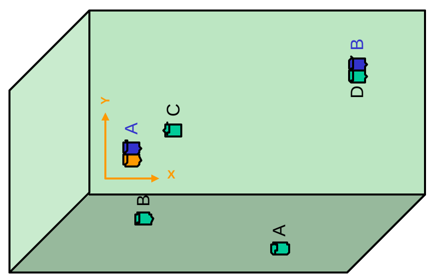
MEMS accelerometers — **100Hz~500Hz**

Strain gages — **5Hz~150Hz**

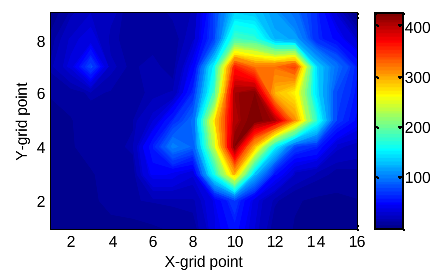
Effective Frequency Range:

SII Results for Individual Sensor (Frequency: 50~500Hz)

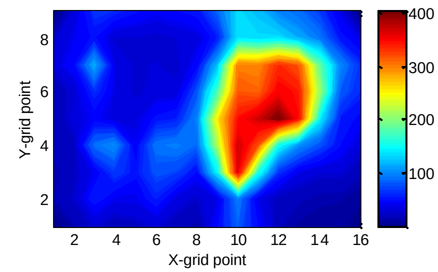
SII with sensor type and location (16 by 9 grids:)



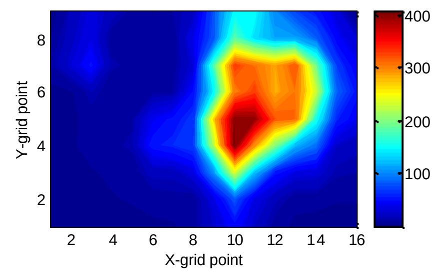
Accel. A



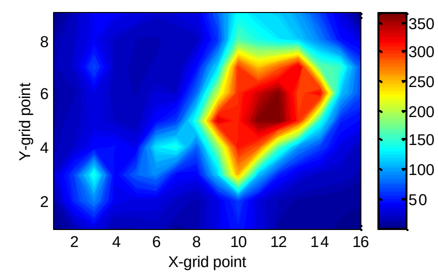
Strain_X



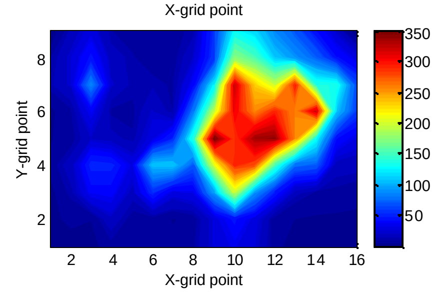
Accel. B



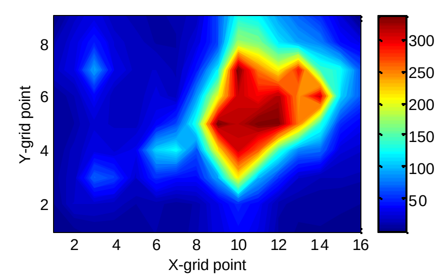
Strain_Y



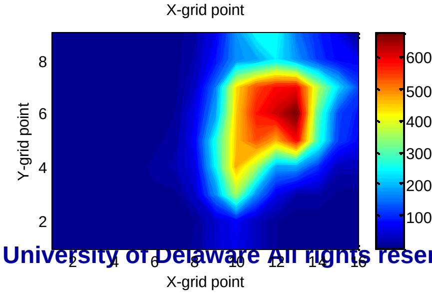
Accel. C



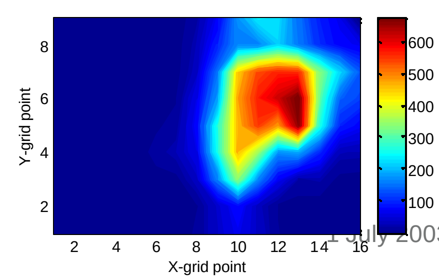
MEMS A



Accel. D



MEMS B



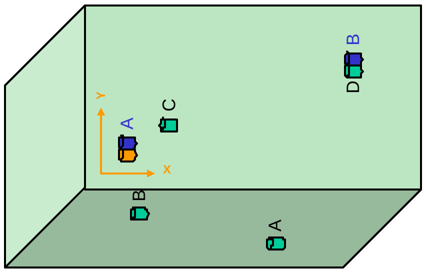
Results:

- All sensors detect damage areas
- But sensors located on large delamination can not detect smaller defects

➔ Multiple sensors are needed to detect all defects

SII for Medium Frequency Range (Frequency: 100~1kHz)

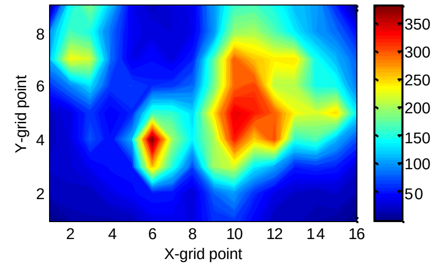
SII with sensor type and location (16 by 9 grids)



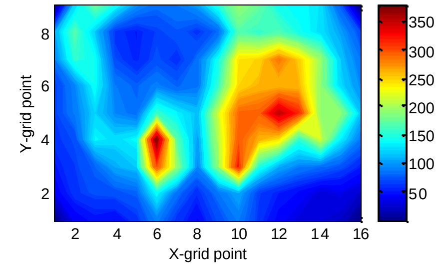
Results:

- Medium frequency range is more sensitive to smaller defects
- The sensor next to damage can detect better the damage (Compare Accel. C & D and MEMS A & B)

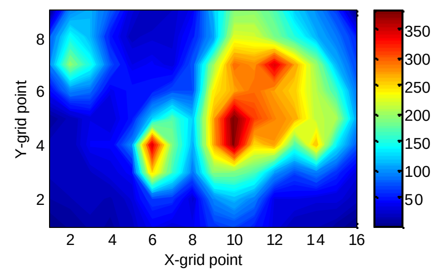
Accel. A



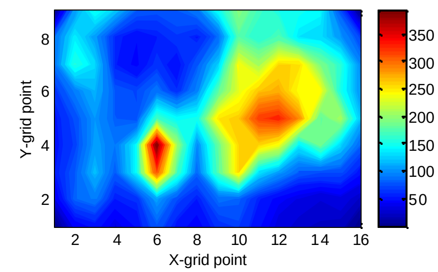
Strain_X



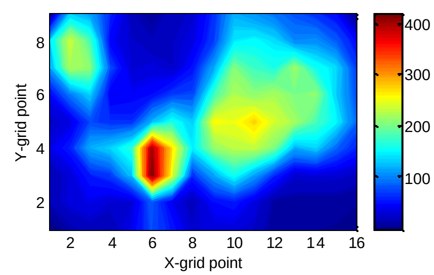
Accel. B



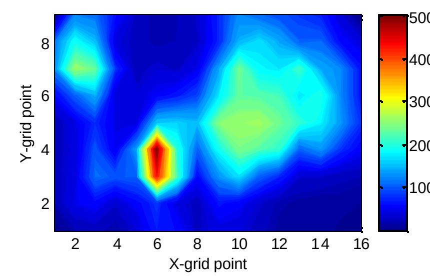
Strain_Y



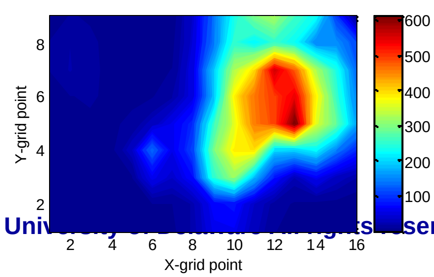
Accel. C



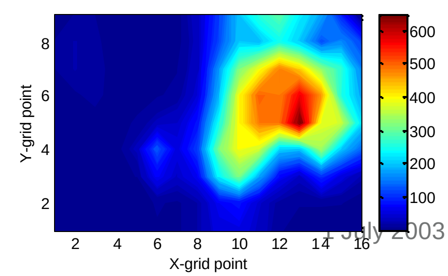
MEMS A



Accel. D

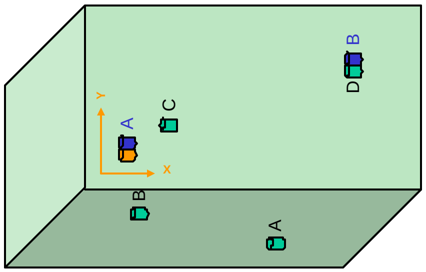


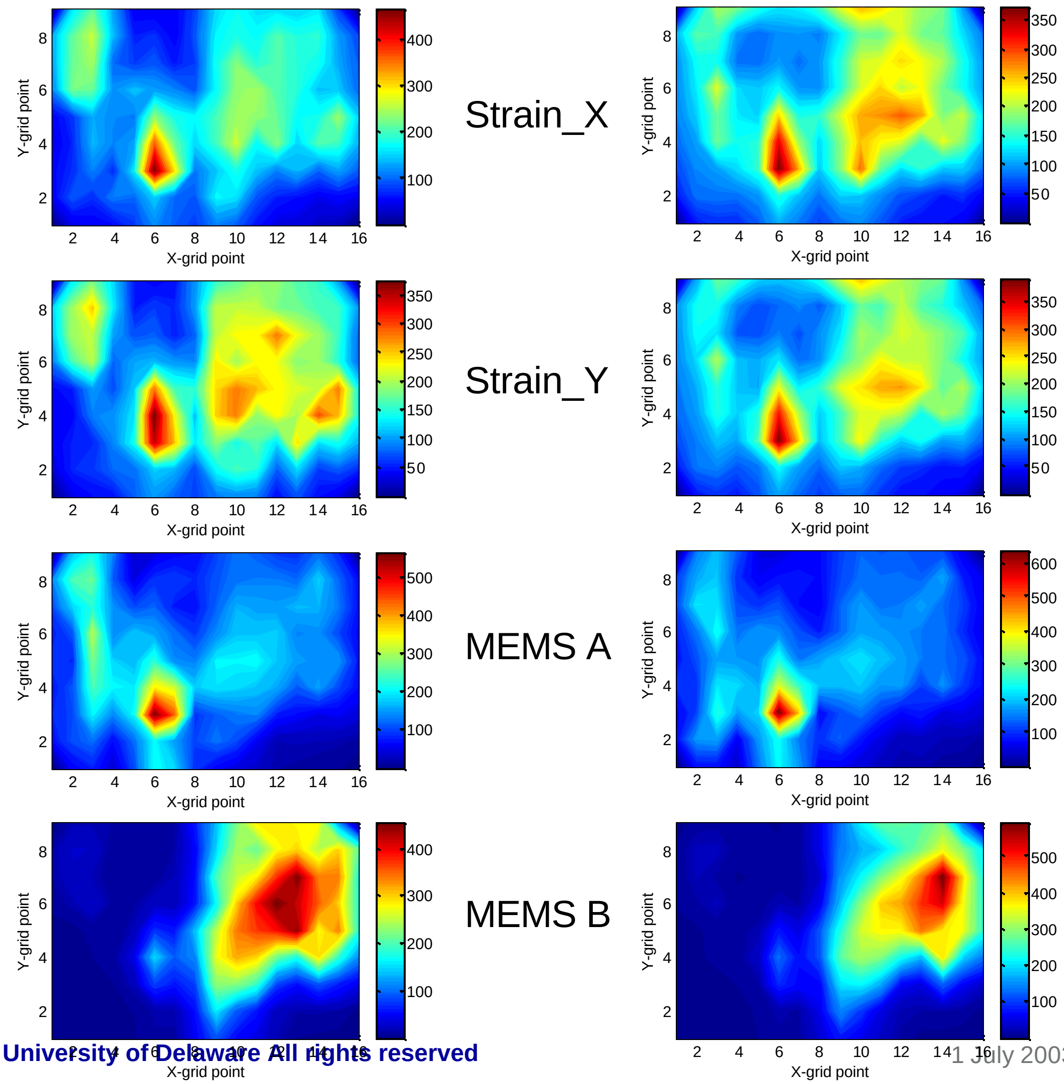
MEMS B



SII for High Frequency Range (Frequency: 100~2kHz)

SII with sensor type and location (16 by 9 grid)



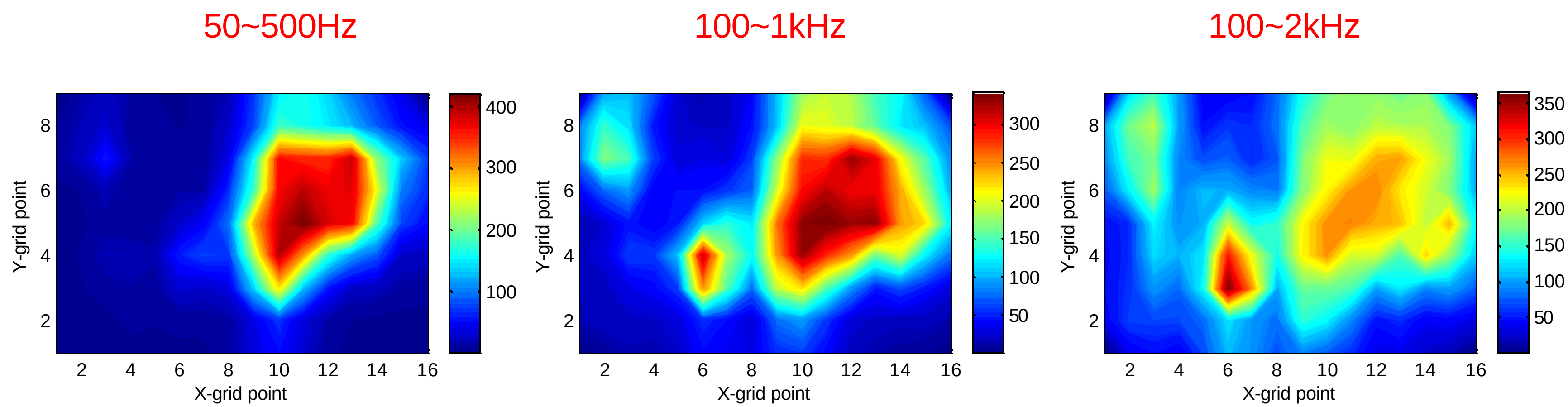


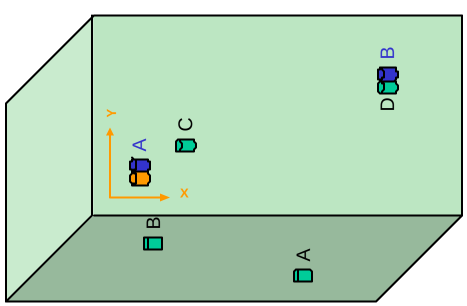
Results:

- Noise due to low coherence above 1kHz reduces sensitivity
- Find optimum frequency range for each sensor selection

Results for CIRTM Structure (Frequency Range)

Results with sensors A+B+C+D (16 by 9 grids)



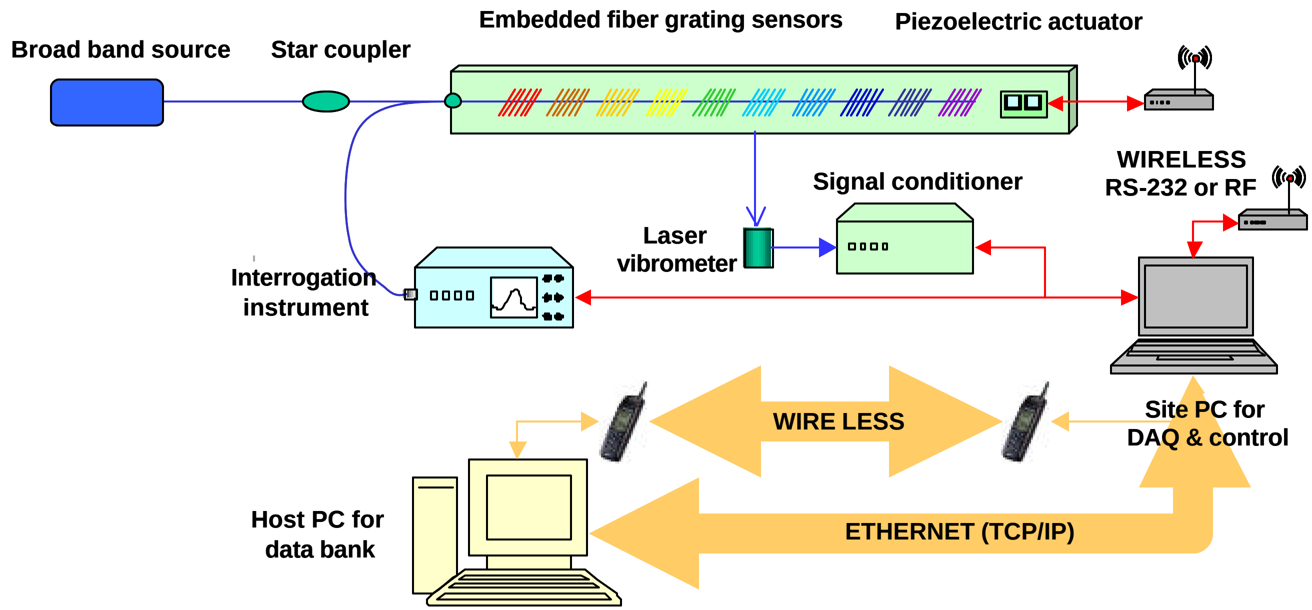


Results:

- Summation of sensor response results in better defect detection of all damages
- Higher frequency is more sensitive to smaller damage but has more noise
- Statistical treatment cannot be applied ← Assumption: Damage area is small compared to total area.

Automation

Motivation: To monitor the condition of structures in real time while in service



AUTOMATED ACTUATORS:
1. Automated impulse hammer
2. Piezoelectric film
3. External car/wind

SENSORS:
1. Smart materials
2. Embedded fiber optics
3. Piezoelectric films
4. Surface mounted strain gages
5. Laser vibrometer
6. Doppler type sensors (radio, ultrasonic, light)

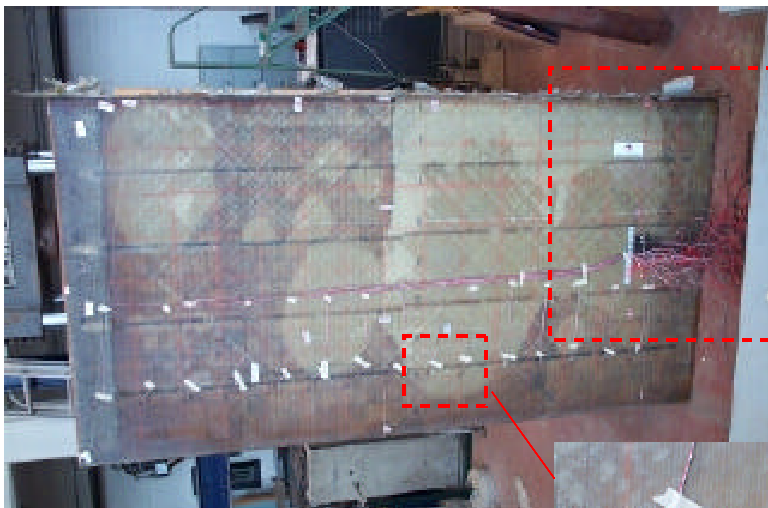
DAQ:
PC-controlled data analysis

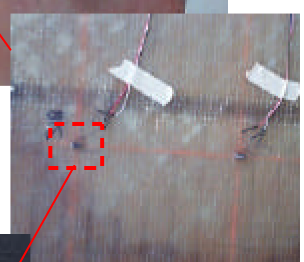
REMOTE MONITORING:
1. TCP/IP
2. Wireless RS-232

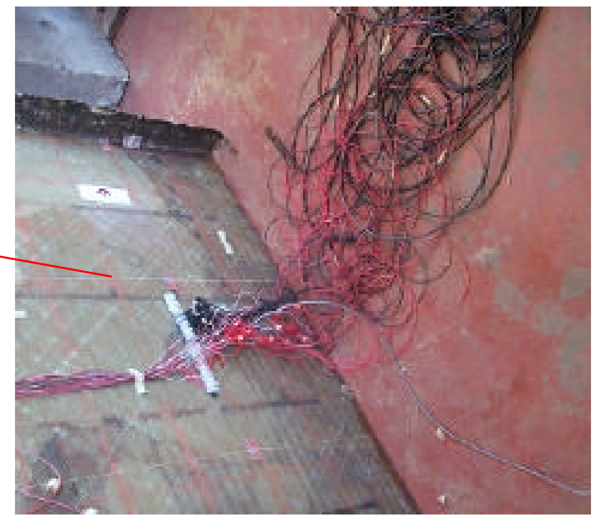
Experimental Setup
(Single Excitation With Multiple MEMS Sensors)

Objective: **Automated Prognostics**

Approach: **Substitute multiple hitting points with sensors (15 x 9=135), actuate limited number of locations**







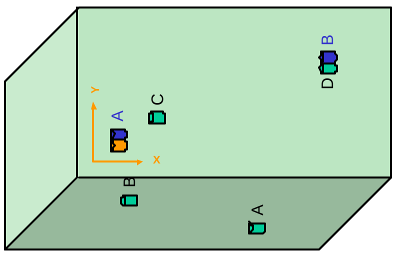
Shift a column of
15 MEMS sensors

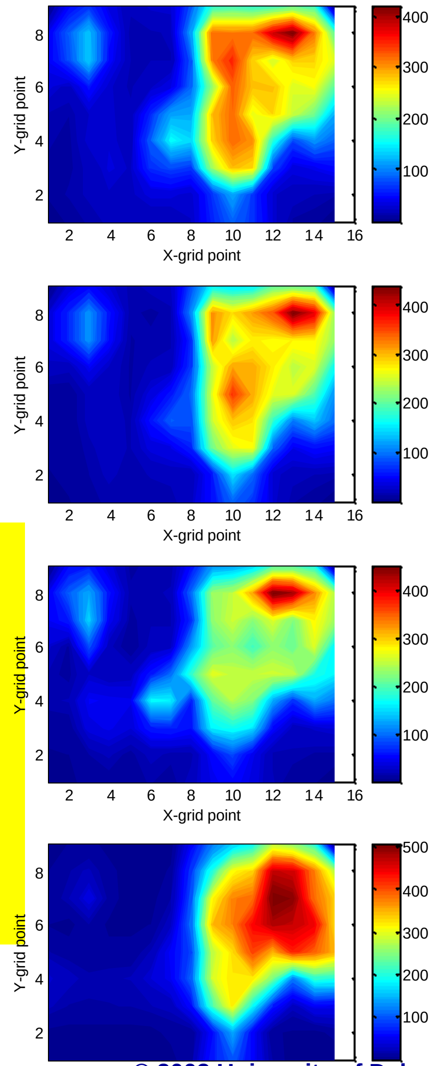
Limitations:
➔ Many sensor wires and connections

Solution:
➔ Wireless sensing system
➔ Sensors on fibers "SMART Structure"

Results for CIRTM Structure
(15 MEMS sensors: 15x9 grids, 100~1kHz)

'NEW' Excitation at one location | **'Classic' Sensing at one location**



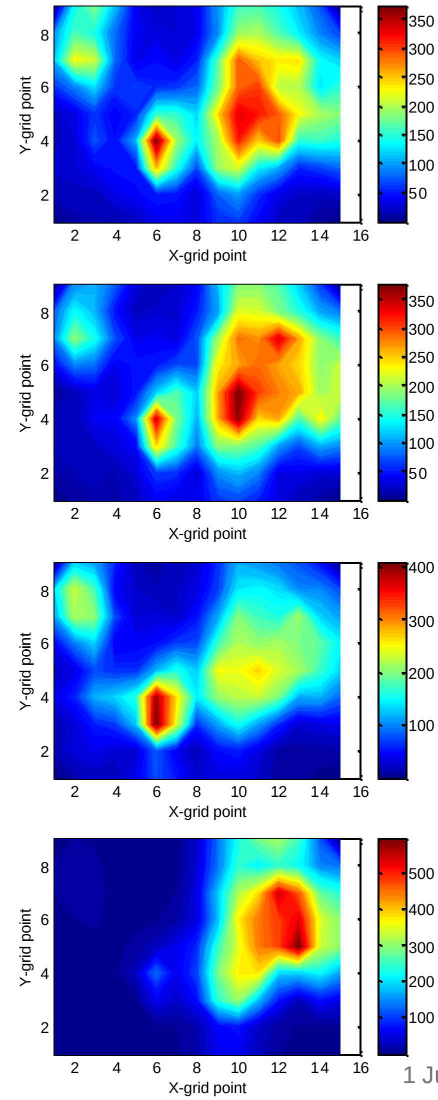


← Excitation A
Sensing A →

← Excitation B
Sensing B →

←Excitation C
Sensing C→

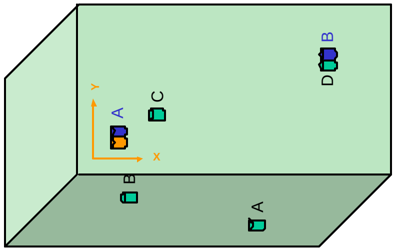
← Excitation D
Sensing D →



Results:

- New method is less sensitive to small damage than classic method
- Approach has been proven, inverting hitting location to sensor location works

Results for CIRTM Structure
(15 MEMS sensors: 15x9 grids, Frequency range)

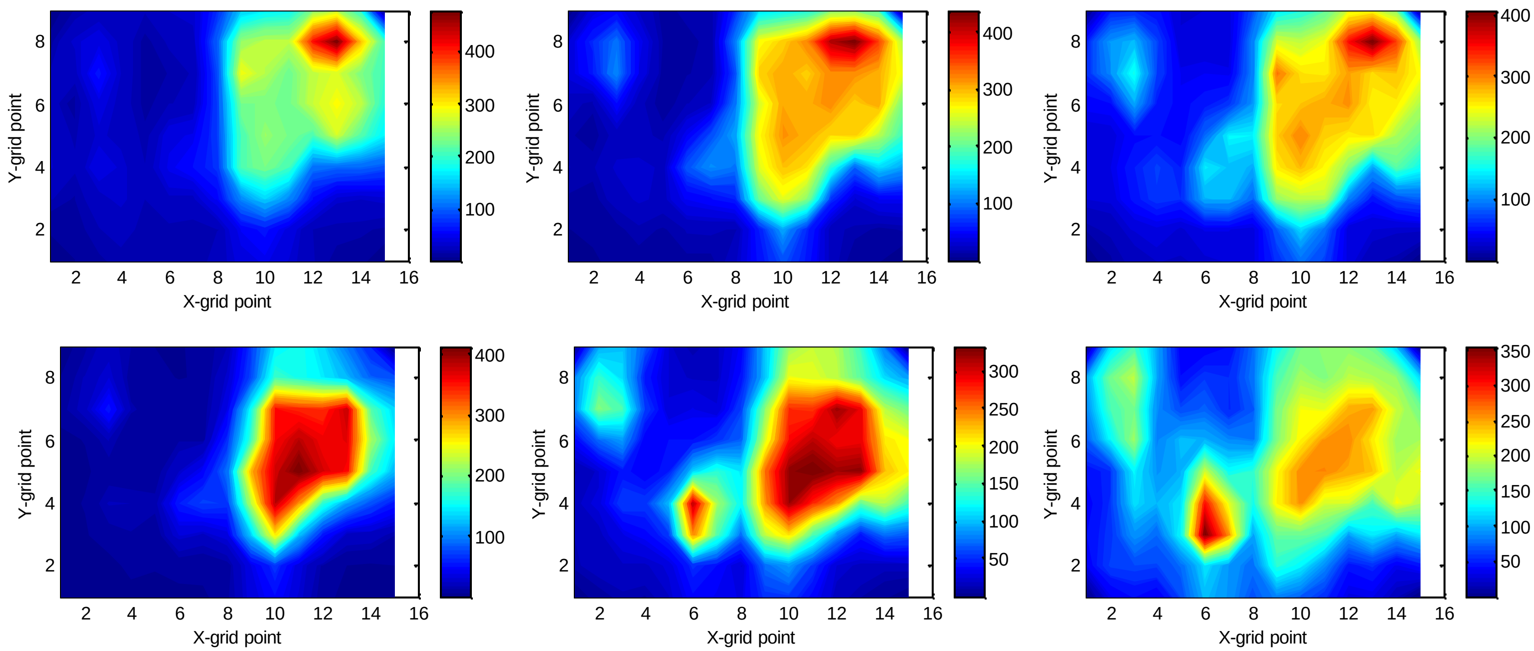


SII with sensors A+B+C+D (15 by 9 grids)

50~500Hz | 100~1kHz | 100~2kHz

Excitation at one location (New) ➩

Sensing at one location (Classic) ➩



Results: Resolution not as good as classic method with accelerometer but acceptable
➔ Improved frequency spectrum of sensor and robust wiring will improve results

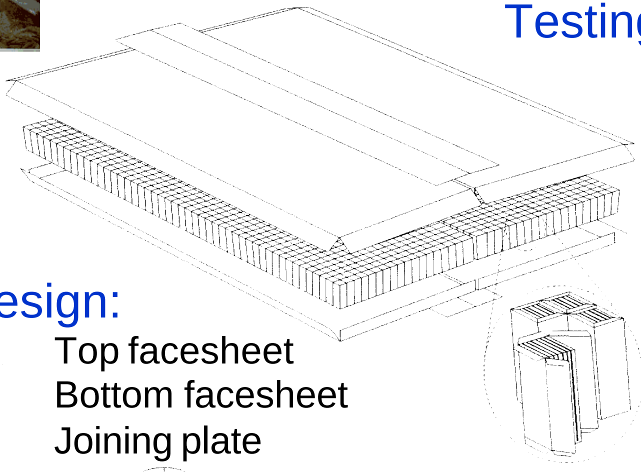
Large-Scale Structure
(Composite Bridge)

NDI Approach:

1. Visual inspection
2. Global NDI testing using vibration techniques ➔ Find anomalies, changes over time
3. Zoom in ➔ Local NDI techniques

Construction

Testing



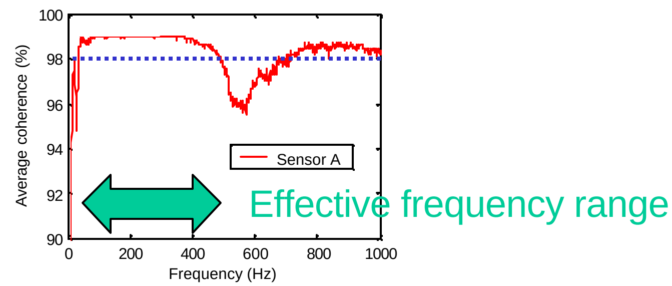
Design:

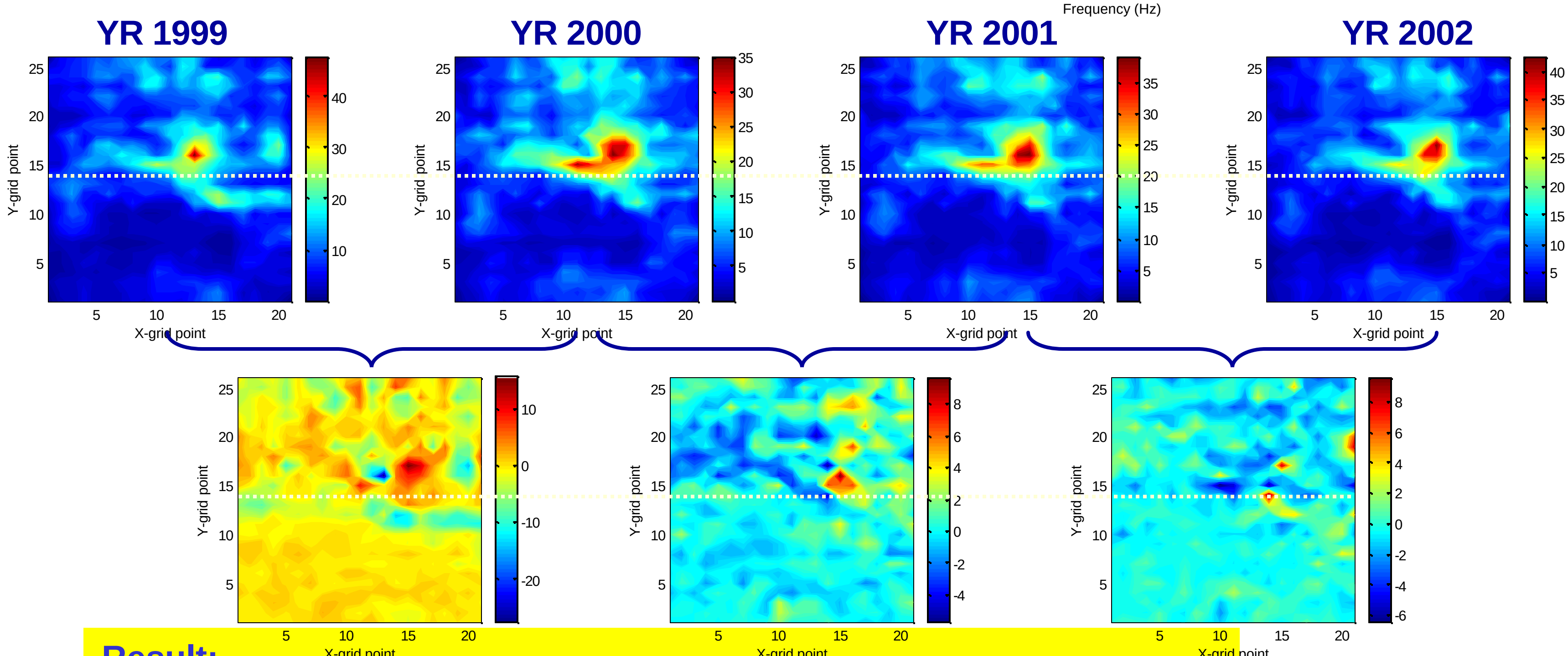
1. Top facesheet
2. Bottom facesheet
3. Joining plate

Results With Year

Frequency range: 50~500Hz
Data from sensor A
Dotted line: Joint line with splice plate

Coherence Function (YR 2002)





Result:

- All the tests show anomaly near joint line
- Anomaly does not change after initial settling in the first year
- Overall change is small in the following years
- Recommendation: Evaluate local anomaly with other NDI techniques

Data courtesy
of Ratcliffe + Crane

Conclusion

Work done:

- Modified 2-D Gapped Smoothing Method
  - Statistically treatment with outlier detection method
- Compared advanced sensors: MEMS & fiber optic strain sensors
- Applied to large-scale composite structures

Issues addressed:

- Large vs. small size of damage
- Definition of damage index (Square vs. absolute of curvature difference)
- Compared MS and ODS data
- Effects of locations of sensors and excitation
- Effects of frequency range
- Multi-excitation with single sensing vs. multi-sensing with single excitation

Ongoing And Future Work

ALGORITHM IMPROVEMENT

- Current algorithm improvement using generic smoothing techniques
- New algorithm for quantitative estimation of stiffness changes with baseline data obtained from FE model
- System integration with Labview programming using ActiveX (LABVIEW+MATLAB+OROS FFT Analyzer+MEScope Modal Analysis SW)
- New algorithm enabling reduced number of sensors with baseline data obtained from FE model

ADVANCED ACTUATORS AND SENSORS

- Piezoelectric actuators
- Fiber optic strain sensors
- Magneto-strictive strain sensors
- MEMS accelerometers
- Sensors on fiber

AUTOMATION OF DAQ AND DATA PROCESSING

- Wireless sensing

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- Dirk Heider
- Colin P. Ratcliffe
- Roger M. Crane

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