Impact Damage Tolerance Guidelines for Stiffened Composite Panels

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Virtual Meeting
Participants

• Principal Investigators & Researchers
  – PI: Prof. Hyonny Kim
  – Co-PI: Prof. Francesco Lanza di Scalea
  – Graduate Students
    ▪ PhD: Chaiane Wiggers de Souza, Ben Katko, Chengyang Huang, Janelle Dela-Cueva, Ranting Cui*, Margherita Capriotti*, Eric Kim*
    ▪ MS: none

* graduated since last review mtg (2019)

• FAA Technical Monitors
  – Lynn Pham, Ahmet Oztekin

• Other FAA Personnel Involved
  – Larry Ilcewicz
Motivation

- Impact to composite structures can cause internal damage
  - difficult to detect via visual inspection
- Ultrasonic guided wave (UGW) based inspection found to be sensitive to presence of internal damage
- External-only NDE needed as well as large-area fast inspection

Overall Objectives:
- Quantify detectable and non-detectable damage characteristics
- Relate Ultrasonic Guided Wave NDE measurements to damage state and residual strength

High Energy Wide Area Blunt Impact (HEWABI)

GSE Impact/Contact
Ultrasonic Guided Waves: structure is a natural “waveguide”

Ultrasonic excitation at 1.666E-04 sec
Previous Results Summary I: SIDO* Transfer Function Scanning Systems

Hybrid “Impact/Air-Coupled” Scanner

Mini-impactor + micro-machined capacitive transducers
“low” and “broad” frequency band
(40 – 270 kHz)
Previous Results Summary II: UGW Damage Detection

Manufactured Damage – Saw Cuts

Hybrid impact/air-coupled scanner
(40 – 270 kHz)

Actual Impact Damage:

stringer heel slit

stringer cap slit

Damage Index

Location (cm)

Damage Index

Location (cm)

(80J)

stringer flange impact

Damage Index

Location (cm)

stringer cap impact
(70J)

stringer cap impact
(50J)

stringer cap impact
(30J)
Previous Results Summary III: Residual Strength vs UGW

UGW vs OHT Experiments
Hexcel [0]_10 plain weave 282/SC780.
Holes from 2.5 mm to 25 mm dia, various frequencies

Comparison with UGW measurements show direct correlation between open hole tension strength reduction and signal attenuation.
New Results
Damage Detection in Stringer-Stiffened Panels: 5-Sensor NDE Scanning System with Impact Excitation

- **Goal 1:** develop a non-contact guided-wave ultrasonic NDE system to detect internal damage in stringer-stiffened panels,
  - access limited to the external side (OML)
  - compensating for varying excitation
- **Goal 2:** detect damage in the scanning direction (along the stringer axis) and further locate damage in the cross-sectional direction
5-Sensor NDE Damage Detection
Experimental Setup

(a) Location needle
(b) Mini-impactor window & LED
(c) Cart brakes

Mini-impactor
Foam layer
17° Wedge
Right angle
3D printed support
Specimens Description

- Curved 2-stringer carbon fiber-epoxy panel (unidirectional with woven outer plies)

- 2-Stringer panel with added mass (2cm diameter steel nuts) simulating damage

- 2-Stringer panel with saw-cut notches

- Stringer heel notch

- Stringer cap notch
UGW Damage Identification: Signal Processing Aspects/1

- Extract ultrasonic guided-wave (UGW) Transfer Function between combination of pairs of sensors ($H_{AB}$) by using a Normalized Cross-Correlation operation that compensates for any variations in impact excitation (“unknown source”).
- Track changes in time-domain Transfer Function to detect and locate damage.

\[
MS_1(f) = S(f) \cdot H_{SA}(f) \cdot RR_1(f) + ST_1(f) \quad MS_2(f) = S(f) \cdot H_{SA}(f) \cdot H_{AB}(f) \cdot RR_2(f) + ST_2(f)
\]

Transfer Function in Frequency domain (normalized cross-power spectrum):

\[
<\text{CrossPower}> = \frac{|S(f) \cdot H_{SA}(f)|^2 \cdot H_{AB}(f)}{|S(f) \cdot H_{SA}(f)|^2} = H_{AB}(f)
\]

Transfer Function in Time domain (inverse Fourier Transform):

\[
H_{AB}(t) = \int_{-\infty}^{\infty} H_{AB}(f) e^{i2\pi ft} df
\]
UGW Damage Identification: Signal Processing Aspects/2

- Process time-domain Transfer Functions through statistical Outlier Analysis along scan to minimize False Positives and maximize True Damage Detections.

Transfer function in time domain

Baseline Signals

Test Signals

Feature vector

\[ x = \{ \text{RMS, Skewness} \} \]

Damage Index (DI) :
(Mahalanobis Squared-Distance)

\[ (x - \bar{x})C^{-1}(x - \bar{x})^T \]

Baseline Vector
Average, Covariance
\( \bar{x}, C \)

Test Vector
\( x \)

Threshold

If DI>Threshold=>Defect
Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/1

Step-1: localize damage along the scanning direction.

Investigated frequency range (Rx - Ry)

Max(∑)
Step-2: localize damage in the cross-sectional direction.

Achieved via combination of receiver pairs.

Example: Zone-5 value (at location 20cm):

\[ R1_{-}R5_{20cm} \times 1 + (R2_{-}R5_{20cm} + R3_{-}R5_{20cm}) \times 0.8 \]

<table>
<thead>
<tr>
<th>Zone number</th>
<th>Dominant</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R1—R2</td>
<td>R1—R3, R1—R4</td>
</tr>
<tr>
<td>2</td>
<td>R2—R3</td>
<td>R1—R3, R2—R4</td>
</tr>
<tr>
<td>3</td>
<td>R3—R4</td>
<td>R3—R5, R2—R4</td>
</tr>
<tr>
<td>4</td>
<td>R4—R5</td>
<td>R1—R5, R3—R5</td>
</tr>
<tr>
<td>5</td>
<td>R1—R5</td>
<td>R2—R5, R3—R5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
<th>Zone 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage location 14cm</td>
<td>0.02</td>
<td>0.55</td>
<td>0.35</td>
<td>0.76</td>
<td>1.00</td>
</tr>
<tr>
<td>(20kHz ~ 110kHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage location 20cm</td>
<td>0.10</td>
<td>0.02</td>
<td>0.01</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>(50kHz ~ 110kHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step-2: localize damage in the cross-sectional direction.

Heel slit cut at 14cm
Stringer-cap slit cut at 20cm
Excitation: Mini-impactor Characterization and Parameterization

Background: intense UGWs excitation achieved via UCSD-created Mini-impactors; frequency content in $10^2$ kHz range (> order of magnitude than traditional impact hammers)

Objective: understand performance characteristics of Mini-impactors on various plate materials, be able to select “best” Mini-impactor for given plate and desired frequency range

1) Select Mini Impactor and Plate Permutation
2) Deflect Mini-impactor, Release
3) Trigger DAQ via Switch Circuit
4) Observe UGW via R15s Sensor
5) Record Excited R15s signal with DAQ

720 Raw Timeseries Experiments

720 Power Spectral Densities

Principal Component Analysis

Multivariate Analysis

Knowledge Discovery

Application Identification
Experimental Data and Signal Processing

Oscilloscope triggered via contact switch; raw voltage data from R15s piezoelectric sensor recorded

720 experiments conducted; time-history data converted to Power Spectral Density (PSD) plot showing frequency content

Testing Details:
• 1.5 mm thick CFRP plate impacted by the 6ply, 57 mm Mini-impactor. Repeated 10x.
• Impact triggers oscilloscope consistently, allowing unambiguous time alignment.

PSDs Used in Signal Analysis

[Graph showing experimental signals and trigger signal]
Data Analysis – A Data-Driven Approach (1)

- **Data Collection**
  - 720 experiments each sampled for period of 200\(\mu\)s at 80Mhz
  - 720 \(\exp\) \(\times\) 16004 \(\text{freq. bins}\) \(\approx\) 11E6 data points (High dimensional space)

- **Principal Components (PC) Analysis**
  1. **Matrix Factorization**
     - Pre-Operations on PSD Data Matrix
       - Subtract PSD Data Matrix Mean
       - Calculate Covariance Data Matrix from PSD Data Matrix
     - Main Operation
       - Eigendecomposition of Covariance Data Matrix *\textit{Akin to Vibrations Analysis Decoupling Step}*
     - Post-Operations
       - Sort eigenvectors by the sorted eigenvalues (descending)
  2. **Knowledge Discovery** (Multivariate Hotelling \(T^2\) Metric)
Data Analysis - A Data-Driven Approach (2)

Analyzed Subsets Of The Total Data. Divided By Plate Material Type

**ISOTROPIC MATERIAL**
- **6061-T6 Aluminum**
- **Heat Treated Steel**

**ANISOTROPIC MATERIAL**
- **7781 8H EGlass**
- **Hexcel 282 3K CFRP**

Isotropic Materials Require More PCs, More Frequencies Excited Across Spectrum

Anisotropic Data Is Described With Only 2 PCs, Less Frequencies Excited Across Spectrum

**Main Take Away:**
Eliminating unnecessary data that is contributing to the total signal can be achieved through this data matrix decoupling. Determining the number of principal components is achieved by truncating the PCs at a threshold value (e.g. 95%). It might be the case that the first 6 principal components achieve 95% contribution but only comprise of 3% of the original data. The remaining 97% of the data can be truncated.
## Results: Mini Impactor Selector

For plate/shell structure of interest, best mini impactor providing UGW excitation:

<table>
<thead>
<tr>
<th>Plate Material</th>
<th>Plate Thickness (mm)</th>
<th>Best Mini Impactor</th>
<th>Max Freq Content (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon/Epoxy</td>
<td>4.86</td>
<td>6 Ply x 57 mm</td>
<td>300</td>
</tr>
<tr>
<td>3K Plain Weave</td>
<td>1.39</td>
<td>8 ply x 88 mm</td>
<td>270</td>
</tr>
<tr>
<td>VARTM Epoxy</td>
<td>0.99</td>
<td>4 Ply x 38 mm</td>
<td>270</td>
</tr>
<tr>
<td>Glass/Epoxy</td>
<td>5.46</td>
<td>6 ply x 57 mm</td>
<td>200</td>
</tr>
<tr>
<td>7781 8HS</td>
<td>1.45</td>
<td>6 ply x 57 mm</td>
<td>250</td>
</tr>
<tr>
<td>VARTM Epoxy</td>
<td>0.99</td>
<td>4 Ply x 38 mm</td>
<td>250</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6.67</td>
<td>8 ply x 88 mm</td>
<td>210</td>
</tr>
<tr>
<td>6061-T6</td>
<td>1.65</td>
<td>8 ply x 76 mm</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>4 Ply x 38 mm</td>
<td>370</td>
</tr>
<tr>
<td>Steel</td>
<td>7.17</td>
<td>6 ply x 57 mm</td>
<td>225</td>
</tr>
<tr>
<td>Heat Treated</td>
<td>1.48</td>
<td>8 ply x 76 mm</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>0.76</td>
<td>4 Ply x 38 mm</td>
<td>400</td>
</tr>
</tbody>
</table>
Objective

• Correlate UGW Measurements to Open Hole Tension Strength for More Complex Layups; Use Analysis of Wave Dispersion
  – Quantify Residual Strength vs Hole Dia. vs UGW Metrics
  – Measure UGW Dispersion Degradation Relative to Baseline State

Methodology

• Specimen Interrogation
  – Excite Specimen with Mini-impactor
  – Observe Stress Waves at Selected Distance with Broadband Acoustic Transducers (BATs)
  – Shift Sensors By $\Delta x$ and Repeat Experiment
  – Calculate Lamb Wave Dispersion for All Cases and Compare

• Open Hole Tension
  – Specimens Cut After UGW Scanning Completed
  – Test to Failure; Full-Field Strain via Digital Image Correlation
UGW Estimation of OHT Residual Strength (2)

New Specimen Series – Quasi-Isotropic Type Layup (previously only $[0_{10}]$)

- Completed Manufacturing of two Hexcel PW 282 3K/ VARTM Epoxy Plates
  - Layup $[0/45/0/-45/0]_s$
- Fabricating Linear Sensor Stage
  - Hole Diameters (inch) – [0.0469  0.0625  0.0925  0.125  0.25  0.50  1.00]
  - Constant Specimen Width to Diameter Ratio $W/D = 4$

Future Work

- Planned Experimentation
  - Baseline UGW measurement (pristine/undamaged panel)
  - Drill holes
  - Damaged state UGW through holes
  - Cut into OHT specimens with $W/D = 4$
  - Test to failure
- Extended to Impact Damage
  - Repeat above but with impact damage instead of drilled holes
HEWABI Results: Test Setup and Failure Modes

1D Table Movement

Loc3

Loc4

Loading Pad

Crack on shear tie corner

Second crack on shear tie

Passenger floor beam crack

Extensive shear tie cracks

Loc3-1_L2

Loc3-2_L4

Loc4-2_L6

Loc4-2_L6

HEWABI Project Concluded 2020
HEWABI Results: Failure Modes

Stringer cut by shear tie

Stringer flange disbond & Stringer heel crack

C-frame crack across Hi-Lok

Shear tie crack originating from mouse hole and following C-frame crack

HEWABI Project Concluded 2020
Conclusions

• Designed a mobile scanning system using five air-coupled ultrasonic sensors and impact excitation.
• Extracted the Transfer Function of the structure between two sensors as output-only system (compensating for variations in “unknown” excitation).
• Proposed a two-step scheme for damage detection and location:
  • Step-1: Detect damage along the scanning direction
  • Step-2: Localize the damage along the cross-section
• Mini-Impactor characterization identifies best impactor configuration for excitation of ultrasonic guided waves
• OHT residual strength correlates strongly with UGW signal attenuation
  • Extension to quasi-isotropic type layups
Benefits to Aviation

- Robust UGW scanning system to detect damage realistically caused by GSE
  - accessing only aircraft external side
- Identification of damage on stringer-stiffened panels along the cross-section
- Mini Impactor provides simple method for creating high-intensity ultrasonic excitation in 100s kHz range
- Residual tension strength strongly correlated with attenuation of UGW measurements – provides ability to non-destructively assess strength loss
Future Work

- Improve damage detection capabilities for small damage, or narrow damage relative to the wave propagation direction
- Automate mini-impactor excitation mechanism for faster scanning
- Extend damage detection/location to more internal components (shear tie and C-frame)
- UGW and OHT strength experimentation on quasi-isotropic type specimens
- Estimation of residual strength reduction of stringer-stiffened panels vs NDE (UGW) measurements