Detection and Classification of Damage in Composite Plates Due to Low Velocity Impact Forces Using Neural Networks

By

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Health Monitoring of Composite Structures

• Advanced Fiber-reinforced Composite materials - used extensively in Aerospace, Civil and other applications.

• Although designed and inspected carefully for fatigue loading, these structures have internal damage or cracks that escape inspection.

• Ever-increasing need to build intelligence in them - They can serve and react accordingly to the environment.

• Field of Smart Structures has emerged and made possible through the merger of Materials Science, Sensor Technology, Structure Mechanics and Advanced Signal Processing Techniques.

• Neural Networks have emerged as a major contender in implementing intelligence in Composite Structures owing to their Parallel processing, Learning and Adaptive capabilities.

• On-line Health Monitoring and Control of composite structures can be implemented by incorporating neural networks for

  * Damage Assessment
  * Fatigue Monitoring
  * Delamination Detection
Damage Detection & Classification

• Important part of Health Monitoring of a Composite Structure.

• Study - concentrated on “Low Velocity Impact Behavior”

• Low velocity impact events can induce localized delamination - significantly reduce the compression strength of composite structures.

• Many times - damage from impact due to low velocity events cannot be detected by visual inspection techniques.

• The experimental determination of impact-induced strain profiles can help predict the extent of damage in composite plates.

• Visual inspection techniques (Surface inspection) may not indicate the severity and extent of the internal damage such as cracking and delamination

• Artificial neural networks can be incorporated for real time monitoring of composites for damage detection and classification.
Experimental Setup

• Several experiments were performed with varying weights falling from different heights (different final velocities).

• Three PVDF (Polyvinylidene Fluoride) piezoelectric film sensors were placed as shown in the ‘X’, ‘Y’ & ‘XY’ directions to measure the respective directional strains.

• The same experiment was simulated using FEA for 5 different locations on the composite plate.

- Sensor in the ‘Y’ Direction
- Sensor in the ‘X’ Direction
- Sensor in the ‘XY’ Direction
• The strain in time is sampled every 4 µs and stored in files for every experiment performed.
Relationship of Strain to Damage

- Experiment - performed with a particular mass dropped from a particular height (having a different terminal velocity); Therefore - different Kinetic Energy \( \frac{1}{2}m*v^2 \).

- Peak contact force \( \propto \) Kinetic energy of the falling mass \( \propto \) Amount of damage (visual inspection)

- Each contact force profile - strain profile - can be used to predict the damage.
Pre-processing of Strain Samples for the Training Set

- Strain X and Y were chosen for the inputs to the neural network. They had to be pre-processed before they could be used for training the neural network.

Strain X = [1005] elements

Strain Y = [1005] elements

Strain X+Y = [2010] elements

All elements scaled between 0 and 1

Strain X+Y = [2010] elements

Vectors are down sampled to remove redundancy

Strain X+Y = [503] elements

Total of 141 Input Vectors, each of 503 elements.

15 vectors for simulation purposes

126 vectors for training purpose
Damage Classification and Setting up of Target Vectors

A total of Seven (7) Classifications were decided upon by visually inspecting the composite plates and the Kinetic Energy of the falling mass. The classification is coded using “GRAY CODE”

<table>
<thead>
<tr>
<th>CLASSIFICATION</th>
<th>KINETIC ENERGY RANGE (J) (0.5<em>m</em>v*v)</th>
<th>CODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO DAMAGE</td>
<td>&lt;=0.1</td>
<td>[0 0 0]</td>
</tr>
<tr>
<td>MINUTE SCRATCHES</td>
<td>0.1&lt; K.E. &lt;=0.3</td>
<td>[0 0 1]</td>
</tr>
<tr>
<td>MINOR PARALLEL SURFACE CRACKS</td>
<td>0.3 &lt; K.E &lt;=4</td>
<td>[0 1 1]</td>
</tr>
<tr>
<td>SURFACE DISCOLORATION &amp; SMALL MATRIX CRACKS</td>
<td>4 &lt; K.E. &lt;= 8</td>
<td>[0 1 0]</td>
</tr>
<tr>
<td>DISCOLORATION &amp; LONG MATRIX CRACKS</td>
<td>8&lt; K.E. &lt;=10</td>
<td>[1 1 0]</td>
</tr>
<tr>
<td>MODERATE DISCOLORATION, DELAMINATION &amp; LONG MATRIX CRACKS</td>
<td>10 &lt; K.E. &lt;=12.5</td>
<td>[1 1 1]</td>
</tr>
<tr>
<td>SEVERE DISCOLORATION, SEVERE DELAMINATION &amp; LONG MATRIX CRACKS</td>
<td>K.E &gt; 12.5</td>
<td>[1 0 1]</td>
</tr>
</tbody>
</table>

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Architecture of the Neural Network

- Multi-layered Feed-forward Network is used
- 10 neurons in the Hidden Layer
- As we have 7 Classifications implemented in Gray Code, we have 3 neurons in the output layer
- Transfer Functions of both hidden and output layer is “LOGSIG”
Training Algorithm

• Backpropagation using several training algorithms were used to train the network.

• Levenberg Marquardt couldn’t be used because of the huge memory requirements for 503 elements of the input vector.

• “Conjugate Gradient Method” & “One Step Secant Method”, used to train the network give good results, with the former converging earlier.

• Conjugate Gradient Method is suited for large size input vectors. One step secant method requires more storage space than conjugate gradient method, therefore takes a longer time to converge.

• The network was trained for 4000 epochs to obtain the required mean squared error.
Performance and Mean Square Error Curves

One Step Secant Method

Conjugate Gradient Method
Results

\[ b = \]

Columns 1 through 12

\[
\begin{array}{cccccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\
\end{array}
\]

Columns 13 through 15

\[
\begin{array}{cccc}
0 & 0 & 0 & \\
1 & 1 & 1 & \\
1 & 1 & 1 & \\
\end{array}
\]

tna =

Columns 1 through 12

\[
\begin{array}{cccccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
\end{array}
\]

Columns 13 through 15

\[
\begin{array}{cccc}
0 & 0 & 0 & \\
1 & 1 & 1 & \\
1 & 1 & 1 & \\
\end{array}
\]

Linear Regression between First Output and Targets

\[ A = (0.998) T + (0.000374) \]

\[ R = 1 \]
Results

Linear Regression between Second Output and Targets

Linear Regression between Third Output and Targets
## Comparison with other Training Algorithms

### Number of Errors using THREE algorithms for all the 5 locations

<table>
<thead>
<tr>
<th>Location 1</th>
<th>TRAINING ALGORITHM</th>
<th>PA (503 ELEMENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD. GRADIENT DESCENT</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>RESILIENT BP</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>ONE STEP SECANT</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location 2</th>
<th>TRAINING ALGORITHM</th>
<th>PA (503 ELEMENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD. GRADIENT DESCENT</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>RESILIENT BP</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>ONE STEP SECANT</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location 3</th>
<th>TRAINING ALGORITHM</th>
<th>PA (503 ELEMENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD. GRADIENT DESCENT</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>RESILIENT BP</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>ONE STEP SECANT</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location 4</th>
<th>TRAINING ALGORITHM</th>
<th>PA (503 ELEMENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD. GRADIENT DESCENT</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>RESILIENT BP</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>ONE STEP SECANT</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location 5</th>
<th>TRAINING ALGORITHM</th>
<th>PA (503 ELEMENTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD. GRADIENT DESCENT</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>RESILIENT BP</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>ONE STEP SECANT</td>
<td>3</td>
</tr>
</tbody>
</table>

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Conclusions & Future Improvements

• A Multi-layered feed-forward neural network was successfully trained to classify damage on Composite plates due to low velocity impact events.

• Accuracy can be increased to 100% by performing more experiments to generate a larger data set for training and simulation.

• This project has demonstrated the ability of a neural network to be incorporated into “Smart Structures” for their Health Monitoring.
Questions