Automatic defect detection in fiber-reinforced polymer matrix composites using thermographic vision data

Gonçalves Maria S., Miguel A. Machado, Telmo G. Santos, Nuno Mendes

Department of Mechanical and Industrial Engineering; NOVA University of Lisbon, Caparica, Portugal

Abstract: The detection of internal defects, not visible to the naked eye from the outside of materials, using non-destructive testing (NDT) are increasingly requested by industrial processes. This study proposes a novel methodology for acquisition and processing of images from a thermographic camera using computer vision methods to test composite materials made of a polymer matrix reinforced with glass, carbon, and kevlar fibers. The image is acquired while cooling the sample, following a suggested procedure. The processing methodology is divided into three steps, image pre-processing, image processing, and data post-processing. In image preprocessing, filters are applied to improve image quality, and methods are proposed to segment and identify the region of interest. In image processing, a blob analysis method is suggested for defect identification, isolation and characterization. A data analysis method is proposed for the post-processing step to characterize the defects identified in the previous step. Samples with known defects in terms of size, geometry, and location were used to test the developed system. The system showed high performance, achieving 98% accuracy, and suitability for defect detection larger than 0.5 mm in thickness and 600 mm² in area. The experimental results showed that the algorithm did not detect any false positives, and that the type of reinforcement used in the analyzed samples had no influence on the results. On the other hand, the depth of the delaminations had an influence on the pixel intensity contrast of the defect region, and its instant of maximum contrast. The lesser the depth of the defects detected, the higher the value of their intensity and the shorter the instant of maximum contrast.
Automatic defect detection in fiber-reinforced polymer matrix composites using thermographic vision data

Nuno Mendes

NOVA School of Science and Technology
Universidade NOVA de Lisboa
Outline

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- Proposed approach
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Motivation

The presence of internal defects, such as delamination, in polymer matrix composites compromises the performance of these materials and the safety of the people who work with them.

There is interest in non-destructive and automated inspection of these materials.

The inspection technique of active thermography may be part of the solution.
Aim

In this study an automatic system for defect detection in composite parts using the technique of active transient thermography in reflection mode is proposed.
Proposed approach

An inspection system was developed at the hardware and software level.

The main hardware:

• Thermography camera IRS336 series from Automation Technology;
• Four high heat transmission halogen lamps of 175 W;
• A DAQmx module from National Instruments; and
• A computer.
Software

Start → Parameter definition → Thermography testing → Image pre-processing → Image processing

Stop ← Presentation of results ← Data Post-processing

Were any defects detected? Yes → Thermograms over time

No
Image pre-processing
The region of interest is cropped from the captured image, frame by frame.

Image processing
Three filters are applied to the captured images, allowing the system to distinguish a defective area from a non-defective area.

• The first two filters are a combination of morphological dilation and an image arithmetic operation.

\[
I_{1_{ij}}(t) = 2 \cdot I_{\text{sample}_{ij}}(t) - A \cdot I_{\text{sample}_{i-m,j-n}}^{i+m,j+n}
\]  
(1)

\[
I_{2_{ij}}(t) = B \cdot I_{1_{i-m,j-n}}^{i+m,j+n} - I_{1_{ij}}(t) + 40
\]  
(2)
• The images resulting from the second filter are then segmented according to the peak of their histogram.

• From this segmentation, blobs that may or may not correspond to defects in the sample are detected. These blobs are discriminated by their area size $[\text{min}A \; ; \; \text{max}A]$.

• Each image is divided into nonoverlapping blocks of 6×6 pixels. The sum of the incidence of blobs in each block over time is then performed and stored in $S_{\text{block}_{k,l}}$.

$$V_{\text{index}_{d,2}} = \begin{cases} (k, l) & S_{\text{block}_{k,l}} > f r_1 \cdot (\text{frame}_{\text{final}} - \text{frame}_{\text{initial}}) \\ \emptyset & S_{\text{block}_{k,l}} \leq f r_1 \cdot (\text{frame}_{\text{final}} - \text{frame}_{\text{initial}}) \end{cases}$$
Data post-processing

• The average position of the centroids ($\overline{P_d}$) of each detected defect is calculated;
• The defect’s average areas ($\overline{A_d}$); and
• The difference between the pixel intensity of each defect detected with the average intensity of its neighborhood over time ($I_{\text{contrast}}$).

$$\overline{P_d} = \frac{\sum_{t=\text{frame}_{\text{initial}}}^{\text{frame}_{\text{final}}} P_d(t)}{\text{frame}_{\text{final}} - \text{frame}_{\text{initial}}}$$  \hspace{1cm} (5)

$$\overline{A_d} = \frac{\sum_{t=\text{frame}_{\text{initial}}}^{\text{frame}_{\text{final}}} A_d(t)}{\text{frame}_{\text{final}} - \text{frame}_{\text{initial}}}$$  \hspace{1cm} (6)

$$I_{\text{contrast}}(t) = |I_{\text{sample}_{ij}}(t) - I_{\text{neighbourhood}_{ij}}(t)|$$  \hspace{1cm} (7)
Experiments

- Thermoplastic polymer polylactide (PLA) samples reinforced with Kevlar (K), carbon (C), or glass (G) fiber were produced by fused deposition modeling (FDM) and tested.
- The samples’ dimensions were $120 \times 120 \times 5.5 \text{ mm}^3$.
- Inside, there were defects (delamination) $12 \times 50 \times 0.5 \text{ mm}^3$ in size, located at different depths:
  - defect type I was located at 1.38 mm.
  - defect type II was located at 2.75 mm.
  - defect type III was located at 4.12 mm.
## Test Parameters

<table>
<thead>
<tr>
<th>Thermography parameters</th>
<th>Image processing parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample heating time (s)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>$minA$ (%)</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>$maxA$ (%)</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Video acquisition time (s)</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>$fr_1$ (%)</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
</tbody>
</table>
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Maria S. Gonçalves  mdr.goncalves@campus.fct.unl.pt
Miguel A. Machado  miguel.m@fct.unl.pt
Telmo G. Santos  telmo.santos@fct.unl.pt
Nuno Mendes  nam.mendes@fct.unl.pt
Results

<table>
<thead>
<tr>
<th>Sample reinforcement</th>
<th>Kevlar</th>
<th>Carbon</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect type</td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>No. of defects detected</td>
<td>5/5 (100%)</td>
<td>4/5 (80%)</td>
<td>5/5 (100%)</td>
</tr>
<tr>
<td>Total no. of defects</td>
<td>5/5 (100%)</td>
<td>4/5 (80%)</td>
<td>5/5 (100%)</td>
</tr>
<tr>
<td>Time of max contrast (s)</td>
<td>38</td>
<td>49</td>
<td>59</td>
</tr>
<tr>
<td>Average defect area (mm²)</td>
<td>731</td>
<td>518</td>
<td>586</td>
</tr>
</tbody>
</table>
Discussion

• The system performed well, achieving 98% accuracy by detecting 44 out of 45 defects present in the samples.

• Only one defect, type II, contained in a Kevlar-reinforced sample was not detected because the centroids of its respective blob over time were on the boundary between more than two divisions.

• The time of maximum contrast observed for each defect type are similar between the different sample reinforcements.

• The areas calculated by the algorithm are close to the actual areas of the defects (600 mm²).
Conclusions

- The methodology suggested in this study proved to be effective for performing thermography NDT and automatic defect detection in composites;
- The system showed high performance, achieving 98% accuracy, and suitability for defect detection with an area of 600 mm$^2$;
- Most of the tests performed in the samples with type I, II and III defects were able to detect all the delamination present in the samples;
- The automatic defect detection algorithm did not detect any false defects in any of the tests performed, proving to be robust and reliable;
- The type of reinforcement used in the samples had little influence on the results.
Thank you for your attention!

Nuno Mendes
(nam.mendes@fct.unl.pt)
NOVA School of Science and Technology
Universidade NOVA de Lisboa