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Thermographic data analytics-based damage characterization in a large-scale composite structure under cyclic loading

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ABSTRACT

Large-scale composite structures such as aircraft wings and wind turbine blades undergo cyclic loading in operation. In-service damage often generates excessive heat due to material frictions and it could be detected by thermography. This study develops a methodology to quantitatively analyze such structural damage based on thermographic data analytics. A full-scale composite wind turbine blade is inspected using passive thermography when it is subject to cyclic loads in laboratory. The damage region is identified from thermographic images and it is tracked automatically using image processing. The damage region is subsequently characterized on both overall and detailed levels. The change of the damage status versus fatigue cycle number is analyzed and the information regarding the growth of the damage area and the damage severity is provided. The initiation and the progress of damage are investigated based on the temperature and the enthalpy change in the damage region. This study provides a viable solution for efficient structural health monitoring and damage prognosis of large-scale composite structures under cyclic loading.

1. Introduction

Infrared thermography allows for non-contact and efficient damage detection in materials, structural components and full-scale structures [1–3]. When loaded dynamically, the damage region within a material can generate more heat than the intact region, e.g., due to material friction [4]. The damage region might be detected from thermographic images. Several studies have demonstrated successful application of thermography to detect cracks and delamination in large-scale composite structures such as wind turbine blades [5–7]. Nevertheless, damage detectability is still challenged by many factors such as surface emissivity and reflectivity of the structure [8,9]. Thermal image processing techniques, e.g., matching filters and thermal signal reconstruction [6], are used to improve the damage detectability. In [10], it was found that the norm of the first derivative of temperature and continuous wavelet transform in 2D were the most effective in detecting cracks that are perpendicular to the direction of heat propagation, whereas the Fourier transform and 1D continuous wavelet transform were successful in detecting delaminations. In [11], the authors described temperature evolution in the damage zone based on the thermoelastic equation. Three distinctive regions in the temperature curve were observed with the initial linear decrease the end of which corresponds to so-called damage stress below which the material did not show any detectable damage. Thermograms of a glass fiber composite plate containing hole defects of different sizes were analyzed in [12] using differential absolute contrast between the damaged and the damage-free regions. Progressive damage of a full-scale wind turbine blade subject to fatigue loading is detected using passive thermography while the blade is in motion [13].

The aforementioned studies focus on the detecting damage using thermography. After the damage is detected, it is important to evaluate the severity of damage. The damage evaluation requires quantitative analysis of the thermal images and an in-depth understanding of the underlying thermal–mechanical mechanism. This motivates the current study, which aims to develop a method to analyze the damage based on thermal images and provide insights into damage evolution in a structure under cyclic loading. The developed method is demonstrated on a full-scale composite wind turbine blade subject to fatigue loads in laboratory. The damage region of the blade is detected remotely based on thermography. After the damage is detected, it is important to evaluate the severity of damage. The damage evaluation requires quantitative analysis of the thermal images and an in-depth understanding of the underlying thermal–mechanical mechanism. This motivates the current study, which aims to develop a method to analyze the damage based on thermal images and provide insights into damage evolution in a structure under cyclic loading.

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thermography image data analytics as shown in Fig. 1. Image pre-
detailed levels. Section 3 presents the experiment of the full-scale blade
of the proposed method. The image processing of the raw thermal video
maximum and maximum temperature range of thermography images.
Subsquently, an intensity thresh-
 ration video. The locations of strucutral damage can be identified due to
quantitative damage characterization. Based on these findings, Section 5
summarizes the major conclusions and outlooks of this study.

3. Experimental setup

The experiment has been conducted by a previous study [14], see
Fig. 2. It is worthy to briefly describe the experimental setup here. The
test object is a 14.3-m full-scale composite wind turbine blade made of
unidirectional, biaxial, and triaxial fiberglass/polyester laminates,
chopped fiber mats, and PVC foams. The blade was subject to cyclic
loading during a fatigue test. A dual-axis electro-actuated exciter is used
to induce a bi-axial cyclic load on the blade. Amplitudes of loading in
 EDgewise and edgewise directions are set to ±8400 N and ±1200 N,
respectively. Loading frequencies are selected to be equal to the
fundamental resonant frequencies – 2.25 Hz in flapwise and 4.37 Hz in
edgewise directions.

Thermography video of the blade under cyclic loading is recorded
using an infrared thermal camera FLIR A655SC containing an uncooled
microbolometer detector with a resolution of 640 × 480 pixels and a
pitch of 17 μm. The accuracy of measurement is ±2 °C or ±2 % of
reading. The field of view (FoV) is 25° × 19°. The camera is placed 9.3 m
above the ground and measures the temperature in its FoV during the
fatigue test. No external heat source is applied to the blade. The surface
damage grew under cyclic loading and generate thermal footprints that
can be detected using passive thermography.

4. Results and discussion

4.1. Extraction of the damage region

A thermal video with a frame rate of 10 fps is recorded which pro-
duces a total number of 751 image frames. Image resolution is 640 ×
480 pixels. A thermal image is shown in Fig. 3 (a), while Fig. 3 (b) de-
picts a zoomed-in view of the surface damage, which is referred to as the
damage region throughout the rest of the study.

The recorded RGB images were converted to grayscale images
through the rgb2gray command in Matlab in order to ease the image
analysis procedure. The grayscale image at frame 1 is shown in Fig. 4 (a)
with the color bar showing the grayscale value intensities. The damage
region is marked with a red circle and the pixel size 26 and 40 along x
and y axis, respectively, is marked in the image.

A rectangular zoomed-in image of 40 × 26 pixels is selected as shown
in Fig. 4 (b). In order to only retain relevant information related to the
damage, a threshold was applied to the zoomed-in image region in Fig. 4
(b) to filter out the lower grayscale values. The selection of the threshold
is based on the distribution of grayscale intensities and it is set to 150
in this study. The value is approximately in the upper quartile of the
intensity range.

The grayscale values of the damage region were transformed into
temperature values. The maximum and the minimum temperatures of
each frame in a thermography video were obtained. Subsequently, the
temperature range was normalized by the maximum gray-scale value in
an image frame as

\[ ΔT_j = \frac{\text{max}(T_j) - \text{min}(T_j)}{255} \]  

(1)

Conversion from gray-scale to temperature maps was achieved ac-

mechanism are investigated in detail. As such, the novelty and the sig-
nificance of this work are as follows:

- We propose an efficient method to characterize progressive damage
  in large-scale composite structures under dynamic loading by
  analyzing thermal images.
- The method evaluates the growth and the severity of damage
  noncontact and in near real-time using passive thermography
  without applying external heat source to the structure.
- The method provides a possible solution for efficient structural
  health monitoring and damage prognosis of large-scale structures
  under dynamic loading.

The paper is organized as follows. Section 2 describes the framework
of the proposed method. The image processing of the raw thermal video
is presented and the image analysis is performed on both overall and
detailed levels. Section 3 presents the experiment of the full-scale blade
 test under dynamic loading and how the raw thermal video is taken.
Section 4 discusses the results from thermal image data analysis for
quantitative damage characterization. Based on these findings, Section 5
summarizes the major conclusions and outlooks of this study.

2. Framework of the proposed method

This study develops a methodology for characterizing damage evo-
uon under complex fatigue loading. This methodology is based on
thermography image data analytics as shown in Fig. 1. Image pre-
cessing starts with extracting the image frames from a thermog-
raphy video. The locations of structural damage can be identified due to
temperature difference. RGB color images are converted into gray-scale
to characterize the intensity of each pixel with just one value instead of
tree to ease further analysis. The damage region is zoomed in and
isolated from the original image and is further analyzed. Due to the
motion of the damage region in the structure under cyclic loading, an
image correlation technique is used to align the coordinates of the
damage region in all video frames. Subsequently, an intensity thresh-
olding is applied to the gray-scale images to identify the damage. The
thresholded gray-scale values are converted to temperature using min-
umin and maximum temperature range of thermography images.
Finally, temperature distribution of the damage region is obtained for
damage characterization.

Evolution of the damage under fatigue loading is analyzed on overall
and detailed levels. Analysis outcomes on overall level provide infor-
mation on the change of damage status, i.e., the growth of damage area
and the increase of damage severity in three distinct stages. Detailed
analysis, on the other hand, gives information on thermal and me-
chanical processes inside the damage region. The underlying thermal–
mechanical mechanism behind the damage growth is investigated by
dividing the damage region into zones of different temperatures and
analyzing the interaction between these zones.

3. Experimental setup

The experiment has been conducted by a previous study [14], see
Fig. 2. It is worthy to briefly describe the experimental setup here. The
test object is a 14.3-m full-scale composite wind turbine blade made of
unidirectional, biaxial, and triaxial fiberglass/polyester laminates,
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\[ ΔT_j = \frac{\text{max}(T_j) - \text{min}(T_j)}{255} \]  

(1)

Conversion from gray-scale to temperature maps was achieved ac-

Nomenclature

$\rho$ material density [kg/m$^3$]
$\varepsilon_p$ specific heat capacity at constant pressure [J/(kg × K)]
$q$ heat flux vector [W/m$^2$]
$\kappa$ thermal conductivity [W/(m × K)]
$\nabla T$ temperature gradient [K/m]
$V_{pix}$ pixel volume in physical space [m$^3$]
$N_x^j$ number of pixels along damage length
$N_w^j$ number of pixels along damage width
$l$ damage length [m]
$w$ damage width [m]
i = 1, 2, ..., I number of pixels within damage region
$j = 1, 2, ..., J$ number of image frames
$n_f$ number of fatigue cycles
$T_i$ absolute temperature in pixel i at frame j [K]
$T_{amb}$ absolute ambient temperature [K]
$\Delta h$ enthalpy change of the damage region at image frame j [J]

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\[ T_i = \min(T_f) + G_i \times \Delta T_j \]

where \( T_f \) is a temperature map and \( G_i \) is a gray-scale map of damage region at pixels \( i = 1:I \) and frames \( j = 1:J \) with \( J = 751 \).

4.2. Alignment of image coordinates

The blade is moving during the fatigue test with respect to the stationary camera. The temperature profiles of the damage region as seen by the camera are not aligned from frame to frame. In order to track the damage growth by comparing the image information in all frames, the coordinates of frame images should be aligned. In this study, a 2D image correlation is used to assess the similarity of two matrices \( [A] \) and \( [B] \) (in our case – two images) in a form of cross-correlation coefficients stored in a cross-correlation matrix \( [C] \). The position of an index with the highest cross-correlation in \( [C] \) gives information of the necessary amount the pixels of matrix \( [B] \) need to be shifted to match the ones of matrix \( [A] \). The procedure is realized as follows:

1. Image \( [A] \) is set as a reference image which is corresponding to the frame 1 and other images are taken at subsequent frames \( [B] \).
2. Calculate the cross-correlation matrix \( [C] \) between a pair of images \( [A] \) and \( [B] \) using a Matlab command \texttt{xcorr2}.
3. Extract the index \( i_{\text{max}}(C) \) of \( [C] \), at which the maximum cross-correlation between the images is achieved.
4. Transform \( i_{\text{max}}(C) \) into row and column indices of an image (input image size and \( i_{\text{max}}(C) \) value).
5. Assess the amount of position each pixel of image \( [B] \) has to be shifted in \( Y \) and \( X \) direction relative to the image \( [A] \).
6. Shift the matrix elements of image \( [B] \) by the amount found in step 4.
7. Repeat steps 3–6 for all image frames.

Alignment of two damage regions is depicted in Fig. 5. An example of
coordinate misalignment for frames 1 and 2 is presented in Fig. 5 (a), while the same damage regions after alignment with a 2D image correlation are shown in Fig. 5 (b).

4.3. Damage characterization

Evolution of damage is analyzed on both overall and detailed levels. In the overall level analysis, the size and the severity of the damage at different stages of the fatigue loading are investigated. The detailed level analysis elaborates on the relationship between damage development, heat generation and enthalpy change.

4.3.1. Overall damage analysis

The increase of number of pixels in a damage region as seen in a thermal image is proportional to increase of damage area physically. In this study, a relative area increase $A/A_0$ is used to assess the growth of the damage size with respect to the original damage size in frame 1. The relative increase of the damage area versus the number of fatigue cycles is shown in Fig. 6 (a).

It is known that internal energy of an object is proportional to its temperature. Enthalpy of an object is the sum of its internal energy and the product of its pressure and volume. Since in a solid the change in pressure and volume can be assumed negligible, the enthalpy change is proportional to the internal energy change with a good approximation. During fatigue damage of a material, the hysteresis energy is dissipated and will mainly be converted to heat. The dissipated heat will increase the internal energy of the material and, accordingly, its enthalpy. As shown in [15], the enthalpy change is mimicking a trend of hysteretic
energy dissipation. The behavior of hysteretic energy dissipation with increasing cycles of fatigue loading has three distinct stages – initial growth, steady state growth and final growth. These three stages are attributed to damage progression from initiation to fast growth. Thus, damage severity at an arbitrary instance of fatigue loading can be qualitatively determined from the three stages of the enthalpy change curve. The enthalpy change is calculated as

$$\Delta h_j = \rho c_p V_{pix} \sum_{i=1}^{I} T_{ij} (T_a - T_i)$$

(3)

The values for the terms in Eq. (3) for the glass fiber composite material are as follows – density $\rho = 1835$ kg/m$^3$ and specific heat capacity at constant pressure $c_p = 903$ J/(kg × K) [15]. Ambient temperature was $T_a = 296.5$ K (i.e. 23.35°C). Pixel volume $V_{pix}$ was calculated by calibrating the image resolution (number of pixels) to known dimensions of damage area through

$$V_{pix} = \frac{t_s l w N_d l N_d w}{N^p N^w}$$

(4)

where $N^p = 40$ and $N^w = 26$, $l = 0.4$m, $w = 0.38$m and $t_s = 0.0036$m. After the calculation, $V_{pix} = 5.26 \times 10^{-7}$ m$^3$ and enthalpy changes are illustrated in Fig. 6 (b).

A clear non-linear relationship of the enthalpy change curve with fatigue cycle number is obtained. The boundaries of damage severity stages are marked with vertical dashed lines drawn through the convex and concave points of the cubic polynomial curve. A cubic polynomial is used to fit the enthalpy change based on [15].

It can be seen that the enthalpy change curve qualitatively reflects three different stages of damage severity. It has a non-linear relationship with fatigue cycle number including an initial ramp-up at stage I, a nearly steady-state at stage II and a final ramp-up at stage III. Finding the concave and convex points of a cubic polynomial fit curve allows the partition the enthalpy change curve into progressive damage stages – the cycle ranges of the three stages I, II and III are $n_f \in (0, 72)$, $n_f \in (72, 257)$ and $n_f \in (257, 328)$, respectively.

4.3.2. Detailed damage analysis

In order to investigate thermal features within the damage region, the temperature range was divided into several sub-ranges: $T_1 (^\circ C) \in [25, 27]$; $T_2 (^\circ C) \in (27, 29]$ and $T_3 (^\circ C) \in [29, 30]$. These three temperature sub-ranges denote three zones within the damage region – the outer zone at $T_1$, the middle zone at $T_2$ and the inner zone at $T_3$. The growth of each individual zone can be explained by accounting for the energy balance of the zone. The energy is in a form of heat that flows from hotter areas to colder areas. The rate and the magnitude of the heat flow is characterized by the heat flux $q$. The heat generated in the hottest inner zone under the fatigue loading due to material friction between surfaces of a crack is flowing outwards into the middle zone and further into the outer zone. Heat conduction in solids in two dimensions is expressed by Fourier’s law of heat conduction.
\[ \overrightarrow{q} = -\kappa \nabla T = -\kappa \left( \frac{dT}{dx} \hat{x} + \frac{dT}{dy} \hat{y} \right) \]  \tag{5} 

where \( q(W/m^2) \), \( \kappa(W/(m \times K)) \) and \( \nabla T(K/m) \) are the heat flux vector, thermal conductivity and temperature gradient, respectively. For small temperature variation, \( \kappa \) is assumed constant. The temperature gradient is a vector pointing in the direction of increasing temperatures and its direction is opposite to the heat flux. Hence, heat flows from hotter to cooler zones.

The extracted temperature profiles of the damage region corresponding to the three stages of the enthalpy change curve are illustrated in Fig. 7 (a)-(c) with a color bar showing temperature in °C. A clear distinction between the defined temperature zones is shown with a color code — red for the inner zone, green for the middle zone and blue for the outer zone. The selected examples are shown at the fatigue cycle number 0, 164 and 328. The registered temperatures in thermography images were in the range from about 17 °C to 31 °C. The lower temperatures were of no interest in this study as they are associated with surrounding objects and not the damage region itself. The temperatures range of an actual damage region was 25 °C-31 °C. The black arrows show the direction and the magnitude of the heat flux. The heat flux is proportional to the temperature gradient, see Eq. (5), and thermal conductivity as a constant. The magnitude of the heat flux can be assessed from the magnitude of the temperature gradient.

The non-linearity of the enthalpy change can be explained by considering Fig. 7. Fatigue loading results in the breakage of the chemical bonds of material. As a result, the rough fracture surfaces start sliding against each other which results in heat generation due to interface friction. Frictional heat generation rises the temperature in the damage region in thermography images, it can be seen as a spot of high temperature. The heat generated by frictional sliding propagates outward from the inner zone of the damage region according to the heat conduction law as shown in Eq. (5).

In stage I, damage initiation results in rapid sliding of the interfaces against each other which have relatively rough surfaces. Rapid sliding and relatively large friction coefficient at the interface lead to large heat generation and thus faster increase of temperature and enthalpy change, see Fig. 6 (b). At the beginning of fatigue loading shown in Fig. 7 (a)), there is only one site of damage initiation in the inner zone with a red color. In stage II, the site of damage initiation from stage I has not grown considerably whereas relatively steady sliding of the fracture surfaces of damages initiated in stage 1 result in relatively constant heat generation and accordingly a steady state increase in enthalpy change in stage II. There is a good correlation between the enthalpy change in stage II and the steady
stage damage growth. Gradually, more damage initiation sites appear in stage II as seen in Fig. 7 (b), however, the damage growth phenomenon dominates the damage initiation. Eventually, the growth of the damages changes from a steady state in stage II to a rapid increase state in Stage III which in turn leads to rapid sliding of the fracture surfaces against each other and thus larger heat generation and enthalpy change. Moreover, the damages initiated in stage II, grow larger in stage III, as seen from the temperature contour of the damage region in Fig. 7 (b). To summarize, the enthalpy change is always increasing with fatigue cycle number due to new damage initiation sites, each of which acts as a heat generation source. The heat flux from the damage initiation area in the inner zone to the surrounding zones is schematically illustrated in Fig. 8.

5. Concluding remarks

This study presents a methodology to characterize structural damages in large-scale composite structures subjected to cyclic dynamic loading using thermal image analysis and enthalpy change phenomenon. The hysteresis energy dissipated during cyclic loading is converted to heat and accordingly results in enthalpy change of material. Damage analysis results revealed that the damage region grows continuously in size with the fatigue cycle number. The severity of the damage region is increasing nonlinearly with the fatigue cycle number and it can be classified into three progressive stages using enthalpy change.

The damage initiation in stage I results in large heat generation and accordingly a large increase of the enthalpy change. The steady-state damage growth in stage II leads to relatively constant heat generation and thus a steady-state increase of enthalpy change. The change of damage growth from a steady-state to a rapid increase state in stage III indicates severe fatigue damage reflected by considerable heat generation and accordingly enthalpy change.

The method presented in this study uses only thermographic data and thermodynamic principles for damage characterization remotely and quantitatively. The method provides a basis for further development of thermography-based structural health monitoring systems for large-scale composite structures such as aircraft wings, wind turbine blades, and other engineering structures under cyclic loading. Further study may include tracking multiple damage regions and field applications considering environmental effects and complex dynamic loading.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compstruct.2022.115525.
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