An approach for structural health monitoring of CFRP using aluminum foil sensors

Mikhail BURKOV 1,2, Sergey PANIN 1,2, Pavel LYUBUTIN 1, Alexander EREMIN 1

1 634021, Akademicheskiy avenue 2/4, Institute of Strength Physics and Material Science SB RAS, Tomsk, Russia, e-mail: svp@ispms.tsc.ru
2 634050, Lenina avenue 30, National Research Tomsk Polytechnic University, Russia

Abstract
For the development of a technique for cyclic deformation assessment using aluminum foil sensors glued onto the specimen surface the fatigue tests of carbon fiber reinforced polymer (CFRP) specimens were carried out. The DSLR camera mounted onto an optical microscope was used for capturing the images of sensors to reflect strain induced relief, which than was numerically estimated using various informative parameters in order to obtain the cyclic deformation assessment of composite. The results are discussed in view of application of this method for the development of Structural Health Monitoring (SHM) approach.

Keywords: image processing, aerospace, structural health monitoring (SHM), carbon fiber reinforced polymer, fatigue damage, strain sensor

1. Introduction
Carbon fiber reinforced polymer, with their superior properties are widely used in the industry, especially in aerospace. Unlike metals composites have complex heterogeneous structures with various reinforcement directions, different properties of binder and filler. Due to the complexity of structure, with many fiber/matrix interfaces, there are a lot of defect types that might nucleate during operation (matrix cracking, fiber breakage, delamination, fiber pull-out, etc.).

However, during the in-service life the structures are loaded mainly cyclically with applied stresses below yield strength that can give rise to fatigue failure. The fatigue failure of composite materials is an extremely complicated process because of a lot of heterogeneities and non-uniformities: complex multilayer heterogeneous structure to vary mechanical response in each ply; sudden brittle failure that can occur at a variety of structural levels due to the accumulation of integral material damage (cracks, chips, delamination and fiber breakage). In this regard it is relevant to develop new techniques for strain evaluation under different loading schemes and conditions. Besides development of the method itself it is of importance to find out numerical parameters to be extracted during surface images processing to correctly characterize deformation and fracture processes occurring in a loaded material.

Many recent papers on the subject of NDT are devoted to Structural Health Monitoring (SHM) systems. Such systems can provide information as the damage occurs and significantly improve the safety of operation, as well as expand the time intervals between the scheduled full-scale diagnostics events.

In the literature an approach described to the monitoring of materials under fatigue is related to the application of thin single crystal foils referred to as “smart sensors” [1,2]. This method is based on optical registration of images of foil (sensor) glued onto the specimen surface. Due to the cyclic loading the strain relief on the foil is formed and it is captured by digital camera. Digital processing of images allows one to calculate the informative parameters to assess the damage state of the material. In [3] “smart sensors” made of single crystal aluminum films were used to evaluate the mechanical state of AA2024 specimen during cyclic tension tests. In [4] the possibility of thin metallic foil sensors application in aeronautics is discussed. There are three fundamentally different functions of such sensors: load path detection, fatigue life sensing and crack assessing. Support to comply with the
Airbus directives and airworthiness rules was given. Expectations in terms of performance and user interface were suggested in the paper. However, in the above-mentioned papers “smart sensors” are offered to apply at fatigue damage evaluation of metals. The aim of the present study is to evaluate the possibility of application of such sensors for composite fatigue evaluation, as well as to develop a set of informative parameters for image processing. Early in [5], we developed a technique to study the deformation of composites under static loading based on the data of digital image correlation and acoustic emission.

2. Materials and methods

Carbon fiber reinforced polymer used for investigation is pseudo-isotropic composite made of unidirectional carbon fiber layers with lay-up $[0^\circ, 45^\circ, -45^\circ, 90^\circ]_{2S}$ with epoxy matrix. Fig. 1,a presents the drawing of the specimen with two edge notches and glued Al foil sensor. The thickness of the specimen is 3.3 mm. Cyclic loading were carried out using servo-hydraulic testing machine UTM Biss-00-201. The loading scheme is cyclic tension with cycle asymmetry of $R = 0.1$. The details of specimens fabrication, illumination and image capturing techniques can be found in [6,7].

Fig. 1,b presents two images of specimen before testing and after failure of the specimen. It is seen that foil on the untested specimen is polished, while the foil surface on the fractured specimen due to the strain relief becomes diffusely reflecting (matte).

For quantitative analysis of the obtained foil sensor image series following informative parameters were calculated: Shannon Entropy ($H$), Mean Square Error ($MSE$).

$MSE$ is calculated under comparison of two images according to the following expression:

$$MSE = \frac{1}{N} \sum_{i=1}^{N} (x_i - y_i)^2$$

where $N$ – number of pixels in each image, $x_i$ – $i$-th pixel intensity (brightness for 8-bit grayscale image, it varies from 0 – black pixel to 255 – white pixel) of first image, $y_i$ – $i$-th pixel intensity of second image. So this parameter characterizes numerically the brightness difference between two images under comparison.

The $H$ parameter is calculated by following expression:

$$H = -\sum_{i=0}^{255} \frac{HIST_i}{255} \log_2 \frac{HIST_i}{255},$$

where $i$ – the intensity value (also brightness), $HIST_i$ – sum of pixels of the whole image with $i$-value of intensity (it is an $i$-value of the image histogram, i. e. brightness distribution of the digital image).

In [6] the Fractal Dimension ($D$), Energy of Fourier spectrum ($E_{FS}$), Univesal Image Quality ($UIQ$) are calculated as well. But due to the results similar to the $MSE$ and $H$ they are offered to be applied only as additional informative parameters.
3. Experimental results

In order to assess the sensitivity of the foil sensors used, cyclic tests were carried out. Summary, 12 fatigue tests were conducted. The upper load was varied and the fatigue failure of the specimens (with the same geometric dimensions) occurred at different lifetimes. Thus, we have obtained the series of foil sensor images with the following cycles to failure: 42000 cycles (specimen №1), 74000 cycles (№2) and 151000 cycles ( №3). Table 1 shows the parameters of cyclic loading used for each specimen.

Table 1. Cyclic loading parameters.

<table>
<thead>
<tr>
<th>№</th>
<th>Cycles before failure</th>
<th>f, Hz</th>
<th>$P_{\text{max}}$, kN</th>
<th>$P_{\text{min}}$, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$42 \cdot 10^3$</td>
<td>10</td>
<td>8,3</td>
<td>0,83</td>
</tr>
<tr>
<td>2</td>
<td>$74 \cdot 10^3$</td>
<td>10</td>
<td>8,25</td>
<td>0,825</td>
</tr>
<tr>
<td>3</td>
<td>$151 \cdot 10^3$</td>
<td>10</td>
<td>8,2</td>
<td>0,82</td>
</tr>
</tbody>
</table>

Presence of the edge notch gave rise to strain localization in the middle part of the specimen where it had the highest level. Such non-uniform strain distribution made it possible to observe sensor regions with strain induced relief being pronounced in various manners and patterns. From the raw initial images with a size of 5184×3456 pixels two square shaped regions were selected with the dimension of 2048×2048 pixels: the first one is located in the center of the foil being located exactly between the edge notches while the other is located above the first one at a distance of 2 mm. Fig. 2 presents images of strain induced relief to form at cyclic loading. It is seen that the character of the relief in the central area differs from that in the upper region: in the center (between notches) the relief has folds located preferably normally to the axis of loading, whereas in the upper region, where stress concentration is lower, considerable area is occupied by folds oriented at an angle of ±45° to loading direction.

Fig. 2. Images of two calculation regions (top and central) for the various number of cycles.

Fig. 3 shows the dependence $MSE$ and $H$ for three specimens as the function of the number of cycles. After analysis of obtained data the following can be concluded:

- $MSE$ graph has 3 easily marked portions: the 1st (from $~3 \cdot 10^3$ to $~8 \cdot 10^3$ cycles) is characterized by the increase of $MSE$ value, the 2nd stage is linear (from $~8 \cdot 10^3$ to $~2 \cdot 10^4$ cycles, it is fitted by straight line on the graph), at the 3rd section the value of $MSE$ increases, but the slope of the curve gradually lowers (from $~2 \cdot 10^4$ cycles to failure).

- In central calculation region the $MSE$ and the $H$ have higher increase rates and higher absolute values, that is due to the higher rate of strain relief formation and higher heterogeneity of its distribution.

- The difference of $MSE$ values between two calculation areas is higher than that for $H$.

- The difference between two calculation areas for both parameters starts to rise from $~10^4$ cycles.
- **MSE** value is almost constant up to $\sim 3 \cdot 10^3$ cycles, the $H$ value start to increase after $\sim 10^3$ cycles.
- Graphs of both parameters are quite similar except for the 2nd stage: the second linear stage on **MSE** graph is much longer than that for the $H$ graph.
- With increase of number of cycles prior to failure the onset of second stage shifts from the beginning of cyclic loading.
- The higher is the number of cycles prior to failure the less is **MSE** value (with higher load level the strain induced relief becomes more heterogeneous).

Fig. 3. Graphs of **MSE** and $H$: the type of the specimen is marked out, dash line corresponds to the top calculation area.

- With increasing number of cycles prior to failure the slope of second stage is decreased (relief formation rate is decreased).
- Similar to **MSE** graphs $H$ have 3-stage pattern. One can see that with increase of load the slope (rate of relief formation) of graph is increased. Also values for top calculation area are less than those for central one. On the other hand there are some differences:
  - On the first stage the values of $H$ start to enlarge practically at the 1000 cycles and increasing rate is higher which testifies for the greater sensitivity of $H$ to beginning of strain induced relief formation.
  - Absolute values of $H$ for three specimens just before fracture are substantially equal.

It can be summarized that despite of different calculation algorithms both parameters demonstrate similar response on changing of loading level (and number of cycles before failure).

4. Discussion

Using the “smart sensors” concept the technique for assessment of cyclic deformation of carbon fiber polymers is developed. The thin foil sensor is prepared using multistage technique of polishing. The original scheme of lightning is used, which in combination with well-polished sensor surface can improve the accuracy of results. Significant attention is paid to algorithms of data processing: for strain induced relief evaluation, formed on the foil surfaces, a set of informative parameters is used.

One must conclude on a difficulty for composite materials testing using such thin foil sensors in contrast with metals. This fact is related to different strength characteristics of metals and composites, so the strain induced relief at composite testing forms much faster.

The possible solution on overcoming this disadvantage is related to the search of other materials to be used as foil sensors, but this aspect of the work was not studied. In the present paper a commercially available polycrystalline aluminum foil is used, and the range of sensitivity was expanded due to modernization of previously used algorithms and calculation
of other parameters. So, using conventional parameters the range where the parameter changed is limited to 15K cycles while the newly proposed parameters (MSE and H) possessed a sensitivity range of higher than 100K cycles. According to the data on cyclic tests of specimens with two edge cracks loaded with varied upper load in cycle and correspondingly different number of cycles prior to failure following features can be identified:

- According to all informative parameters used the rate of formation of strain induced relief and its heterogeneity are higher in central calculation area rather than in top one. This fact highlights high sensitivity of foil sensor to the stress concentration effect.
- The graphs of all informative parameters have the 3-stage shape, but the duration of each stage slightly differs for each of them. At the first stage it is related to slow rate of strain induced relief formation. The values of parameters remain practically constant and the duration of this stage is 4K cycles for MSE and 1K cycles for H. The second stage is characterized with high rate of relief formation and the values are increasing rapidly. This stage lasts up to 10K-20K cycles. At the third stage the values demonstrate slight increase. It can be concluded that the joint analysis of all parameters is required to obtain correct conclusions.

Proposed informative parameters for strain induced relief evaluation provide more reliable results than those used in literature. So even using the aluminum foil the relief changes can be monitored and estimated up to 150K cycles.

5. Conclusion

The cyclic tests of carbon fiber composite specimens with thin foil sensors were carried out, showing that:
1. All informative parameters used to evaluate the strain induced relief possess a 3-stage pattern: at the first stage the values remain constant, at the second there is great increase while at the last stage the slight increase up to failure is observed.
2. MSE and H parameters (traditionally used to assess the quality of images) provide better results in contrast with conventionally used to evaluate the strain induced relief. It is proposed to use these parameters as additional ones to primary evaluation.
3. The sensor made of aluminum foil shows high sensitivity to stress concentration in specimen with two edge notches, as well as to different load levels. Thus it is possible to construct the nomographs for specific loading schemes, conditions and material type and to evaluate remaining service life of structures.

Present work was focused on the developing of data processing algorithms to achieve better evaluation of foil sensor images. Further research will be related to the study of sensor sensitivity to other factors, for example to different stress strain intensity (specimens with one edge crack or with central hole).

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References


