Multiscale strain investigation of stressed carbon fiber reinforced composites based on data of strain gauging, digital image correlation, acoustic emission

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Abstract. A combined method for investigation of localized deformation processes in carbon fiber reinforced composite specimens is applied in order to reveal characteristic stages of strain and fracture. Stress concentrators have the shape of a circular hole and edge crack of various sizes. Use of simultaneous strain data registration has allowed us to register and compare parameters under analysis during entire time of the experiments. The reasons of similarity and difference of the results are shown and discussed. It is offered to apply the obtained results for the aims of non-destructive testing of structural materials being based on revealing characteristic stages of strain development and a particularly prefracture stage.

Keywords: strain gauging; digital image correlation; acoustic emission; carbon fiber composite, non-destructive testing, health monitoring of structures.

1. Introduction

In compliance with literary data and results of our previous investigations [1, 2] the stage character of deformation development can be registered with various methods of studying and estimation of strain. Each method due to operation principle is sensitive to particular scale level. In situ application of 3 methods: strain gauging, acoustic emission (AE) and digital image correlation (DIC) allows one to obtain complete pattern of deformation and fracture of stressed structural materials. Application of stain gauging and AE is described in papers [3, 4] while use of DIC method is explained in [5, 6].

Thus depending on physical principle of a method used it is possible with high sensitivity to register and characterize quantitatively the deformation processes at each scale. Strain gauging characterizes macroscale level or response of a specimen as a whole on applied stress. DIC (Meso II) describes level which is comparable with macrolevel, because in DIC the area of observation considers with whole width of a specimen under testing. AE (Meso I) complies level generally of debonding on matrix-fiber interface. AE characterizes changes inside material, while DIC method is revealing processes in outer ply of a specimen, that is critical to composite materials with different fiber layers orientation.

For numerical analysis of data information parameters for 3 methods were chosen. For the AE method count rate dN_{AE}/dt was calculated; for DIC - γ shear strain intensity, for strain gauging - $d\sigma/dt$ (time derivative of the external applied stress).

2. Materials and investigation technique

CFRC is pseudo-isotropic composite made of unidirectional carbon fiber layers [0°, 45°, -45°, 90°] sintered in carbon matrix. Dimensions of specimens were taken according to ASTM D5766/5766M. Strain localization degree is varied by different dimensions of stress concentrators (central hole diameter 7; 10; 13 mm; depth of edge crack 14,5; 18; 21,5 mm).

Dimensions of the specimens are presented on Fig.1.

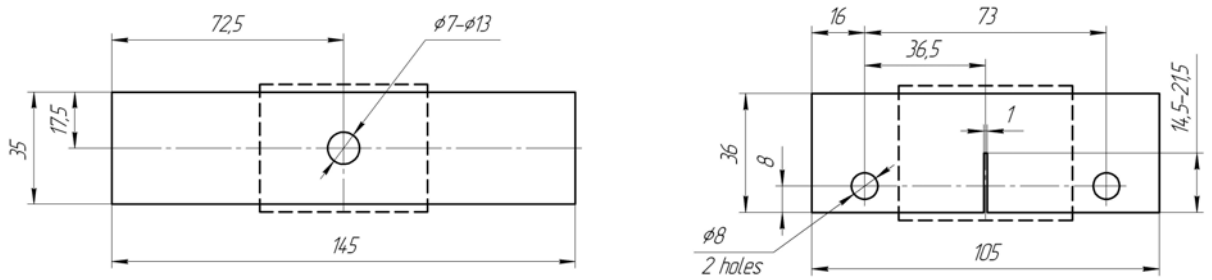

Fig. 1. Scheme of the specimens, thickness 4 mm: a) specimen with central hole; b) specimen with edge crack.

Specimens were stretched under static loads at electro-mechanical testing machine Instron 5582. Strain gauging data was registered using integrated transducer of the testing machine.

Registration of acoustic emission (AE) signals was performed by PC-based hard-software measuring technique [7]. For analysis of acoustic emission data, the derivative on AE events accumulation over loading time (acoustic emission count rate) was calculated as the basic informative attribute of AE data.

Surface imaging was carried out by Canon EOS 550D DSLR camera. The camera has been equipped by telephoto lens Canon EF-S 100-400 mm 1/4-5.6 IS. A certain region of the image was determined for calculation of the average value of shear strain intensity. For example, specimen with central holes the area of the image with the size of 3300×4950 pixels (the physical sizes ~32×52,5 mm) was taken. The sizes of the regions for strain estimation were chosen in order to ensure observation of formation and development of macro scale shear–bands for various types of specimens.

Use of simultaneous registration has allowed us to register and compare parameters under analysis during entire time of the experiments

3. Experimental results

3.1. Macroscale level. Analysis of strain gauging data

Loading diagrams of specimens with central holes and edge cracks are resulted in fig. 2. With increase of the notch dimension for both types of specimens the elongation and ultimate strength at fracture are decreased. The derivative dσ/dt was calculated and is shown on fig. 3.

Further, for comparison of the deformation behavior of specimens with central holes and edge cracks, the results obtained by 3 methods for the composite specimen with ∅7 mm hole and 14,5 mm edge crack are described.

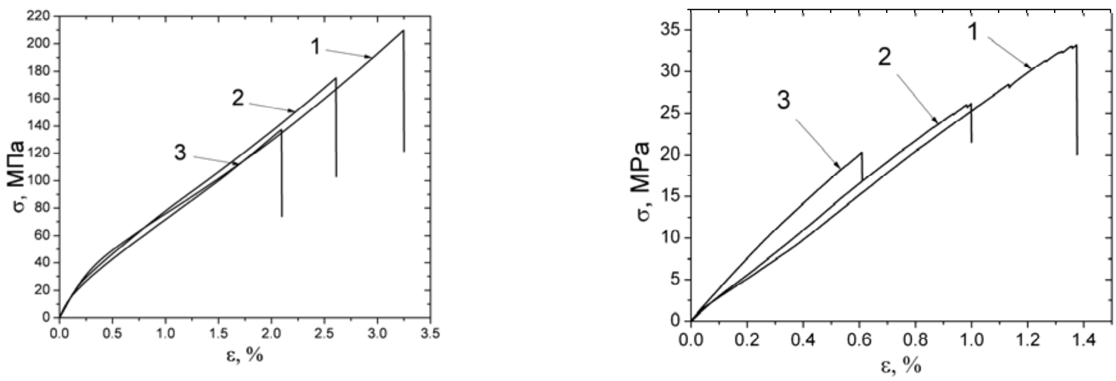

Fig. 2. «σ-ε» graphs: a) specimens with open holes: 1) ∅7mm, 2) ∅10mm, 3) ∅13mm); b) specimens with edge cracks: 1) 14,5mm, 2) 18 mm, 3) 21,5 mm

3.2. Meso I level. Analysis of AE registration data

Dependences of AE count rate versus loading time dN_{AE}/dt for specimens are shown in fig. 3. This parameter was chosen for the analysis as being most "sensitive" to change of a leading scale level of deformation in a specimen under loading. The point graphs of AE count rate were smoothed by average curves. For both types of specimens it is visible, that generation of AE pulses begins practically from the beginning of loading. However appreciable increment of the AE count rate starts at time related to transition of key role of deformation to the meso-scale level.

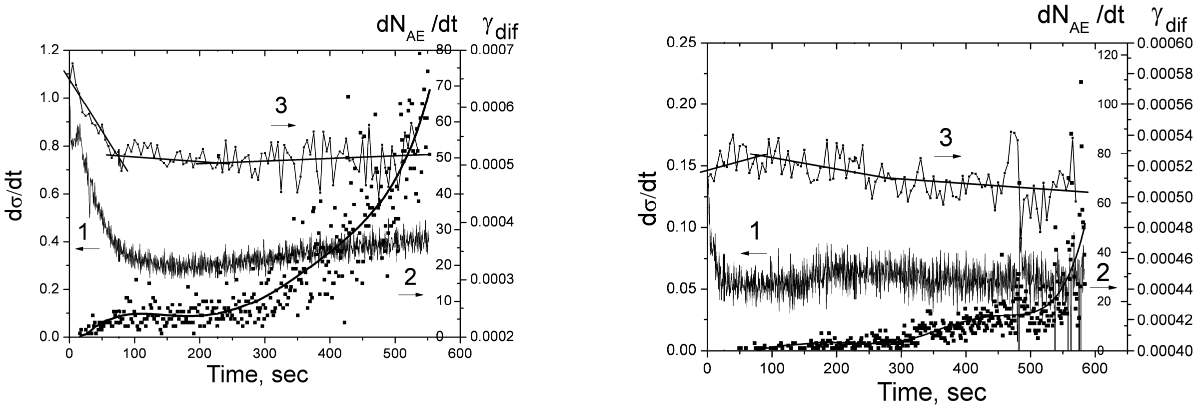

Fig. 3. Combined $d\sigma/dt$ - γ_{dif} - dN_{AE}/dt graphs: a) specimen with central hole: ∅7 mm; b) specimen with edge crack: 14,5 mm.

3.3. Meso II level. Shear strain intensity

The analysis of strain evolution at the meso II level was made by 2 methods of image processing: integral and differential (detailed description of the technique is given in paper [8]). In the first case displacement vectors were mapped by comparison of a first (initial) image with each current ones, while at the differential method of calculation a current and a subsequent images of a deformed specimen surface were compared.
Dependences of the shear strain intensity calculated by the differential method of the image processing which is more sensitive to local strain changes, for both types of specimens are presented in fig. 3. These dependences are sectionally-linear approximated.

4. Conclusions

Combination of DIC and AE data used in the research allows us to examine stage patterns for deformation development at various scale levels. In our previous investigations aluminum specimens were tested [9]. For aluminum specimens at the initial stages of loading the AE method seems to be the most sensitive to deformation processes. At greater degrees of deformation the method of digital images correlation (DIC) more precisely characterizes the change of the key role from meso- to macroscopic scale of the deformation development.
For CRFC specimens AE method have high sensitivity and ability to describe processes inside material, strain gauging characterizes response of specimen on applied stress and allows to identify transition between stages, DIC method can be used to visualize deformation processes with their numerical estimation.
The results are offered to be applied for the aims of non-destructive testing of structural materials being based on revealing characteristic stages of strain development and particularly prefracture stage.

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