EAN 2012
50th annual coference on experimental stress analysis

The Deformation Analyses of an Elastomeric Composite Reinforced by Superelastic Wires

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Abstract: Hybrid composites reinforced by superelastic SMA (shape memory alloy) wires are attractive for applications in smart structures. The incorporation of more compliant elements, such as silicon rubber, into connective matrix can improve the achievable deformation and the characteristics of the resulting composite (i.e. non-permeability). This paper presents the geometrical analysis of deformations under uniaxial tensile test of the NiTiTex (hybrid composite with elastomeric matrix reinforced by polyester-NiTi fabric). Digital images of the samples with visible fabric pattern were recorded during experiment. The orientation of fabric fibers was analyzed using in-house developed software BinaryDirections. The software employs an algorithm of the *Rotation Line Segment* to determine significant directions in digital images. It was found that dominant directions of the fabric fibers are linearly dependent on the stretch reached in the samples. It was also concluded that the deformation is not homogenous within the entire sample.

Keywords: Hybrid composite; Stress; Wire; Deformation

1. Introduction

Hybrid composites reinforced by superelastic SMA (shape memory alloy) wires are attractive for applications in smart structures. The exceptional properties of these materials are induced by the Nitinol (roughly equi-atomic nickeltitanium alloy). Shape memory, superelasticity and good biocompatibility are the most important of them [1, 2].

The incorporation of more compliant elements, such as silicon rubber, into connective matrix can improve the achievable deformation, and the characteristics of the resulting composite (i.e. non-permeability). Up to date scientific literature reports few examples of NiTi wire-polymer matrix composites [3-6].These hybrid composites show potential for application in different areas: i.e. new designs of hydraulic valves or pumps with NiTi membranes [7], aerospace industry, automotive applications, and medical applications (implants and medical devices) [3].

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The aim of the present study is to correlate macroscopic mechanical response of the hybrid composite with a behavior of individual constituents in uniaxial loading.

2. Materials and Methods

Samples of a hybrid composite made from elastomeric matrix reinforced by polyester-NiTi fabric (NiTiTex) were obtained at the Institute of Physics of the Czech Academy of Sciences. Uniaxial tensile tests were performed on the Zwick/Roell testing machine, Fig. 1. Digital images with visible fabric pattern were recorded during the experiments. The deformations were obtained by image analysis of a video recording.

The reference geometry (thickness and width) was determined by a caliper (Mahr, Göttingen, Germany). The experimental engineering (nominal) stress of an sample elongated within uniaxial tension was computed according to Eq. (1). Here B and H denote the reference width and thickness; F denotes the applied load.

$$\sigma_{EXP} = \frac{F}{BH} . \qquad (1)$$

Two dominant directions (angles β_1, β_2) of the fabric bundles were analyzed during the uniaxial loading, Fig. 2. At first the fibers of the fabric had to be set off. It was performed manually in Adobe Photoshop (Adobe Systems). The sequences of digital images were then processed using in-house developed software BinaryDirections. The software employs an algorithm of the *Rotation Line Segment* to determine significant directions in digital images. Three bundles of fibers in each area and each direction were analyzed. The data in each loading step were then averaged to obtain final orientation of the fibers.

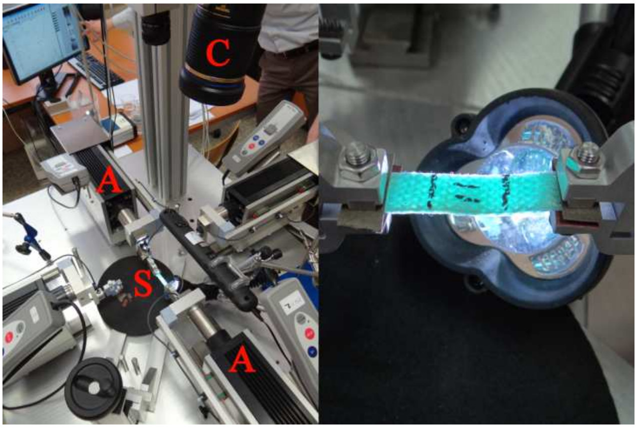

Fig. 1. The Zwick/Roell testing machine (left): A – actuators, C – camera, S – sample. The mounted specimen highlighted for good visibility of the fabric pattern (right).

2.1. Fabric orientations

The first aim was to find out how are the dominant orientations of the fabric fibers affected by the deformation reached in the sample. The angles β_1 and β_2 were analyzed in the middle of the specimens because the deformation is not affected by clamps, (Fig. 2, area M). A total number of four samples were analyzed.

2.2. Inhomogeneous deformation

The second goal was to determine, how the deformation is affected by mounting the sample in the clamps of the testing machine. The images were divided into three parts and the orientations of the fabric were obtained in the middle (M) and side (L and R) areas of the sample, see Fig. 2.

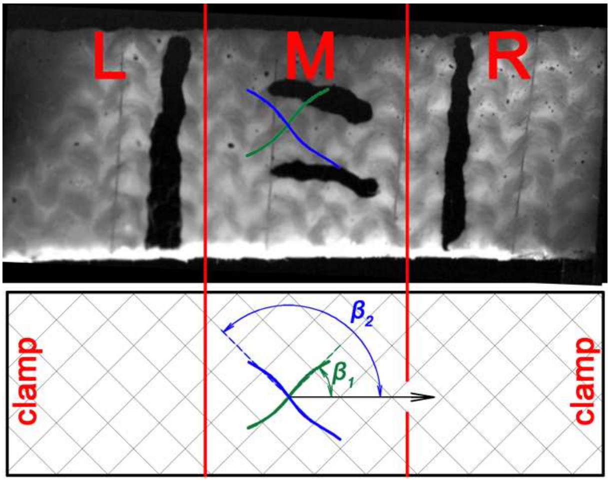

Fig. 2. The sample divided into three areas (up). Definition of the orientation angles of the fabric β_1 and β_2 (down). The black horizontal and vertical curves are markers for stretch analysis.

RoLS Algorithm

A binary pixel map can be viewed as a matrix with the elements uniquely corresponding to pixels. The algorithm explores the neighborhood of each non-zero pixel (called the target pixel) in the image using the rotating line segment. The neighborhood of the target pixel is a square represented by NxN submatrix **M**, where N is an odd integer. Now the imaginary line segment is rotated step by step around the midpoint (target pixel) of the neighborhood. Each rotating step, β, of the line segment is represented via additional NxN matrix $\mathbf{L}^{\beta}$. $\mathbf{L}^{\beta}$ has only non-zero elements in positions corresponding to the rotated line segment.

The aim of *RoLS* is to find the predominant directions in an image. This procedure is based on the so-called matching coefficient $C(\beta)$. The matching coefficient is the normalized number of non-zero pixels shared with the line segment and the neighborhood of the target pixel at a given rotating step. For this purpose, $C(\beta)$ is defined via equations (2) and (3). The normalization procedure is related to the length of square neighborhood N and the number of pixels creating the line segment l.

$$C(\beta) = \frac{1}{Nl} \sum_{i=1}^{N} \sum_{j=1}^{N} M_{ij} L_{ij}^{\beta} \tag{2}$$

$$l = \sum_{i=1}^{N} \sum_{j=1}^{N} L_{ij}^{\beta} \tag{3}$$

The final results were obtained by averaging the results from all target pixels in all histological sections. The algorithm presented here was used in [7] to determine the orientations of the collagen fibrils and the smooth muscle cell nuclei. *RoLS* is similar to the so-called volume orientation (*VO*) method, which operates with a point grid and searches for the longest intercept in the target volume. *VO* was first described in Odgaard et al. [8]. The interested reader can track details in [9] or in a recent review by Sander [10].

3. Results

3.1. Fabric orientations

It was found that the orientation of the polyester fibers in the middle area was linearly dependent on the stretch reached in the sample. It was confirmed in all four specimens, Fig 3. The data of all samples were then merged together and the linear approximation was estimated, see Fig. 3. It was concluded that the absolute value of gradients of the lines (k_1 = 41.67 and k_2 = -44.82) are approximately equal. It means that the symmetry of the bundles of fabric remains during loading.

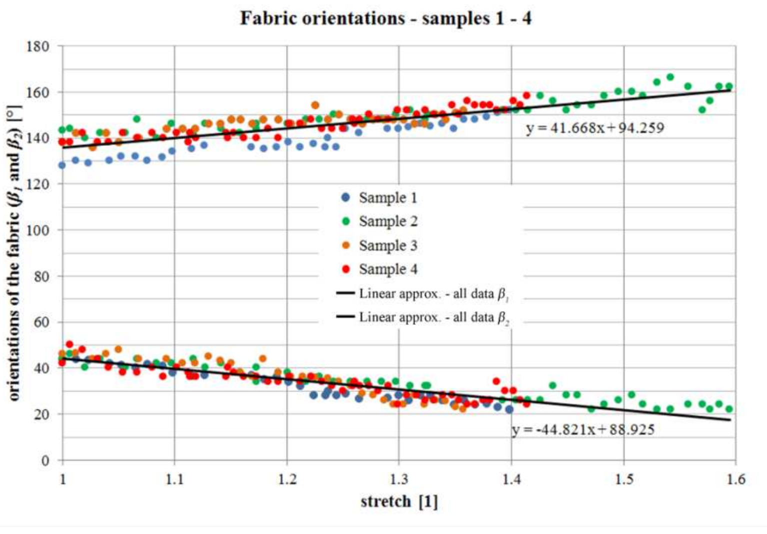

Fig. 3. The orientation of the fabric during uniaxial tensile test for four tested samples.

3.2. Inhomogeneous deformation

One sample from the fabric orientation analyses was chosen and digital images were divided into three areas (L, M, R; Fig. 2). The evaluation of the dominant direction of the fabric was performed in each area. It was found that dominant orientations in left and right third are very similar, Fig. 4. The slope of linear approximation is higher in the middle of samples than in the left and right side of the image, Fig. 4. It was proved that the deformation on the margins of sample is influenced by the clamps.

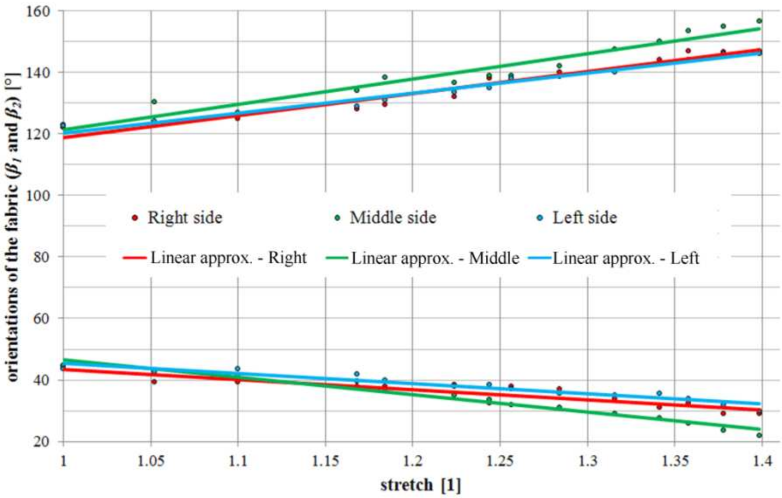

Fig. 4. The orientation of the fabric during uniaxial tensile test for three different areas on the sample.

4. Discussion

Our study aims to geometric analyses of the structure of the hybrid composite NiTiTex (elastomeric matrix reinforced by polyester-NiTi fabric) during uniaxial tension. The dominant directions of the polyester fabric fibers were investigated. It was found that there are two dominant orientations and that the orientation of the fabric fibers in the middle area of the samples was linearly dependent on the stretch reached in the specimen, Fig. 3. It was also validated that the deformation is not homogenous within the entire sample, Fig. 4. Left and right area are influenced by the clamps of the testing machine.

In this study, there are some potential sources of errors. Especially, since the bundles of the fabric fibers are thick, the manual setting off of the fabric fibers before automatic evaluation could lead to imperfections in the orientation analyses. To avoid this fact, three different bundles in each area and each direction were chosen and analyzed. The data in each loading step were then averaged to obtain final orientation of the fibers.

Another limitation is that due to light conditions during the experiment, it was impossible to track the same material points in all testing steps. It was assumed that in a small area the deformation is homogenous. However it may be impossible to follow the same bundle of the fabric all the time of experiment. In this case another bundle of fabric in near neighborhood was chosen.

Acknowledgements

This work has been supported by the Czech Ministry of Education, by the Czech Science Foundation under project GA P108/10/1296, and by the Czech Technical University in Prague under project SGS10/247/OHK2/3T/12.

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