Acta Polytechnica CTU Proceedings **42**:46–50, 2023
https://doi.org/10.14311/APP.2023.42.0046

Published by the Czech Technical University in Prague

VOLUME CHANGES MEASUREMENT OF ELASTOMERS USING 3D DIC

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Abstract. The presented research aims at measuring the volume changes of elastomers using digital image correlation (DIC) in the 3D configuration (stereo DIC). The deformation measurement method in stereo configuration was applied during the mechanical testing of two types of test specimens (dumbbells, cylinders) in uniaxial tension. In this configuration, two cameras were used. The test specimens were measured up to a specified strain value, and the measured data were used to obtain the strain dependence of Poisson's ratio and the bulk modulus, which are crucial for hyperelastic models. The measurement results reveal that the stereo DIC method provides relatively less scattered data in the low-strain regions for dumbbell-shaped test specimens and is suitable for measuring various test specimen shapes.

Keywords: Elastomer, DIC, volume change, bulk modulus, Poisson's ratio.

1. Introduction

Elastomeric materials are generally considered volume incompressible in many applications. This deduction is a result of a Poisson's ratio approximately 0.5. Rubber-like materials are then characterized by a significant change in shape and a slight change in volume under loading. The properties of elastomers mainly depend on the rubber compound and the production technology. Therefore, obtaining data from the literature is limited to a specific material compound, and due to the non-standardized material characteristics of elastomers compared to, e.g., metals, it is necessary to measure the exact data for a different compound individually. The main observed characteristics of elastomers are the bulk modulus and Poisson's ratio indicating the degree of compressibility, which lacks a standardized measurement method.

Many different experimental methods based on static loading have been developed and applied to detect volume changes in elastomers. In terms of compression dilatometry testing, deformations can be induced by hydrostatic or piston compression [1]. In uniaxial loading conditions, the determination of the Poisson's ratio is often approached by creep and cyclic loading tests [2–4]. Changes in the volume of elastomers can be observed as a function of time, temperature, and cyclic loading [5], either compressive or tensile. However, the dependence of the bulk modulus on loading for elastomers still needs to be determined. The development of modern technology of digital image correlation (DIC) enhances the possibilities in the field of observing and quantifying deformations and related volume variations [6] not only in elastomeric materials. DIC is a non-contact optical method for measuring deformations by comparing reference and deformed images using a speckle pattern applied to the specimen surface [7, 8]. The DIC method is generally divided into planar measurements (2D, mono) and spatial measurements (3D, stereo) [9]. The 2D DIC method uses only one recording device (camera). The ideal application of 2D DIC is limited to planar surfaces where in-plane deformations are expected and the camera must be positioned perpendicular to the measured object [10]. The 2D DIC devices can also include a video-extensometer, which can be implemented to a universal testing machine [11]. The 3D DIC systems use two or more cameras, and the software is able to record the position of a specific point of the measured object in the spatial area. In addition, 3D DIC systems are also more efficient in measuring planar deformations compared to 2D DIC systems. Planar deformations are accompanied by out-of-plane motions that are caused by circumstances such as deviations from planarity, specimen bending, or even measured Poisson's ratios [12].

This study focuses on the application of the stereo DIC method using two types of test specimens to measure the volume changes in elastomeric materials. The aim of the research is to determine the method for measuring the dependence of the bulk modulus on the strain using DIC and to verify whether this method is applicable to selected types of test specimens. The presented paper also investigates how the stereo DIC configuration differs from the 2D DIC method, which the authors have already examined in the previous research [11].

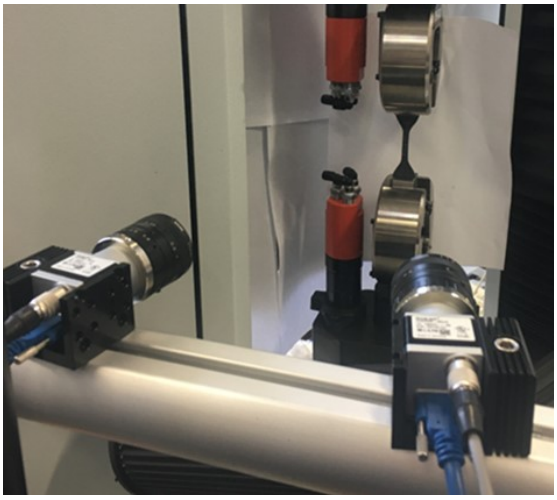

Figure 1. Experimental setup of the stereo DIC measuring device

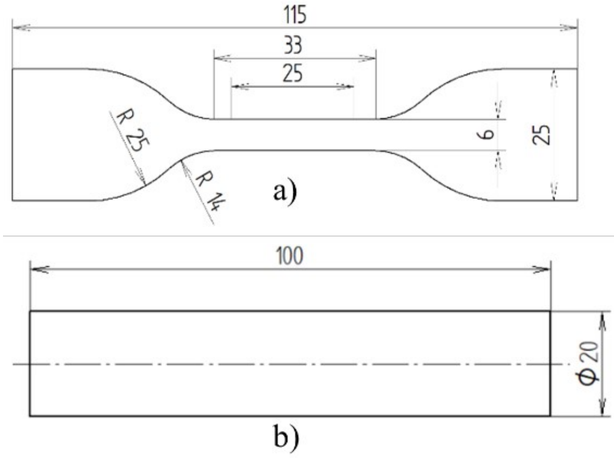

Figure 2. Dimensions of test specimens a) dumbbell, b) cylinder

2. Materials and methods

The volume changes of elastomers were measured with the DIC device (Sobriety) with software Mercury RT connected to the universal testing machine SHIMADZU AGS – 50kNXD during the tensile test. The DIC device was set up in the stereo configuration, i.e. using two cameras Basler acA2040–90um with Kowa Lens LM25HC F1.4 f25mm (Figure 1). The cameras with a maximum frame rate of 90 fps and resolution of 4 Mpx were placed at a distance of 400 mm from the measured test specimen and had an angle of 25°. The recorded images were 688×2048 px, pixel size $5.5 \times 5.5\,\mu$m with an acquisition rate of 5 fps. Two M-Tech WLO603 LED lamps were used to ensure optimal lighting conditions. The DIC setup was calibrated with a grid spacing of 2 mm, and the correlation window size used was 80×80 px.

Two types of test specimens were selected for the experimental measurements, with a sample size of 20 pieces for each type. The dumbbells were cut by press machine with standardized dimensions (Figure 2) from 2 mm thick plates which were made from a compound of natural rubber (C_5H_8, NR) and styrene-butadiene rubber ($C_{12}H_{14}$, SBR) with a carbon black content of 74 phr (parts of weight per hundred parts of rubber). The cylinders were supplied externally and were extruded from a compound with specified NR with 25 phr of carbon black and the dimensions are shown in Figure 2. The test specimens were coated with a speckled pattern using a white spray, and the measurement area was also defined. This preparation of the surface of specimens is important for further software setup of the DIC. The ideal speckle pattern contains a consistent size and shape of speckles and is high contrast. The test specimens were clamped in the pneumatic jaws of the universal testing machine, and the crosshead speed was selected: for dumbbells following the standard ISO 37200 200 mm min^{-1} and for cylinders 50 mm min^{-1}.

The line probes in the transverse and longitudinal direction were set for measuring the elongation and transversal contraction, and the quantities in the equations and diagrams were assigned to these probes for the following computational analysis. The measured deformations were between 0 and 100 % for the dumbbells and 0 and 40 % for the cylinders. The range of measured deformations was planned to be the same for both types of test specimens; however, the cylinders were slipping from the pneumatic jaws of the universal testing machine during the measurements, and therefore the deformations were only 40 %.

To calculate the Poisson's ratio, which is defined as transverse strain to longitudinal strain in the direction of the applied force, the following equation was used, where ν [-] is the Poisson's ratio, transverse strain ε_{T} [-] and longitudinal strain ε_{L} [-].

$$\nu = -\frac{\varepsilon_{\mathrm{T}}}{\varepsilon_{\mathrm{L}}} \tag{1}$$

The test specimen examined under volume changes exhibits these changes in all directions and, in the case of uniaxial loading, deforms in one longitudinal and two transverse directions, and the relative volume change θ [-] can be defined by the following equation.

$$\theta = (1 + \varepsilon_{\mathrm{T}})^2 \cdot (1 + \varepsilon_{\mathrm{L}}) \tag{2}$$

The bulk modulus K [MPa] describing compressibility is defined as the ratio of the stress σ [MPa] and the relative volume change θ [-].

$$K = \frac{\sigma}{\theta} \tag{3}$$

3. Results

The bulk modulus and Poisson's ratio values were determined according to Equations (1),(2), and (3). The curves of the dependence of the bulk modulus on

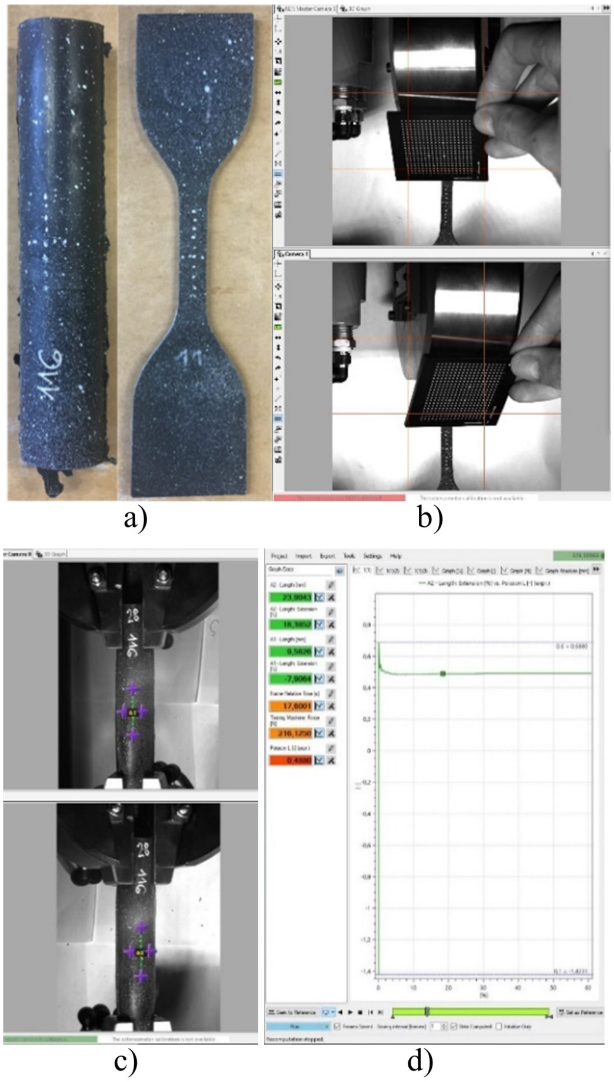

FIGURE 3. The measuring process divided into 4 steps a) preparation of test specimens, b) test setup, c) measurement, d) data processing and results evaluation

strain were obtained from these data, and all measured points were fitted with a cubic polynomial, complexly describing the prediction using the method of least squares. The range of scatter in the measured data for individual test specimens is typical for this type of material. The mechanical properties of elastomeric test specimens from the same batch are particularly affected by the quality of the homogenization of the rubber compound, the degree of vulcanization, and the quality of the technological process. Measured data in the low-strain region are partially impacted by the resolution of the measurement method and therefore appear scattered in this region.

3.1. DUMBBELLS

The dumbbell-shaped test specimens were measured to 100 % strain with simultaneously recorded stresses using stereo DIC device. The resulting dependence of the bulk modulus as a function of strain is shown

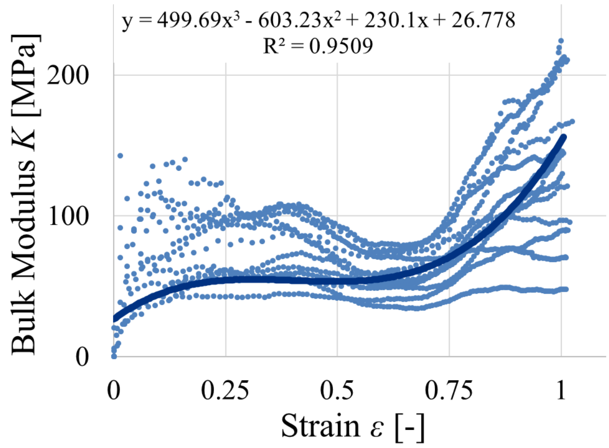

FIGURE 4. The bulk modulus as a function of strain for dumbbells

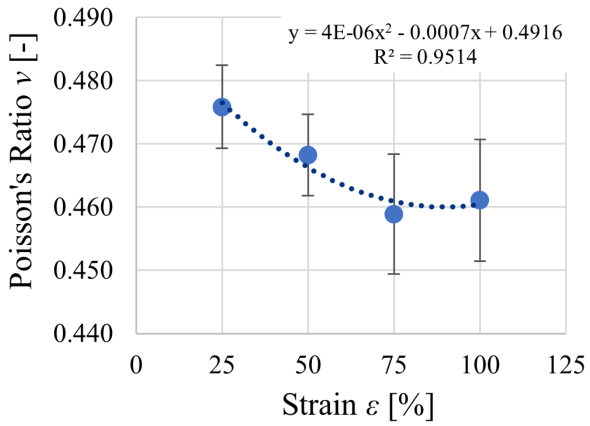

FIGURE 5. The average values of Poisson's ratio as a function of strain for dumbbells

in Figure 4. The fitting curve corresponds to the theoretical S-shape characteristic for rubber like materials stress-strains. The beginning of the dependence displays a rise followed by a plateau and the classic S-shape is completed with another rise.

The data were evaluated at 25 %, 50 %, 75 %, and 100 % strain values. The average values of Poisson's ratio and the bulk modulus were determined and are presented in Table 1.

ε [%]	ν [-]	K [MPa]
25	0.476 ± 0.007	100.0 ± 21.5
50	0.468 ± 0.006	87.3 ± 28.6
75	0.459 ± 0.009	94.8 ± 38.2
100	0.461 ± 0.010	147.4 ± 28.0

TABLE 1. Poisson's ratio and the bulk modulus

Figure 5 shows the dependence of Poisson's ratio on strain with consideration of average values for defined strain values. The values of bulk modulus versus strain are presented similarly in Figure 6.

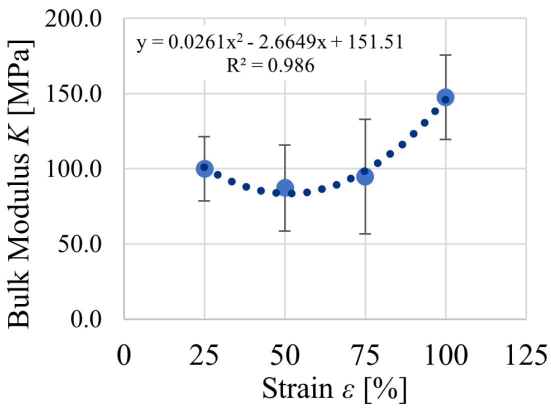

FIGURE 6. The average values of the bulk modulus as a function of strain for dumbbells

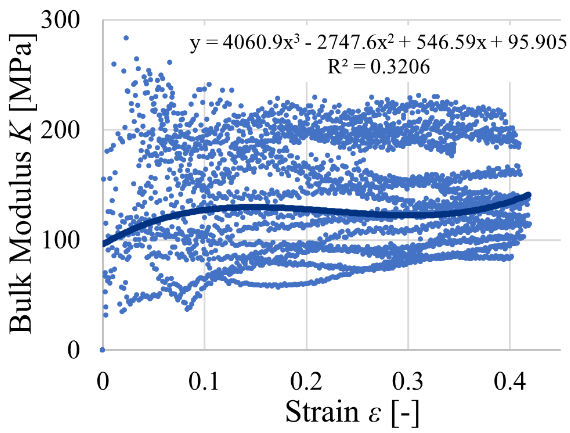

FIGURE 7. The bulk modulus as a function of strain for cylinders

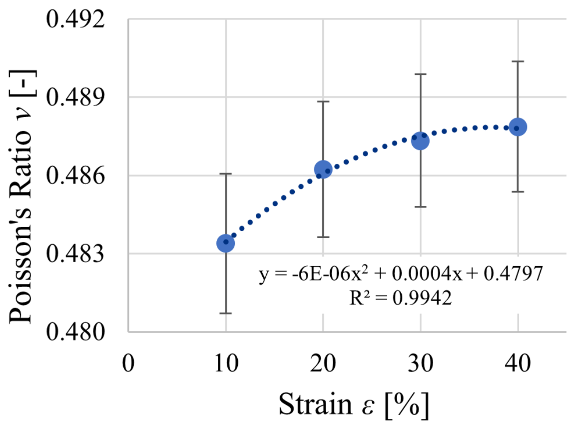

FIGURE 8. The average values of Poisson's ratio as a function of strain for cylinders

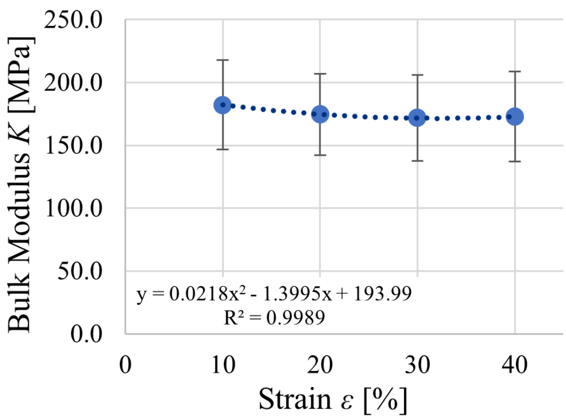

FIGURE 9. The average values of the bulk modulus as a function of strain for cylinders

ε [%]	ν [-]	K [MPa]
10	0.483 ± 0.003	182.2 ± 35.5
20	0.486 ± 0.003	174.5 ± 32.4
30	0.487 ± 0.003	171.8 ± 34.0
40	0.488 ± 0.003	172.7 ± 35.8

TABLE 2. Poisson's ratio and the bulk modulus

3.2. CYLINDERS

The data measured during cylinder testing were evaluated to strain values slightly above 40 %. At higher strains, the cylinders were slipping out of the jaws of the universal testing machine; therefore, a higher clamping force had to be applied, and the test specimens were pre-deformed at the edges. Despite this, the measured data interleaved with the fitting curve shows the characteristic S-shape of the dependence of the bulk modulus on the strain for elastomeric materials. The apparently wider scatter of the cylinder data is caused by the differently sized scale of x (strain) axis in Figures 4 and 7.

The data were evaluated in 10 %, 20 %, 30 %, and 40 % strain values. The average values of Poisson's ratio and the bulk modulus were determined for these strain values and are given in Table 2 and graphically represented in Figures 8 and 9.

4. CONCLUSIONS

The presented paper examines the use of the DIC measuring device in the stereo configuration to record volume changes in elastomers. The test specimens of two different shapes (dumbbells, cylinders) subjected to uniaxial tension were used. The DIC device, which allows the measurement of strain and displacement in multiple directions, was used to record transverse and longitudinal strains for determining Poisson's ratio and the bulk modulus.

The measured and calculated data evaluated in the dependences of the bulk modulus and Poisson's ratio on the strain fit the predicted curves. The results show that the observed parameters are non-constant as a function of the strain. The obtained values of the bulk modulus and Poisson's ratio are necessary for commonly used hyperelastic computational models. The measurement method used is suitable for applied mechanical testing. The measurements of the dumbbells were proceeded standardly. However, using a more extended length for measuring the cylinders for proper clamping in the pneumatic jaws would be preferable. Another option is using test specimens of different shapes or selecting a different clamping system.

Measurements with the DIC device are generally beneficial due to the post-processing and overall universality. The resolution of the method is dependent on several factors including camera specifications, image quality and interpolation, correlation algorithm, size of correlation window, noise, or speckle pattern. Measurements of a similar set of test specimens were conducted in a previous study using the 2D DIC. The setup of the 2D DIC system is more straightforward in many aspects, as the position of the cameras relative to each other and the measured object is essential in the 3D configuration. The used Mercury RT software includes a neck gauge tool for 2D measurements, simplifying the setup of the input measurement quantities. The 3D DIC method is characterized by less scattered data in the low-strain region, and the influence of deformations in non-measured planes is reduced due to spatial recording.

Acknowledgements

The research was realized with the support of the project IGA/FT/2023/004 TBU in Zlín.

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