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# INFLATION-EXTENSION TEST OF SILICON RUBBER TUBE REINFORCED BY NITI WIRES

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**Abstract:** *The composite tube fabricated from elastomer matrix reinforced with NiTi wires was tested within simultaneous inflation and extension. Four different longitudinal weights were applied (m = 41 g; 188 g; 488 g; and 785 g). The inflation was induced with repeating pressurization up to 200 kPa. No significant hysteresis and material instability, typical for elastomeric tubes, were observed. Simplified model, assuming the tube to be anisotropic hyperelastic continuum, was adopted in order to estimate material parameters by analytical model of the thick-walled vessel. This model was only successful in fitting the data corresponding to the smallest longitudinal weight. It was concluded that NiTi reinforcement reduces elastomer viscoelasticity in macroscopic response, which can not be fully described with the model considering the effect of wires only as the introduction of anisotropy.*

**Keywords:** ***Anisotropy, hyperelasticity, inflation-extension test, nitinol, silicon rubber.***

## 1. Introduction

Structures based on thin NiTi wires, due to shape memory, superelasticity and biocompatibility, have become increasingly utilized in biomedical engineering. So-called self-expandable stents, which are used upon revascularization treatments in stenotic arteries, are frequently made of nitinol wires (Stoeckel et al., 2004). Such wires can be designed in 2D and 3D structures using standard textile production methods (weaving, knitting, and braiding). Generally, the shape memory allows these materials to be programmed by means of metallurgical treatment. Such products can afterward be employed as mechanical controlling units. On the other hand, rather large recoverable strains (in comparison with metals) of nitinol can be utilized in a design of actuators. Combining above mentioned and considering hydraulic systems nonconventional pumps or ventils may be constructed.

The aim of the present study is to investigate mechanical response of elastomeric tube reinforced with thin NiTi wires. Pressure-diameter and longitudinal extension-force relationships were obtained within the inflation-extension test with the silicon rubber tube with implemented wires. This is only the pilot study which can not report final conclusions and constitutive model of the structure which is composite in its nature. Nevertheless, preliminary results will direct us at suitable computational model.

## 2. Methods

### 2.1. Sample preparation

NiTi wire with a diameter 100 μm used in this study was purchased from Fort Wayne Metals (Indiana, USA). Tubular sample of silicon elastomer-NiTi wire composite was fabricated at the Institute of Physics of the Czech Academy of Sciences. Metallic part of the final composite was fabricated as fenestrated cylindrical shell (braided structure of NiTi fibers) with 36 helically coiled wires. Wires were wound around in two families of helices symmetrically disposed along the longitudinal axis of

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the cylinder with the pitch angle approximately ±58° (circumferential axes-helix). Tubular NiTi structure was subsequently annealed at 450°C for 30 minute. Mechanical properties of the wires are summarized in Table 1. For detailed description of the mechanical behavior of nitinol wires see Heller et al. (2008).

Used polymer matrix belongs to the group of silicon elastomers (trademark Sylgard 160) obtained as mixture of soft and hard phase. NiTi textile-polymer composite sample was prepared by infiltration of braided structure laid in a mold with the polymer and hybridizing it by curing at room temperature. Final composite vessel had outer and inner radius equal to $R_o$ = 3.025 mm, and $R_i$ = 1.25 mm, respectively.

*Tab. 1: Composite tube summary.*

| ***NiTi wire*** | |
|---|---|
| *Young modulus of austenite* | *46.2 GPa* |
| *Young modulus of martensite* | *18.0 GPa* |
| *Transformation yield stress of austenite at room temperature* | *553 MPa* |
| *Maximum recoverable transformation strain* | *5.23 %* |
| *Thickness* | *100 μm* |
| *Number* | *36* |
| *Heat treatment* | *450°C for 30 min.* |
| *Reference radius of the helices* | *1.75 mm* |
| ***Composite structure*** | |
| *Cylindrical tube with silicon elastomer matrix reinforced with NiTi wires* | |
| *Reference outer radius* | *3.025 mm* |
| *Reference inner radius* | *1.250 mm* |
| *Helix angle (between circumferential axis)* | *±58°* |
| *Reference length of the tube* | *5 cm* |

### 2.2. Experiment

In order to obtain mechanical response of the sample to external load the inflation-extension test was carried out at the Laboratory of Human Biomechanics, Faculty of Mechanical Engineering of the Czech Technical University in Prague. Within the inflation-extension test the sample is loaded by internal pressure and axial force. The force is originated by the pressure which is applied to the end of the tube (closed tube configuration) and with additional weight. The experimental setup is documented in Fig. 1. The pressurization was carried out manually by a syringe. Four different weights were consecutively applied to induce longitudinal prestrain; $m$ = 41 g; 188 g; 488 g; and 782 g (this is the total mass of longitudinal load under zero transmural pressure). Four pressurization cycles were repeated with each weight.

Displacements of the inflated tube were recorded by point optical probes Chrocodile M4 (Precitec Group, Germany). Two of these sensors were involved in longitudinal displacement and torsion angle measurement. The change of the diameter was recorded with the laser scanner ScanControl LLT 2800-25 (Micro-epsilon, Germany). The internal pressure was monitored with the pressure transducer Kulite XLT-123B-190M-3.5BAR-D (Kulite Semiconductor Products, USA). All quantities were recorded into a PC for further post-processing.

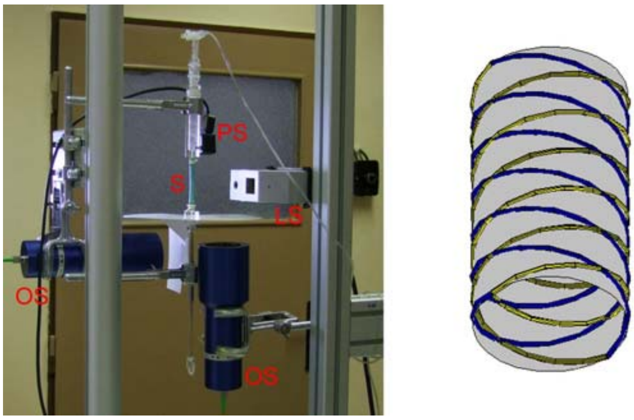


*Fig. 1: The experimental setup (left) and the sketch of the composite structure. The letters on the left side denote: OS – optical sensor Chrochodile M4; LS – laser scanner ScanControl; PS – pressure transducer Kulite; and S – sample.*

### 2.3. Model

Several assumptions were made in order to keep simplicity necessary for analytical treatment of the problem. The material of the final structure was homogenized. It means that reinforcement wires were considered to define preferred directions in hyperelastic continuum. Thus, their influence was reduced to originating anisotropy. Both families of wires were presumed to be mechanically equivalent. It results in so-called locally orthotropic material (Holzapfel, 2000, ch. 6). Viscoelastic properties of the silicon rubber were neglected due to the reinforcement with the stiff elastic fibers. The strain energy density function $W$ was considered to be decoupled into isotropic part (Mooney-Rivlin; elastomer contribution) and anisotropic part (contribution of the wires). $W$ is defined in (1).

$$W = \tfrac{\mu}{2}\left(I_1 - 3\right) + \tfrac{\nu}{2}\left(I_2 - 3\right) + c\left(I_4 - 1\right)^2, \qquad (1)$$

where $\mu$, $\nu$, and $c$ denote stress-like material parameters. $I_1$ and $I_2$ are first and second principal invariants of the right Cauchy-Green strain tensor $\mathbf{C}$. It can be written as $\mathbf{C}=\mathbf{F}^{\mathrm{T}}\mathbf{F}$, where $\mathbf{F}$ is the deformation gradient. $I_4$ denotes additional invariant generated by anisotropy of the continuum. Considering simultaneous extension (uniform) and inflation of incompressible tube (due to rubbery matrix) $\mathbf{F}$ is obtained as $\mathbf{F}=\mathrm{diag}[RL/(rl),r/R,l/L]=\mathrm{diag}[\lambda_R,\lambda_T,\lambda_Z]$. Here $R$ and $L$ denote radius and length in the reference configuration. Lowercase letters indicate spatial configuration. It results in $I_4=\lambda_T^2\cos^2(\beta)+\lambda_Z^2\sin^2(\beta)$. Mention that mechanical equivalency of two families of reinforcing fibers implies that one helical family is disposed under $\beta$ and second one under $-\beta$; here considered as the declination from circumferential direction. Details of this approach can be found in Holzapfel et al. (2000), and Ogden (2009). Also equilibrium equations for inflated and extended thick-walled cylindrical tube were adopted from the latter. Observed internal pressure, $p$, and longitudinal load, $F$, can be predicted in such a way.

## 3. Results

Data sample intended for parameters estimation was collected from the last pressurization cycle of each longitudinal load. It is shown in Fig. 2. Pressure-circumferential stretch relationships suggest that macroscopic response of the sample holds the response typical for inflated polymer tube (concave curve). No material instability (non-uniform bulge), however, was observed. Implemented wired structure probably prevents the tube from it. Observed small torsions (0-2.5°/5cm) were not considered to be materially intrinsic.

Material parameters were estimated using weighted least square optimization in Maple 13 (Maplesoft, Canada). They are listed in the caption of Fig. 2. However, it has to be said that the model failed in the prediction of entire range of the experiment. Only data for the first longitudinal weight were fitted successfully. Especially longitudinal load was dramatically underestimated (error reached up to ≈5.5 N at the peak value). It suggested to fit data corresponding to the first weight ($m$ = 41 g) separately. This result is depicted with continuous curves in Fig. 2.

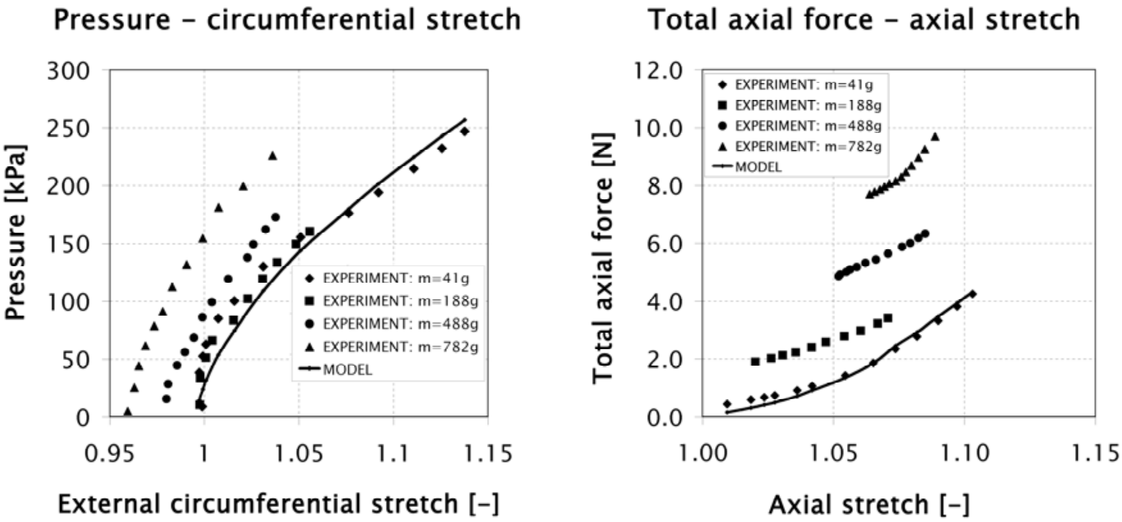


*Fig. 2: Comparison of the model predictions (first weight only) and experimental data. Parameters involved in (1) were estimated as $\mu$=-18.37kPa; $\nu$=220.9kPa; c=34.62kPa; and $\beta$=0. Total axial force means the force generated by hanged weight and by the pressure acting on the end of the tube.*

## 4. Discussion and Conclusions

It was concluded that NiTi reinforcement reduces elastomer viscoelasticity in macroscopic response, which can not be fully described with the model considering the effect of wires only as the introduction of anisotropy. It should also be noted that the best fit model predicts parameter $\beta$ to be zero, which is not in accordance with the fabricated structure. It suggests that the reinforcement is the most propagated as the stiffening in the circumferential direction.

This is only the pilot study. It clearly shows, however, that the structural model, probably based on non-affine deformation of the elastomeric tube and NiTi wires, is needed. In other words – any model for elastomer-wire kinematic interaction; because the present model presumes the same strains sustained by both components and it seems to be the weak point. Similar effect might be obtained incorporating bending stiffness of wires. But, development of such models should be accompanied with advancing of experimental techniques. Involving of x-ray tomography in future experiments is of our concern.


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## References


Duerig, T.W., Tolomeo, D.E., & Wholey, M. (2000) An overview of superelastic stent design. Minimally Invasive Therapy and Allied Technologies, 9, 3-4, pp.235-246.

Heller, L., Kujawa, A., Šittner, P., Landa, M., Sedlák, P. & Pilch, J. (2008) Quasistatic and dynamic functional properties of thin superelastic NiTi wires. European Physical Journal: Special Topics, 158, 1, pp.7-14.

Heller, L., Vokoun, D., Majtás, D., & Šittner, P. (2008) Thermomechanical characterization of shape memory alloy tubular composite structures. Advances in Science and Technology, 59, pp.150-155.

Holzapfel, G.A. (2000) Nonlinear solid mechanics. John Wiley and Sons, Chichester.

Holzapfel, G.A., Gasser, T.C., & Ogden R.W. (2000) A new constitutive framework for arterial wall mechanics and a comparative study of material models. Journal of Elasticity, 61, 1-3, pp.1-48.

Stoeckel, D., Pelton, A. & Duerig, T. (2004) Self-expanding nitinol stents: material and design considerations. European Radiology, 14, 2, pp.292-301.

Ogden, R.W. (2009) Anisotropy and nonlinear elasticity in arterial wall mechanics, in: Biomechanical Modelling at the Molecular, Cellular and Tissue Levels (G.A. Holzapfel & R.W. Ogden eds), Springer, Wien, pp.179-258.