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Supplementary Materials for

Strain rate–dependent mechanical metamaterials

S. Janbaz*, K. Narooei, T. van Manen, A. A. Zadpoor

*Corresponding author. Email: s.janbaz@tudelft.nl

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The PDF file includes:

Fig. S1

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/6/25/eaba0616/DC1)

Movies S1 to S6

We performed uniaxial compression tests on rubber disks ($D = 28.5$ mm, $h = 12.5$ mm, maximum compressive strain = 0.3) to determine the elastic and viscous properties of silicone rubber and 3D printed parts (Agilus, Stratasys, US). We used the Neo-Hookean material model to define the elastic properties of the silicon rubber used for creating the hyperelastic beam. The Neo-Hookean material constant (C_{10H}) was calculated by fitting the data from quasi-static uniaxial compression tests to the Neo-Hookean material model using the fitting algorithms available in Abaqus. To determine the material properties of Agilus, we performed stress relaxation experiments whose data was then divided into two parts, namely instantaneous and relaxation responses. In order to achieve the instantaneous compression condition, we set the speed of the testing machine (Lloyd, LR5K) to the maximum, 1000 mm/sec. In addition, to stabilize the speed of the crosshead before the compression process, a gap (10 mm) was introduced between the moving crosshead of the machine and the specimens. The instantaneous response was used to determine the elastic properties of Agilus while the viscous properties were calculated using the relaxation part of the data. The loading rate was considered in the evaluation of the instantaneous response. The material parameters were determined by minimizing the difference between the stress values predicted by the material model and the experimental data as:

$$error = \sum_{i=1}^{n_l} \frac{\left(\sigma_i^{loading} - \sigma_i^{exp-loading}\right)^2}{\left(\sigma_i^{exp-loading}\right)^2} + \sum_{i=1}^{n_r} \frac{\left(\sigma_i^{relaxation} - \sigma_i^{exp-relaxation}\right)^2}{\left(\sigma_i^{exp-relaxation}\right)^2} \quad \text{(E1)}$$

where (n_l, $\sigma_i^{loading}$, $\sigma_i^{exp-loading}$) and (n_r, $\sigma_i^{relaxation}$, $\sigma_i^{exp-relaxation}$) are the number of experimental points, theoretical stress, and experimental stress in the loading and relaxation parts of the experiment, respectively. The defined error was minimized using the *fmincon* function that is available in MATLAB (Mathworks, US). The details of this constraint minimization procedure can be found in our previous works (*39, 40*). The fitting process for the viscous part was performed both using a single-term and seven-terms Prony series. Figure S1 compares the stress-strain curves predicted by both types of material models with experimental observations.

To evaluate the reliability of our predictions (the buckling direction in the bi-beams), which are based on computational models with a single-term Prony series, we performed experiments as well as computational analysis with an accurate visco-hyperelastic material model consisting of seven-terms Prony series. The geometric and material imperfections present in the bi-beams were accounted for by fine-tuning the Neo-Hookean constants of both materials using the data available from one of the experiments (*i.e.*, one aspect ratio and geometrical design). The coefficients C_{10H} and C_{10V}^{∞}(s) were, therefore, revised to 0.170 (MPa), 0.088 (MPa), in models with one-terms Prony series, and 0.065 (MPa) in models with seven-terms Prony series (Figure

[1] Corresponding author, s.janbaz@tudelft, Tel: +31 (15) 2783133

4b). The same parameters were then used for simulations corresponding to all the other experiments.

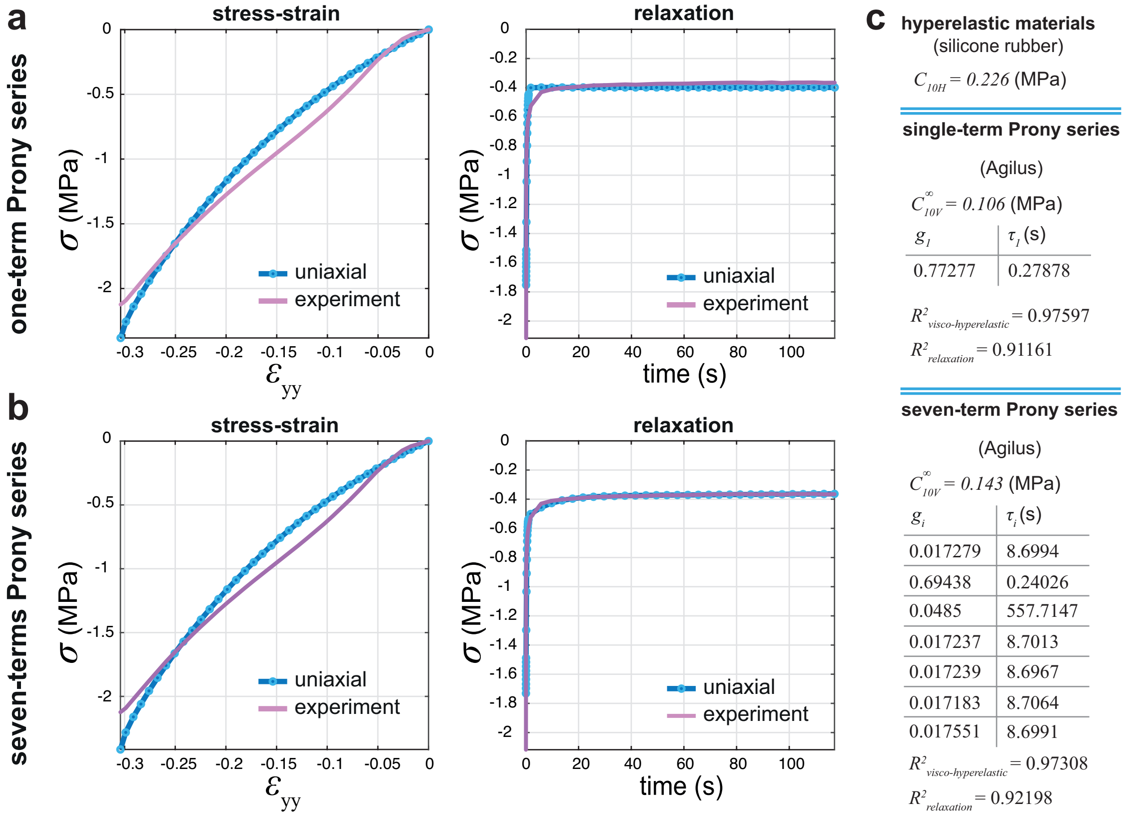

Figure S1. Fitting of material models to experimental data. (a) The fitting of the instantaneous (left) and relaxation (right) data to a single-term Prony series, (b) The fitting of the instantaneous (left) and relaxation (right) data to a seven-terms Prony series. (c) The numerical values of the material parameters determined for silicone rubber and Agilus.