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A micro-mechanical approach towards modeling the inelastic behavior of fiber-reinforced aerogels

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Abstract. *Fiber-reinforced aerogels are known for retaining the exclusive thermal and acoustic properties of aerogels and at the same time possessing a good load bearing strength as a result of the reinforcement. Along with strong nonlinearity, these aerogels demonstrate many inelastic features such as stress softening and residual strains. In this study, we present a micro-mechanical model describing this behavior of fiber-reinforced aerogels.*

Keywords: fiber-reinforced; aerogel; stress-softening; permanent set; beam; bending; elastic foundation.

1 INTRODUCTION

Fiber-reinforced aerogels are a class of aerogels prepared by adding a fiber batting to the sol before the sol-gel process [1]. These aerogels exhibit a good load bearing strength while still retaining the exclusive properties of native silica aerogels, such as, low thermal conductivity and low acoustic velocity. The resulting fiber-reinforced aerogels are also hydrophobic. These features have made fiber-reinforced aerogels attractive towards various applications in the industry. Although their primary applications are insulation, its mechanical behavior is extremely important in the context of the structural stability. Fiber-reinforced aerogels exhibit many inelastic features, which are captured through a micro-mechanically motivated constitutive model briefly described below.

1.1 Uniaxial compression tests

Cylindrical samples of glass-fiber reinforced aerogels were subjected to uniaxial quasi-static compression tests. A high non-linearity, cyclic stress softening, and permanent set are observed [2]. This cyclic stress softening is similar to the Mullins effect as observed in rubber-like elastomers.

Hysteresis measurements show a low dissipation up to about 30% of applied maximum strain, beyond which there is a sudden rise in the energy dissipation [2]. According to [3] and these tests, the mechanism responsible for damage in the low dissipation region is the brittle particle network collapse and local bending of fibers. In the large dissipation region, the damage is attributed to the excessive bending and breakage of fibers.

2 MODELING

2.1 Assumptions

We consider fiber bending and breakage as the main sources of elasticity and damage in the material, respectively. Accordingly, fibers are assumed to behave as beams and the aerogel particles are assumed to form an elastic foundation under the fibers. Since the fibers are randomly distributed within the sol during the preparation process, the fiber orientations are random. Thus, a homogeneous and isotropic distribution of fibers is assumed. These three assumptions are the basis of our model (see Fig. 1).

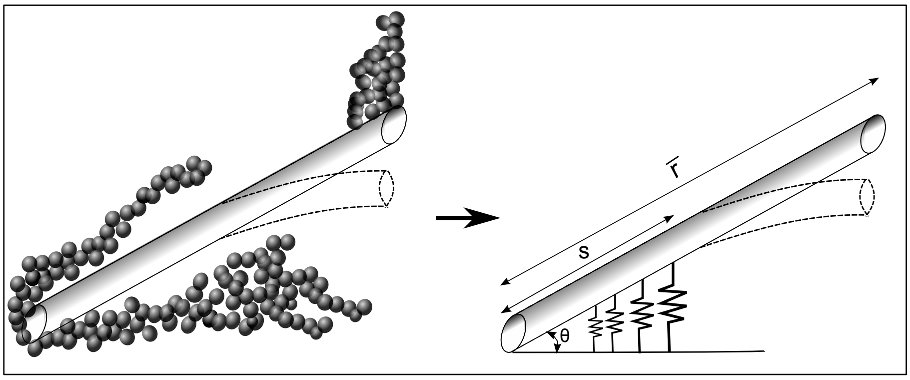

Figure 1: Model assumption.

2.2 Model

The strain energy of a beam on an elastic foundation (of the Winkler type) is formulated according to the Euler-Bernoulli beam theory for large deflection [4, 5], and is represented as a function of the length of the fiber ($\bar{r}$), the angle of orientation of the fiber with respect to a reference plane (θ) and the displacement of the fiber (δ). The displacement is then geometrically expressed in terms of the stretch (λ) in the loading direction. Thus, the strain energy can be expressed as

$$\psi = \psi(\bar{r}, \theta, \lambda). \tag{1}$$

The network damage is based on the fiber failure after exceeding its critical/maximum bending stress value. Hence the damage criterion can be expressed as:

$$\sigma > \sigma_{max}. \tag{2}$$

For a given applied displacement, the shorter fibers are considered to fail first as they reach the critical displacement first. Hence the damage is assumed to propagate from the shorter to the longer fibers. The standard Gaussian distribution is used to express the probability distribution of fiber breakage. This can be visualized through the following Fig. 2

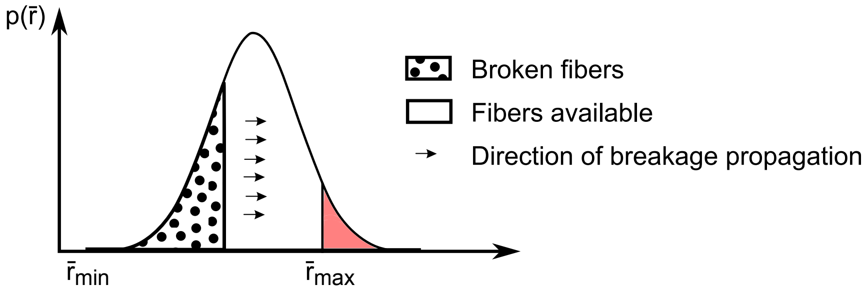

Figure 2: Illustration of the fiber distribution expressing the damage behavior.

The network energy is then obtained using the number of fibers $N(\bar{r})$, and can be mathematically expressed in terms of the available lengths of fibers r_a as:

$$\psi^d = \int_{r_a} N(\bar{r})\psi(\bar{r}, \theta, \lambda) d\bar{r}. \tag{3}$$

The 3D generalization is carried out using numerical integration over the unit sphere wherein 45 integration points are used as they provide the best trade off between numerical error and computational costs [6]. Accordingly,

$$\Psi = \frac{1}{A} \int_S \psi^d dS \cong \sum_{i=1}^{k} \omega_i \psi_i^d, \tag{4}$$

where A represents the area of the unit sphere and ω_i denote the weight factors corresponding to the collocation directions d_i $(i = 1, 2, 3, ..., k)$.

2.2.1 Material parameters

The model consists of six constituent parameters and two distribution parameters. The first two parameters $\bar{r}_{min}$ and $\bar{r}_{max}$ denote the minimum and maximum fiber lengths. This is followed by the extent of elastic foundation s, the stiffness in the foundation κ (which is basically the stiffness due to the aerogel particles), the maximum stress required to break the fibers σ_{max}, and the initial number of fibers N_0. The last two parameters are the distribution parameters; the mean fiber length $\bar{r}_{mean}$ and the standard deviation in distribution m.

2.3 Results

The model predictions are validated against experimental data from tests conducted on glass fiber-reinforced aerogels. The validation is visualized through Fig. 3 and it is seen that the model gives a good estimation not only for the loading but also for the unloading behavior.

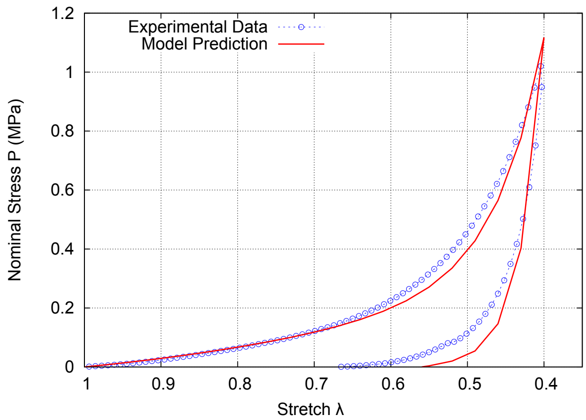

Figure 3: Model prediction vs experimental data.

3 CONCLUSIONS

A micro-mechanically motivated constitutive model is presented that is capable of capturing the inelastic effects, such as cyclic stress softening and permanent set, in fiber-reinforced aerogels. The model is shown to provide good validation against experimental data.

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