Modeling a Soft Composite Accumulator for Human Mobility Assist Devices

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Modeling a Soft Composite Accumulator for Human Mobility Assist Devices

Robert Shaheen and Marc Doumit

Abstract*—Research in the field of human mobility assist devices, aiming to reduce the metabolic cost of daily activities, is seeing the benefits of the exclusive use of accumulators to store and release energy during the gait cycle. The Pneumatic Artificial Muscle, used in a passive state, has proven to be a superior choice for these devices when compared to its alternatives, however, challenges regarding muscle pressure dissipation and a limited elongation potential have been identified. A recently developed, novel Soft Composite material has been shown to experimentally replicate the distinctive mechanical behaviour of the Pneumatic Artificial Muscle, without the need for internal pressurization. This paper presents two separate constitutive models to provide a closer insight into the behaviour of these Soft Composite accumulators. Both models were derived from methods involving finite elasticity theory and employed either a structural strain energy function of Holzapfel, Gasser, and Ogden's type or a phenomenological strain energy function of Fung's type. Both models were in good agreement with the experimental data that were collected through a modified extension-inflation test and, therefore, provide a basis for further examination as a Soft Composite design model.

***Index Terms*—Soft Composite, Accumulator, Mobility Assist Devices, Exoskeleton, Finite Elasticity**

I. Introduction

Human mobility assist devices have seen the benefits of using accumulators to store and release energy during the gait cycle [1], [2]. Researchers are implementing accumulators with a nonlinear stiffness response into novel exoskeletal designs, with the hopes of reducing the metabolic cost of daily activities [3], [4]. The Pneumatic Artificial Muscle (PAM) is a soft actuator that provides the ideal stiffness properties for this application, however, challenges regarding pressure dissipation and limited elongation potential have been noticed [5].

This motivated the development of a novel accumulator with mechanical properties comparable to the PAM while omitting internal pressurization. The desired elastic behaviour, analogous to that of biological connective tissue, is described by a force-elongation response consisting of an initial toe region and subsequent linear region. A novel Soft Composite (SC) accumulator, illustrated in Fig. 1, that fits these requirements was proposed in [6], which outlines the details regarding SC fabrication and experimental characterization.

The SC consists of an axisymmetrical braided sleeve that is embedded in an elastomeric matrix. An example of a specimen mold before the curing process is shown in Fig. 2. The operation of the SC is simple. During the rest phase the matrix holds the braided sleeve near its compressed jamming state. As

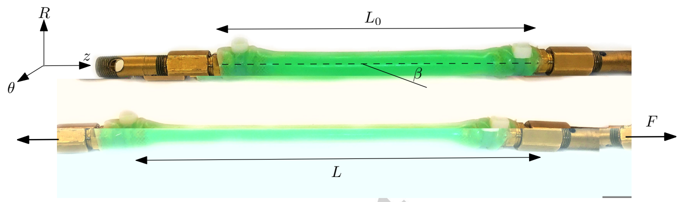

Fig. 1. A SC specimen made with a shown in its resting (top) and stretched (bottom) configurations.

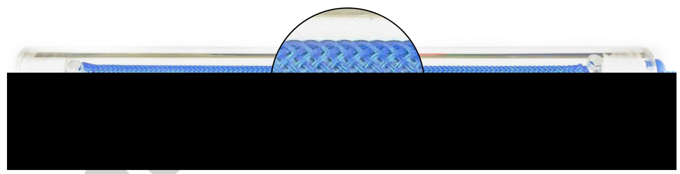

Fig. 2. SC mold, ready for impregnation, with a magnified segment to illustrate axisymmetrical braiding style.

tensile forces are applied to the SC, it elongates, and the fibres begin to align parallel to the applied force. The SC's resistive tensile force increases as it continues to be stretched until it reaches its maximum elongation potential which occurs at its tensile jamming state. Designers will benefit from models that predict the accumulator's tensile behaviour when accurately selecting a SC for mobility assist devices.

One approach that could be used is derived from using finite elasticity theory regarding hyperelastic materials. The SC, in this case, is assumed as a single continuum. This type of model works by employing a constitutive formula to express the Cauchy stress tensor of a material as a function of its Green strain tensor. A strain energy function (SEF) is employed to guarantee the absence of energy dissipation during deformation, and it is governed by several material constants that are determined by training the model with empircal data. For a cylindrical tube, these experimental data are typically collected from extension-inflation tests originally proposed by Boonstra *et al.* [7] but made popular by Vankergo *et al.* [8].

One could derive their own SEF for a specified application but many can be found in open literature, classified as either a phenomenological or a structural SEF. Phenomenological SEFs purely base their integrity through fitting the model with experimental results while a structural SEF gives some insight to the anisotropic properties of the material. In the case of SC tubes, structural SEFs tend to acknowledge a preferred direction within the material which is correlated to the direction of the fibres that are embedded within the

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