MPI 2026 Workshop Problem

Cable Flexing, Polymer Deformation, and Fatigue

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1. Background and Business Need

W.L. Gore & Associates, Inc. develops high-performance cables for semiconductor manufacturing, aerospace, and defense applications [1,2]. These cables are frequently installed in systems that require continuous motion, such as robotic positioning equipment, pick-and-place tools, advanced bonding systems, inspection equipment, and other automated manufacturing platforms. In many applications, these cables are subjected to repeated bending and flexing for millions of cycles while maintaining electrical performance and mechanical reliability. Failures can result in costly downtime, reduced equipment availability, and increased maintenance requirements.

The primary objective of the Mathematical Problems in Industry (MPI) workshop is to improve understanding of the mechanical behavior of flexing cables and to develop predictive tools that can estimate service life. Specifically, Gore seeks methods to quantify stress, strain, and strain-rate distributions within a cable during cyclic motion and to connect these mechanical responses to material fatigue and long-term degradation. An additional goal is to translate real-world cable deformation into laboratory test conditions that can be used for accelerated material characterization.

2. Cable Construction and Failure Mechanisms

A typical cable consists of several layers, starting with a stranded copper conductor core, polymer dielectric insulation, optional metallic shielding, and an outer polymer jacket. When a cable bends, the strands in the copper conductor can rotate and partially unfurl to accommodate deformation. At the same time, the surrounding polymer materials in the insulation layer and outer jacket stretch, compress, and shear in response to the imposed motion.

There are three principal failure mechanisms in high-flex applications. Those are degradation and fatigue of the polymer dielectric, fatigue of the copper conductor or shield, or failure near cable terminations. The primary focus of the workshop is degradation and fatigue of the polymer dielectric and jacket materials because polymer performance is strongly influenced by loading history, strain rate, and environmental conditions. We will assume ideal and non-degrading properties for the other layers.

3. Problem Definition and Operating Conditions

The targeted application are trackless cables used to connect moving devices that demand high reliability over long service lives, requiring flex-life durability exceeding 10 million cycles. The common geometry in these applications consists of a cable fixed at one end while the opposite end moves through a prescribed stroke according to a velocity profile (see Fig. 1). Key geometric parameters are total cable length, bend radius, lead length, cable diameter, and internal cable architecture. For this workshop, we consider several geometric simplifications, including homogeneous cable models, concentric constructions, and other geometries. We will not consider gravity for this workshop.

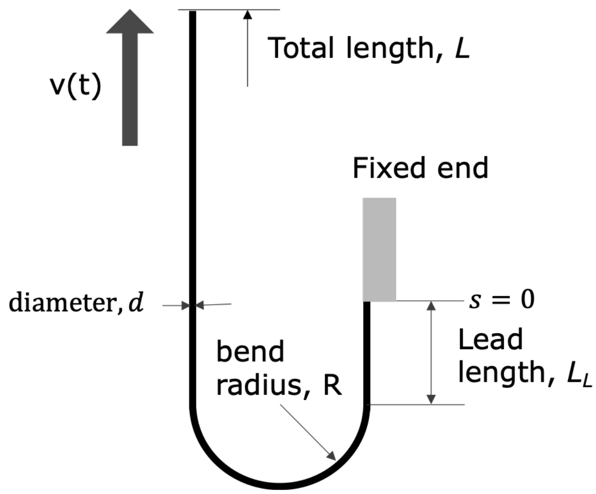

Figure 1: Geometrical representation of bending cycle

4. Mechanical Modeling Framework

Mechanical modeling of cable architectures has been explored in the literature [3-6] for materials that follow a simple linear elastic stress-strain relationship. The cable bending and motion generates complex three-dimensional deformation states that experience both normal and shear loads. Polymer materials also often exhibit viscoelastic behavior resulting in a response that depends not only on the strain magnitude, but also on the loading rate and loading history.

In this workshop we would like to extend the framework for mechanical deformation of cable assemblies from a linear elastic model to one that includes viscoelastic behavior and represent time dependent deformation (e.g. 3-component Maxwell model [7]). Using this model, we will determine the stresses and strains experienced by the cable assembly. All material properties and parameters for the constitutive equations will be provided.

An important aspect is comparing the cable flexural behavior with torsional rheology. Gore routinely characterizes polymers using dynamic torsional testing, which measures shear stress, shear strain, angular displacement, angular velocity, and shear rate. If a reliable mapping can be developed between cable bending and torsional loading (or potentially another geometry), laboratory measurements could be used directly to predict field performance.

Once the strain and strain rates for cable bending have been identified, we will use an S-N approach [8-10] to estimate the durability of the cable assembly and attempt to predict lifetime based on different properties of a variety of polymers used for the dielectric material.

5. Key Research Questions and Desired Outcomes

The ultimate deliverable is a predictive framework that links cable geometry, motion conditions, material behavior, and fatigue mechanisms to the flex-life of the cable assembly. Such a framework would enable improved cable design, accelerated qualification testing, and more accurate lifetime predictions for future products. Therefore, we pose four major technical questions.

1. What are the stress, strain, and strain-rate distributions inside a cable for different geometries and motion profiles (refs [3-6])?
2. How does the choice of polymer mechanical model, including viscoelastic and rate-dependent behavior, alter these distributions (ref [7])?
3. Can the complex deformation state experienced during cable bending be translated into equivalent torsional shear test conditions (ref [5])?
4. How do cycling frequency, velocity, and loading history influence long-term performance and fatigue life (refs [8-10])?

6. References

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