

MATERIAL CHARACTERIZATION OF A DIELECTRIC ELASTOMER FOR THE DESIGN OF A LINEAR ACTUATOR

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ABSTRACT

Electrical motors and/or hydraulics and pneumatics cylinders are commonly used methods of actuation in mechanical systems. Over the last two decades, due to arising market needs, novel self-independent mobile systems such as mobility assistive devices have emerged with the help of new advancements in technology. The actuation criteria for these devices differ greatly from typical mechanical systems, which has made the implementation of classical actuators difficult within modern assistive devices. Among the numerous challenges, limited energy storage capabilities by mobile systems have restricted their achievable operational time. Furthermore, new expectations for device weight and volume, as well as actuator structural compliance, have added to this quandary.

Electroactive polymers, a category of smart materials, have emerged as a strong contender for the use in low-cost efficient actuators. They have demonstrated great potential in soft robotic and assistive device/prosthetic applications due to their actuation potential and similar mechanical behaviour to human skeletal muscles. Dielectric Elastomers, in particular, have shown very promising properties for these types of applications. Their structures have shown large achievable deformation, while remaining light-weight, mechanically efficient, and low-cost.

This thesis aims to characterize, and model the behaviour of 3M™ VHB polyacrylic dielectric elastomer, in order to establish a foundation for its implementation in a proposed novel linear actuator concept. In this thesis, a comprehensive experimental evaluation is accomplished, which resulted in the better understanding of the elastomer's biaxial mechanical and electro-mechanically coupled behaviours. Subsequently, a constitutive biaxial mechanical model was derived in order to provide a predictive design equation for future actuator development. This model proved effective in providing a predictive tool for the biaxial mechanical tensile response of the material. Finally, a simplified prototype was devised as a proof of concept. This first iteration applied experimental findings to validate the working principles behind the proposed actuator design. The results confirmed the proof of concept, through achieved reciprocal linear motion, and provided insight into the design considerations for prototype optimization and final actuator development.

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CHAPTER 1

Introduction

Over the last two decades, technological advancements have allowed researchers to develop many novel self-independent mobile systems. Among these innovations are mobility assistive devices, which enhance people's ability to walk and achieve quotidian activities. Powered by electrical motors and/or hydraulics and pneumatics cylinders, they provide a considerable improvement to human physical abilities. Their development is not, however, without its limitations. The success of these devices is greatly restricted by the operational times currently achievable, which are limited by high system energy requirements and low energy-storage capacities. Moreover, the present weight and volume of these devices are less than favourable for self-independent mobile devices.

These limitations have led to new interests in the application of smart materials to produce novel types of actuation. As part of this newer class of materials, electroactive polymers have emerged as a strong contender for the use in low-cost efficient actuators. Among their many appealing properties, they have proven particularly useful for soft robotic and assistive device applications due to their mechanical behaviour similar to human muscle [1, 2]. A subcategory of these polymers, namely dielectric elastomers, has shown very promising properties for these types of applications. Their structures have shown large achievable deformation, while their material composition has demonstrated high dielectric strength [3, 4].

A novel concept for a dielectric elastomer based linear actuator is proposed as part of the scope of this thesis. The proposed actuator design aims to achieve a simple and customizable configuration, in order to provide tailorable features for a variety of applications. The structure of this concept can be seen in Figure 1.1. It consists of a multi-layered dielectric elastomer flat core, which is held in a stretched configuration by a series of flat springs. These springs are fixed in a circumferential arrangement to provide the actuator with sufficient lateral support during actuation.

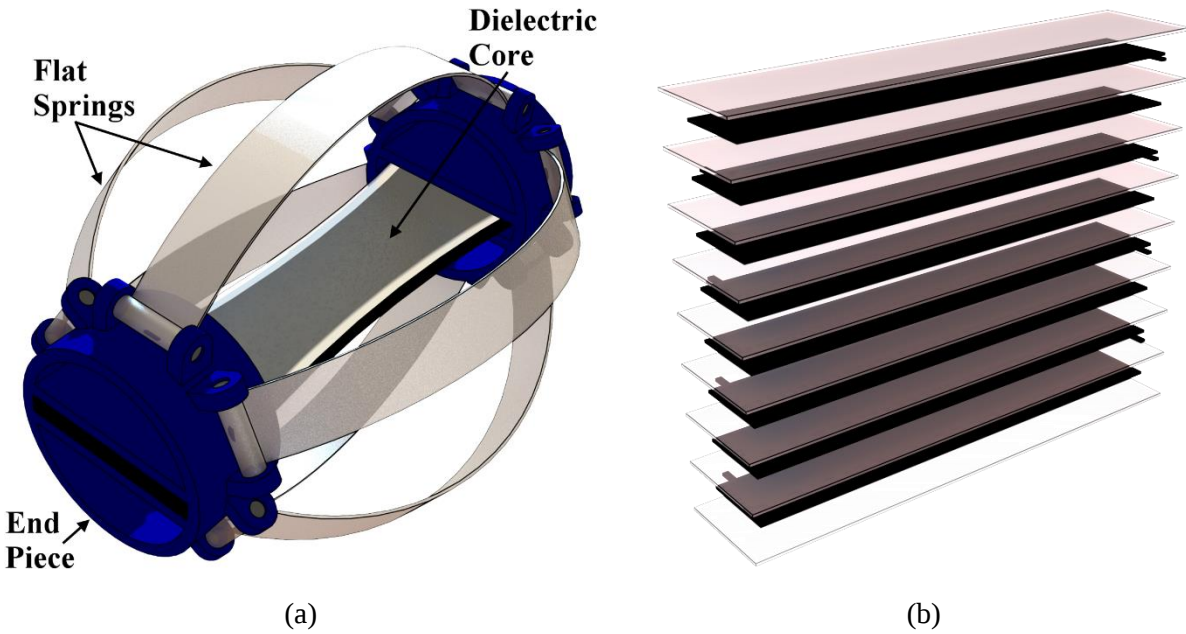


Figure 1.1: Proposed linear actuator concept
(a) Full actuator assembly, and (b) Multilayer core exploded view

The core of the actuator consists of several layers of pre-stretched elastomer films, sandwiching alternating-polarity conductive electrodes, which would be connected to an external power source. The working principle of this concept is simple. When no voltage is applied, the elastomer core is in an inactive mode and the actuator is in initial equilibrium state. In this state, the tension of its core is counteracted by the external load of the flat springs, as shown in Figure 1.2 (a). Once a voltage is applied to the electrodes, the induced electric field across the dielectric elastomer core produces a compressive force on the elastomer layers and results in an expansion (or “relaxation”) of the material. This disrupts the force equilibrium, causing an elongation of the actuator, as shown in Figure 1.2 (b). Through a carefully designed circuit control system, the actuator could be synchronized to contract and expand in unison with various mechano-biological processes.

Among others, the primary distinctiveness of the proposed concept is the core’s flat geometry and the use of external springs as a means for pre-stretching. Currently available off-the-shelf polyacrylic dielectric elastomers come in flat rolls. Keeping a planar core geometry would simplify manufacturing of the actuator. It also provides a customizable inner stiffness based on layer dimensions and quantity. Similarly, external springs would allow for easier assembling of the actuator, and provide the designer with adjustable stiffness parameters.

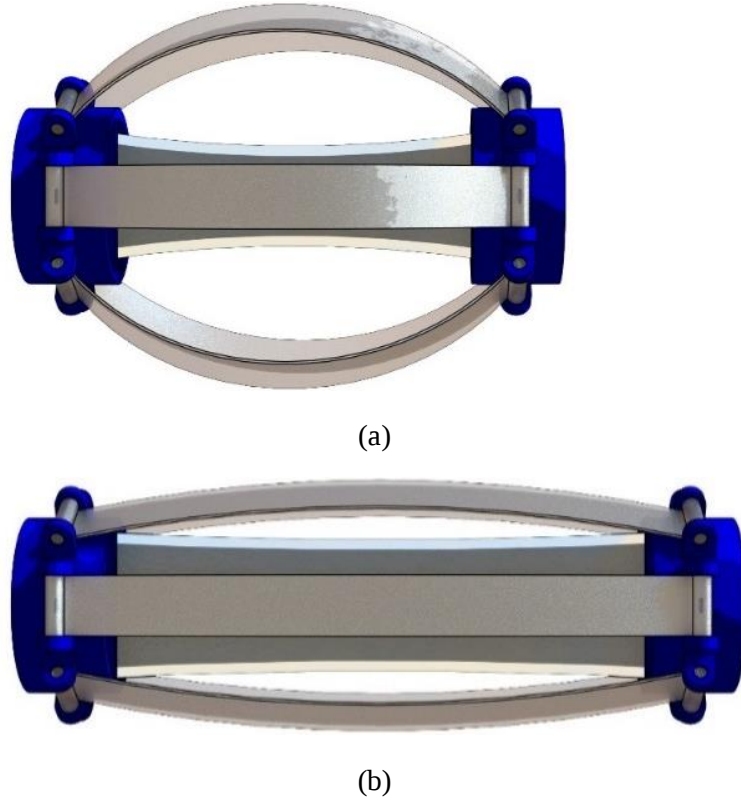


Figure 1.2: (a) Contracted (b) Relaxed (elongated) state of proposed actuator design

1.1 Objectives

While the ultimate goal of this thesis was to develop a dielectric based linear actuator, initial prototype development and testing proved challenging. This enlightened the author to the absolute need to first characterize the dielectric material prior to its implementation in a feasible prototype. Thus, the objectives of this thesis are threefold. It first aims to study the mechanical and electro-mechanical behaviours of 3M™ VHB polyacrylic dielectric elastomer from a biaxial tensile perspective. It then aims to develop a hyper-viscoelastic biaxial mechanical model, to characterize these behaviours analytically. It finally sets out to accomplish preliminary prototyping development, based on the working principles of the aforementioned actuator concept. This last portion intends to demonstrate achievable reciprocal linear motion and potential parameter customization of the actuator design.

1.2 Methodology

In order to achieve the thesis objectives, a four-part methodology was applied. Firstly, understanding the mechanical response of the material was essential to properly characterize its behaviour under various loading conditions. More specifically, a series of biaxial tests were performed to quantify the dielectric elastomer's tensile properties. Secondly, the dielectric elastomer's electro-mechanical response was evaluated, by testing its static and dynamic tensile properties while applying an external electric field. After gaining a better understanding of the mechanical and electro-mechanically coupled behaviours, a biaxial constitutive model was developed to provide a predictive design equation for future actuator development. The original model was first validated through uniaxial tensile consideration, and later modified to characterize the behaviour for biaxial stretching. Finally, a simplified initial prototype was developed as a proof of concept. This first iteration applied experimental findings to build the prototype, and validate the working principles behind the proposed actuator design.

1.3 Contribution

This thesis provides a comprehensive experimental evaluation of 3M™ VHB polyacrylic dielectric elastomer under biaxial tensile loading, which is the first of its kind. The viscoelastic rate- and time-dependent responses of the polymer were studied for different loading conditions at various stretch rates. These experiments provide essential insight into the behaviour of the elastomer for actuator design purposes. Further experimentation provided a better understanding of the effects of pre-stretching on the electro-mechanical changes in tensile forces of the elastomer. These tests demonstrated its effects on static and dynamic loading of the VHB elastomer.

Based on this comprehensive experimental evaluation, the elastomer was illustrated to be isotropic along its planar configuration. This has provided a firm validation for previously assumed properties of the material.

The research also proposes a novel modification to a rheological constitutive model to characterize the material's tensile response in biaxial conditions. This model has demonstrated good agreement with experimental data, for cases of equiaxial stretch ratios. It also demonstrated potential in

predicting stresses for non-equibiaxial stretch rates. In both cases, the prediction of stress along orthogonal tensile axes provides valuable information for actuator design and development.

Finally, this research proposes a novel prototype design for linear actuation based on a single dielectric elastomer membrane. This provides good preliminary proof of achievable linear reciprocal motion using the working principles of the proposed full actuator design, and delivers a simple testing and optimization process for further actuator development.

1.4 Thesis Outline

This thesis is organized into 6 chapters. Chapter 1 introduces the proposed dielectric elastomer based linear actuator, the thesis objectives, methodology, and contributions. Chapter 2 presents the relevant findings from literature, which have been subdivided into three main categories. First, it provides a background on electroactive polymers as a class of smart materials and then discusses the specifics of dielectric elastomers, their material properties, and mechanical modelling. Lastly, a section on design parameters and considerations, illustrating current actuator geometries, is provided.

Chapter 3 delivers a comprehensive mechanical and electro-mechanical experimental evaluation. The VHB elastomer is subjected to biaxial tensile tests, including load-unload tests, and stress-relaxation tests, at varying stretch rates. These were performed to illustrate the polymer's viscoelastic rate- and time-dependant mechanical behaviours. The material was then subjected to static and dynamic electro-mechanical testing, to better understand its response to an applied electric field under various configurations.

Chapter 4 presents a rheological constitutive model for the elastomer, which is based on a three-dimensional network of fluid-filled cubes. This hyper-viscoelastic model was selected for its straightforward approach to illustrate viscoelastic behaviour. It was first validated for a series of simple uniaxial tensile tests, and further developed to predict stresses under biaxial deformation.

Chapter 5 describes the design, working principles, and preliminary tests of a linear actuator prototype using a single-membrane dielectric elastomer core. The actuator was tested with various configurations to achieve reciprocal linear motion, as a proof of concept.

Chapter 6 presents the conclusions of the thesis. It also provides considerations for forthcoming research, including changes in experimental methods, enhancements to the analytical model, and suggestions for prototype optimization.

CHAPTER 2

Literature Survey

The following chapter presents a comprehensive review and report of pertinent topics towards the scope of the thesis. The review first identifies current applications of electroactive polymers, and elaborates on the specific characteristics of 3M™ VHB polyacrylic tape as a dielectric elastomer. Furthermore, the review presents material constitutive modelling approaches, design considerations, and finally a summary of currently reported actuators in marketplace and research laboratories.

2.1 Current Actuator Technologies

Conventional methods of actuation can be categorized into three main types of systems: hydraulic, pneumatic, and electric. These types of actuators have demonstrated strengths and weaknesses in transmitting mechanical energy.

Hydraulic systems have proven effective at generating both linear and rotary motion. They are typically superior at resisting larger loads, and can deliver greater power at faster speeds due to the highly incompressible nature of the hydraulic fluids. They are, however, difficult to control due to the varying properties of fluids resulting from changes in temperatures, and pose a potential leak hazard that could prove dangerous in biomedical applications [2, 5].

Pneumatic systems, on the other hand, are typically advantageous due to their lightweight and relatively smaller structures. They typically have a higher payload-to-weight ratio, and can be considered simpler than their hydraulic counterparts. This is due to their ability to function without the need of a closed-loop fluid system. Their overall load resistance capabilities are lesser, however, due to their lower achievable pressures. They also tend to be less efficient compared to hydraulic systems, as they lack the ability to self-lubricate [2, 5].

Electric systems come in a large variety of configurations, and require smaller power supplies with respect to the latter. They are also typically considered simpler systems as the connections between the supply and device is straightforward (i.e. wires versus pipes/tubes). Their power output is considered relatively lower with respect to their weight and size, and they typically work more efficiently at higher speeds. This leads to the requirement of speed reduction mechanisms, which adds complexity and weight [2, 5].

Due to the drawbacks of the current methods of actuation, demand for a better alternative has increased in the fields of robotics, mechatronics, and biomedical engineering. In particular, for applications in biomimetics, an alternative that can provide high power-to-weight ratio and efficiency, while also being compliant to complex biological geometries, is a necessity.

2.2 Electroactive Polymers

Due to the limitations of the aforementioned conventional actuators, a growing interest in smart materials has developed over the years. Alternatives such as shape memory alloys, magnetostrictive materials, piezoelectric materials, as well as electroactive polymers have been proposed as viable solutions for these new actuation requirements. They have demonstrated a wide range of advantages such as low power consumption, larger active stresses, greater ranges of operating temperatures, and overall beneficial material and mechanical properties (e.g. strength, elasticity, etc.) [1, 2]. The use of smart materials as actuators has also been of growing interest due to their relative simplicity. Unlike current transducers, active-material based actuators do not typically consist of many interacting mechanical parts. This allows the actuators to be fully integrated as part of the active structure, which in turn improves the system's output efficiency and reliability [2]. A typical smart actuator structure can be seen in Figure 2.1. The transducer must be accompanied by a control system and a power supply for it to function.

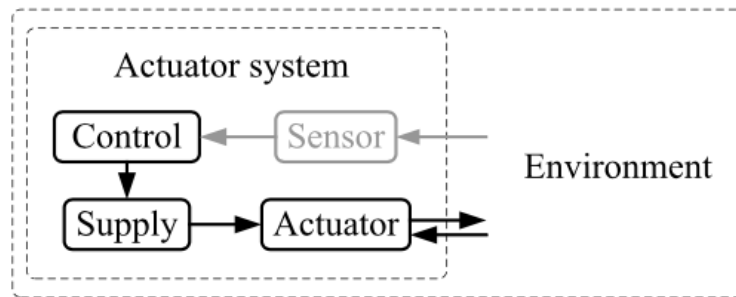


Figure 2.1: Typical smart-material based actuator system [2]

Within this multifaceted realm, a large subclass of polymer-based smart materials has been of particular interest to researchers. Named actively deforming polymers, these materials possess inherent attributes that have set them apart from their competition. Their intrinsic structural compliance, light weight nature, and relatively lower cost give them great potential in solving challenges of system integrability, mechanical efficiency, and cost-effectiveness [6]. As can be seen in Figure 2.2, smart polymers are categorized by their corresponding activation stimulus. More specifically, these stimuli are either of magnetic, thermal, electrical, chemical, and/or optical nature [1, 2].

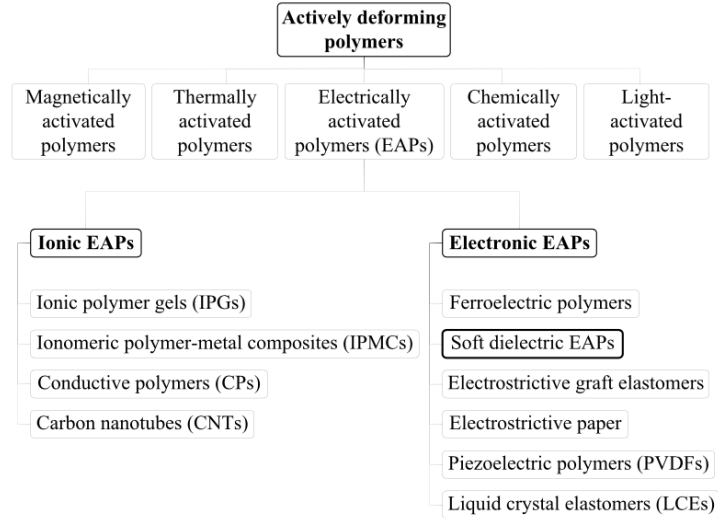


Figure 2.2: Actively deforming polymer categories and sub-classification of electroactive polymers [2]

Electroactive polymers (EAPs) are a specific class of actively deforming polymers that change their state due to an electrical stimulus. These can be further divided into two main sub-classes, based on their principle of operation, namely: ionic and electronic. Ionic EAPs exhibit a change of state (mainly shape or volume) due to an active displacement of ions through an electrolyte. This type of change is typically activated by an externally applied electric field, and results in an electro-mechanical change of the material [1, 2, 5]. Ionic EAPs are also sometimes referred to as “wet” EAPs, since the electrolytic medium in which diffusion occurs is usually aqueous [7]. In contrast, electronic EAPs exhibit a change of state due to electrostatic (Coulomb) forces. Electrical charges are displaced when the polymer is activated, which results in their attraction and/or repulsion. This subsequently leads to electro-mechanical changes of the material [1, 2]. Electronic EAPs do not necessitate an additional liquid medium in order to achieve actuation, and are therefore also referred to as “dry” EAPs.

Both types of EAPs possess distinct sets of characteristics, that make them suitable for different applications. Table 2.1 summarizes and compares their main properties [2]. When considering the design of a linear actuator, it is clear that electronic EAPs can be considered a more suitable candidate. Among other properties, electronic EAPs demonstrate a large planar deformation, as opposed to ionic EAPs which are more suitable for bending applications. This would imply that the former will be able to achieve linear motion, whereas the latter may prove challenging to implement for such applications. The difference in response time can also be an asset, depending

on the intended purpose of the actuator. When considering the use in biomimetics, a rapid response would be more favourable in a majority of scenarios. Finally, the need for an electrolyte to activate ionic EAPs make them more complex with respect to system integration. For these reasons, only electronic EAPs are considered for this thesis.

Table 2.1: Qualitative property comparison of ionic and electronic EAPs (adapted from [2])

	Ionic EAPs	Electronic EAPs
Type	Mostly bending actuators with strong bending capability.	Planar actuators with large in-plane deformations.
Operational condition	Actuators require electrolyte.	Actuators work also in the dry state.
Activation voltage	Low voltages in the range of a few volts.	High activation voltages in the range of several kilovolts.
Response time	Slow response (tenths of a second) and relaxation (minutes).	Rapid response (milliseconds) and relaxation (seconds).
Maintained activation	Strain/stress against an external load is not held under DC activation.	Deformed state/stress against an external load is maintained under DC activation.
Active stresses	Fairly low activation stresses.	Fairly large activation stresses.
Long-term stability	Production of stable material/actuator difficult.	Long life under ambient conditions.
Components	Expensive, often not commercially available.	Inexpensive, usually commercially available.
Additional issues	Hydrolysis in aqueous conditions ($> 1.23 \text{ V}$).	Requires compromise between achievable strain and stress.

The following sections will summarize the operational mechanisms involved for different electronic EAPs, excluding dielectric elastomers (see Section 2.3.3).

2.2.1 Ferroelectric Polymers/PVDFs

Ferroelectric polymers are a class of electronic polymers that exhibit a spontaneous change in internal polarization after the application of an external electric field. Similar to piezoelectricity, this response involves a noncentro-symmetric shape transformation, which is sustained even after the removal of the field application. They have demonstrated small induced stretch ratios of less

than $\lambda = 1.05$, however, they also possess a high mechanical energy density. Additionally, they have proven to demonstrate rapid response, and can be active within multiple mediums (including air, water, and vacuum). Ferroelectric polymers require relatively high voltage for activation, and are typically difficult to mass produce [1, 6, 7, 8, 9].

2.2.2 Electrostrictive Graft Polymers

Electrostrictive graft polymers consist of two-part structure, where randomized polar crystalline side-chains are attached to a flexible backbone structure. When an electric field is applied, these side-chains reorient and align in the field's direction, and induce a deformation of the graft elastomer. These polymers have demonstrated low induced stretch ratio levels of $\lambda = 1.05$, but can produce relatively large force. They have also proven rather inexpensive to produce and have shown a high stiffness property relative to their counterparts [1, 6, 8, 9].

2.2.3 Liquid Crystal Elastomers

Liquid crystal elastomers are composite materials consisting of a liquid crystal elastomer network structure containing a dispersed conductive polymer within its structure. They have the ability to be activated through various stimuli including light, temperature, or electric field. Upon application of an electric field, a reorientation of the liquid crystal compound induces stresses and stretch ratios within the structure. These electroactive polymers have demonstrated large achievable stresses and stretch ratios of approximately 200 kPa and up to $\lambda = 1.45$ respectively. They also require much lower electric field than their counterparts. Liquid crystal elastomers, however, have a much slower response and exhibit large internal energy dissipation (i.e. hysteresis) [1, 6, 8, 9].

A quantitative comparison between different (specific) electronic EAP actuators can be seen in Table 2.2. This table has been adapted from Kornbluh et al. [3], with data from more recent publications (sources listed in table). It should be noted that, due to the lack of standard testing protocols for these new types of materials, the information provided in this table should be carefully interpreted. The data should be seen as a representation of the materials' behaviour trends rather than a definitive parameter valuation. Following the compilation of this data, an example of a first attempt at testing standardization has been proposed by Carpi et al. [6] in a recent paper. This article provides the general scope for potential future material characterisation and quantitative comparison, specific to dielectric elastomer transducers. If such standards were to be

accepted for advancements in EAP characterization, they would allow research groups to properly compare the properties of various polymers in a more consistent and representative fashion.

Table 2.2: Comparison of various electric EAP performances (adapted from [3])

Actuator Type (Specific Examples)	Maximum Stretch Ratio [-]	Maximum Pressure [MPa]	Specific Elastic Energy Density [J/g]	Elastic Energy Density [J/cm ³]	Maximum Efficiency [%]	Relative Speed (Full Cycle)
Dielectric Elastomer ¹	1.63-4	3.0-8.2	0.75-3.4	0.75-3.4	60-90	Medium- Fast
Electrostrictive Polymer ²	1.04-1.05	24-45	0.26-0.6	0.48-1.0	~80 (est.) [7]	Fast
Liquid Crystal Elastomers ³	> 1.45 [9]	> 0.3	> 0.10	2 [6]	~ < 10	Slow
Ferro/Piezoelectric Polymer ⁴	1.001	4.8	0.0013	0.0024	n/a	Fast
Human Skeletal Muscle ⁵	>1.40	0.35	0.07	0.07	> 35	Medium

¹Acrylic and Silicone, based on actuators described by Pelrine et al. (1992) [10]

²P(VDF-TrFE-CFE), based on actuator described by Xia et al. (2003) [11], and Graft Elastomer [3]

³Unspecified [7]

⁴PVDF, based on values at maximum electric field of 30 V/μm [3]

⁵Hunter and Lafontaine (1992) [12]

2.3 Dielectric Elastomers

Dielectric Elastomers (DEs) have demonstrated promising characteristics for potential use in actuator, generator, and sensor applications. Known also as electro-statically stricted polymers, they have proven superior in both their overall achievable deformation and energy density (relative to other types of field-activated materials) [3, 4]. DEs have shown the best results when using silicone rubber films (derived from polydimethyl siloxane) and acrylate elastomers (more specifically 3M™ VHB 4910 acrylic tape series) [13]. The following sections will discuss the basic principles of actuation, material properties and modelling implications of DEs.

2.3.1 Basic Functioning of Actuation

The actuation of dielectric elastomers is based on a simple principle of attractive forces created by a voltage application on opposing surfaces of the material. As can be seen in Figure 2.3, the polymer is sandwiched between two compliant electrodes. A voltage is applied to these electrodes,

which creates electrostatic charges across the surface of the film. The opposite charges of the electrodes will attract each other, and (based on the principles of Coulombic interaction) will apply compressive forces on the membrane [14]. Due to the elastomer's largely incompressible nature [2, 4, 6, 14], the film is forced to expand in planar area due to the contraction of its thickness.

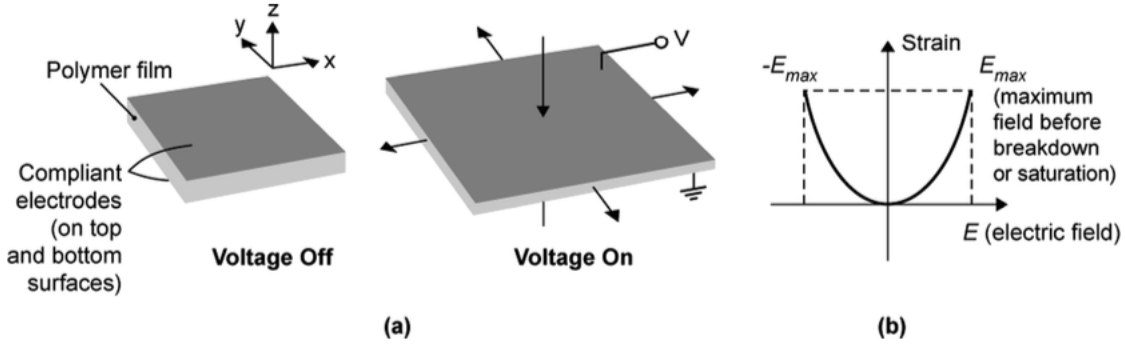


Figure 2.3: Principles of operation of DE actuator [4]

(a) Visual representation of elastomer deformation based on applied voltage.

(b) Typical planar strain response relative to electric field applied with no external loading

This signifies that DEs are not a conventional active material, in that it is passive and requires the electrode coating in order to produce deformation under electrical stimulation. From a different perspective, DE actuators can also be seen as compliant variable capacitors [6]. Evidently, in order to allow the elastomer to deform without hindrance, the electrodes must also be mechanically compliant. Types of electrodes will be discussed in Section 2.4.

The simple electrostatic model in Figure 2.3 allows the derivation of an equation representing the effective Maxwell pressure (or stress) being applied to the film by the electrodes [14]:

$$p = \epsilon_r \epsilon_0 E^2 = \epsilon_r \epsilon_0 \left(\frac{V}{t} \right)^2 \quad (2.1)$$

where p is the acting pressure, ϵ_0 is the free-space permittivity constant ($8.85 \frac{pF}{m}$ [15]), ϵ_r represents the relative dielectric constant of the elastomer, and E is the applied electric field. The field can further be expressed as a ratio between the applied voltage V , and the film thickness t . It can be seen that this value is exactly twice the pressure produced across a parallel plate capacitor. This is justified by the fact that DEs have a second degree-of-freedom for electro-mechanical transduction. More specifically, unlike parallel plate capacitor devices that have rigid

plates, the electrodes of DE actuators can expand planarly in addition to becoming closer together [2, 14].

Based on this actuation configuration, two working directions can be deduced: planar direction, and thickness direction. An accurate representation of these two scenarios was elaborated on by Lochmatter [2] and Zhang [16], and is summarized below. An illustration of both cases can be seen in Figure 2.4.

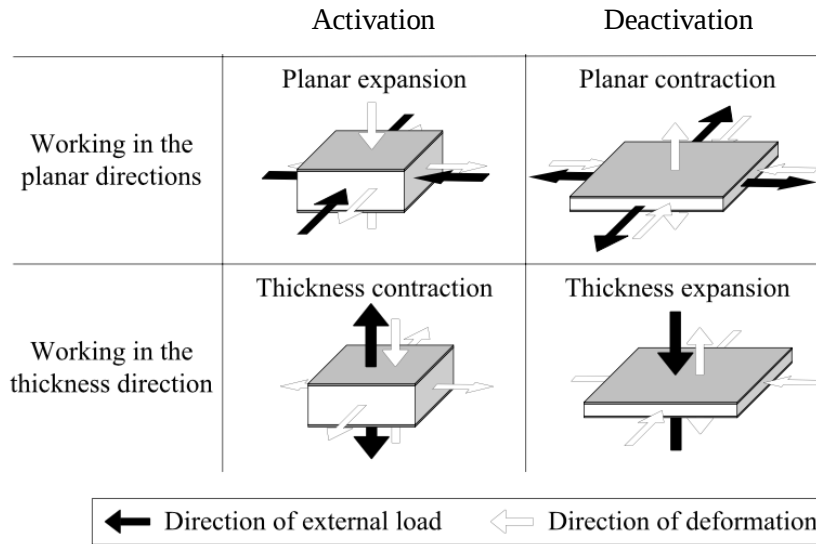


Figure 2.4: Working directions of DE actuator for simple actuator unit [2]

“Planar working directions” involve the case where the film is working against external forces in the planar direction. In this case, the actuator will need sufficient reinforcement against bending, or else it will buckle during activation (this type of reinforcement can be achieved by stacking many layers of film together, and will be discussed in Section 2.4.1). Although counterintuitive, considering the principle of operation of DEs, the actuator will work against external loads when *deactivated*, and release when *activated* (as can be seen in Figure 2.4 - Planar Direction). This is due to the fact that the film dilates when electro-mechanically activated, and contracts when voltage is removed. In this configuration, the actuator film’s bending stiffness is not of great concern since it will be working against tensile loading conditions. Although this representation considers the case of biaxial actuation, the same idea applies to uniaxial motion. In order to achieve actuation in a single direction, boundary conditions for one of the two planar axes needs to be stiffened (or fixed) in order to encourage motion along a single path [2, 16].

“Thickness working directions” involve the case where the film is working against external forces along its thickness. This is done by making use of the thickness compression caused by the Maxwell stresses applied by the electrodes. Contrary to planar actuation, the principle of operation for this mode is parallel to voltage application. In other words, the actuator will work against external tensile loads when *activated* (since the tape is being compressed), and will be in a relaxed state when *deactivated* (as can be seen in Figure 2.4 - Thickness Direction). For this working mode, due to the very thin profile of the tape, the actuator will heavily rely on a stacked configuration in order to achieve noticeable linear displacement. It should also be noted that, when resisting tensile external loads, these stacked layers will require adequate adhesion to withstand the interlaminar tensile stresses transmitted by the loading conditions [2, 16].

Both working modes’ effectiveness can be evaluated by observing the strain comparisons in all three directions. Taking the coordinate system from Figure 2.3, in-plane axes are x and y, and the thickness is along z. Considering the material’s aforementioned incompressibility, the stretch ratios along all three directions can be related with the following condition:

$$\lambda_x \lambda_y \lambda_z = 1 \quad (2.2)$$

where λ_i represents the stretch ratio in axis i . Stretch ratio is also known to be $\lambda_i = s_i + 1$, where s_i is the engineering strain of the system for the same deformation. From this, (2.2) can be expressed in terms of strain [2, 17]:

$$(s_x + 1)(s_y + 1)(s_z + 1) = 1$$

$$s_z = \frac{1}{(s_x + 1)(s_y + 1)} - 1 \quad (2.3)$$

For the case where equiaxial planar deformation is applied (i.e. $s_x = s_y$), therefore allowing free boundaries (i.e. $\sigma_x = \sigma_y = 0$), the coupled planar-thickness strain (2.3) can be expressed as:

$$s_z = \frac{1}{(s_x + 1)^2} - 1 \quad (2.4)$$

In the case where the film is restricted to a single axis of deformation (e.g. $s_y = 0$), the coupled planar-thickness strain (2.3) can be expressed as:

$$s_z = \frac{1}{(s_x + 1)} - 1 \quad (2.5)$$

A graphical representation of equations (2.4) and (2.5) is provided in Figure 2.5. Comparing slopes along the curve, planar versus thickness deformation can be compared. It can be seen that, for the case of a biaxial free-deforming situation, the film will achieve greater deformation in thickness than in planar direction for expansions of $s_x = s_y \geq 26.0\%$. Between strains of $26.0\% \leq s_x = s_y \leq 61.8\%$, the film's surface will grow larger than the thickness will compress. It can be noticed that the resulting x-y strain rate will not, however, surpass the thickness compression until $s_x = s_y \geq 61.8\%$. In contrast, for the case where the film is restricted to deform uniaxially, the planar (or axial, in this case) strain will always exceed that of the tape's thickness compression. For these reasons, it can be concluded that, in the case of biaxial deformation, using the tape in a thickness-based working direction is beneficial for planar axial strains below 62%. By contrast, uniaxially deforming film configurations will only benefit a planar-based working direction. These derivations provide directly applicable considerations when developing a DE actuator [2].

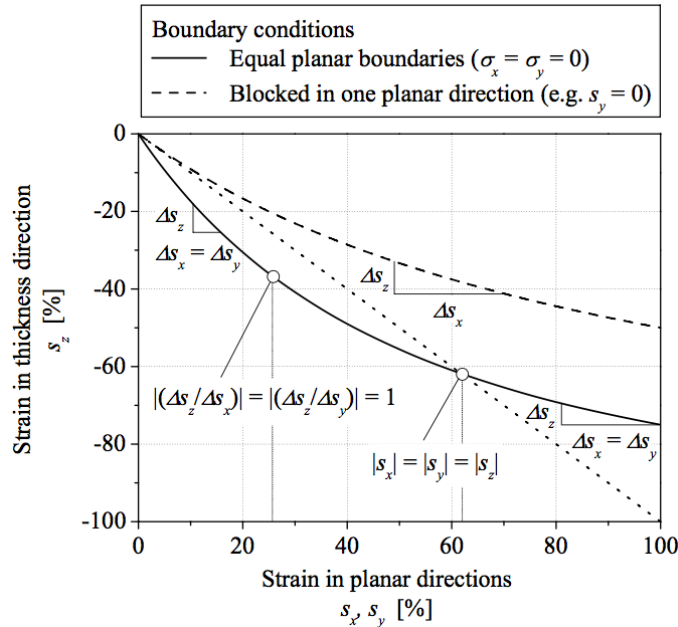


Figure 2.5: Planar and thickness strain coupling for biaxial and uniaxial DE deformation [2]

When considering these behaviours, it must, however, be noted that the values represented are of strains, not of total elongation. It is clear that, in all cases, the membrane thickness will be much

smaller relative to its planar dimensions. Based on this notion, the values of deformation achieved along the thickness will thus be inferior to those along the membrane's plane in all cases but one. To consider an actuator utilizing the film's thickness compression as the mode of electro-mechanical transduction, the stacked geometry of the DE films will require at minimum a cuboid geometry. In other words, the equivalent thickness of a multi-layered DE assembly will need to be equal or greater to its cross-sectional (planar) dimensions, in order to effectively exploit the compressive strain.

2.3.2 Material Properties

Several elastomeric materials have been considered in research for their use in DE-based actuators. These include silicones, fluoroelastomers, polyurethanes, isoprene rubber, and acrylic elastomers [6, 17, 18, 19, 20, 21]. A comprehensive table summarizing and comparing the properties of 30 different DE materials can be found in [6]. From these various findings, a greater interest in silicone and acrylic based elastomers has developed. This was attributed to their promising material and actuation characteristics, especially after finding their abilities to achieved strains exceeding 100% [6, 22, 23]. The factor enabling such large deformation was pre-stretching of the material. Effects of pre-stretch will be further discussed in this section. A comparison of acrylic and silicone properties is displayed in Table 2.3.

Table 2.3: Comparison of best performances achieves for silicon and acrylic DEs (adapted from [20])

Parameter	Acrylics	Silicones
Maximum actuation stretch ratio (-)	4.80	2.20
Maximum actuation pressure (MPa)	8.2	3.0
Maximum specific energy density in actuation (MJ/m ³)	3.4	0.75
Maximum frequency response (Hz)	> 50 000	> 50 000
Maximum electric field (MV/m)	440	350
Relative dielectric constant	4.5-4.8	2.5-3.0
Dielectric loss factor	0.005	< 0.005
Elastic modulus (MPa)	0.1-3.0	0.1-2.0
Mechanical loss factor	0.18	0.05
Maximum electro-mechanical coupling, k^2	0.9	0.8
Maximum overall efficiency (%)	> 80	> 80
Durability (cycles)	> 10 000 000	> 10 000 000
Operating range (°C)	-10 to 90	-100 to 260

Different conclusions can be drawn from this comparison, depending on the intended use of the actuator. With the exception of operating range, dielectric loss, and mechanical loss, acrylics have demonstrated an overall superior performance to that of silicones. DE-based actuators' efficiency generally relies on two global material properties: mechanical and electrical. With a greater maximum actuation strain, actuation stress, elastic modulus, and relative dielectric constant, acrylic elastomers have more potential for use in actuator applications.

Both acrylic and silicone based DEs possess static and dynamic viscoelastic properties, that require consideration during actuator design. These characteristics affect the material efficiency and speed of response when actuating, and create rate- and time-dependant behaviours such as mechanical hysteresis, creep, and stress-relaxation effects when deformed [3].

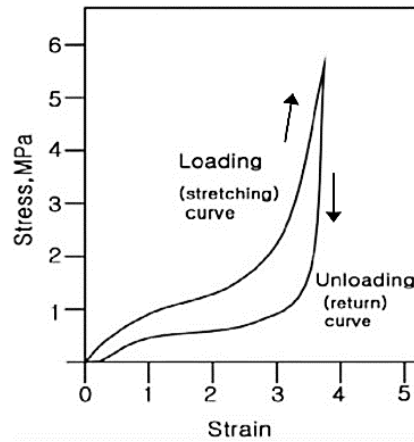


Figure 2.6: Typical stress-strain curve for conventional elastomer (hysteresis loop) [24]

Rate-dependant stress response and mechanical hysteresis are two properties that can greatly affect the overall performance of an actuator design. As to be expected from any rubber-like material, both acrylic and silicone DEs demonstrate a sensitivity to strain-rate, as well as a clear dissipation of internal energy (as can be seen in Figure 2.6) during a load-unload tensile test. It should be noted that, for elastomers, not only does this behaviour occur in all cases, but the unloading curve will also typically not return to the origin. They will usually require an additional resting period before returning to zero-strain state. It can be seen that, during the loading cycle, elastomers exhibit a change in stress-stretch behaviour. Their mechanical response begins with a “softening”, where a decaying tangential slope can be observed. Once the material has reached a certain elongation, a strain-hardening effect will induce increasing stiffness of the material, which results in an exponential stress evolution. It should also be noted that, during cyclical load-unload

testing, the peak values of mechanical stresses of the hysteresis loop will gradually decrease. They eventually converge to produce a stable, reproducible curve geometry [24].

Dynamic (or cyclical) properties of these materials are also of particular interest when considering them for their implementation as mechanical transducers, for evident reasons. A comparison of cycle frequency variation in the viscoelastic properties between both acrylic and silicone DEs (specifically: 3M™ VHB 4910 tape, and NuSil CF19-2186), and passive mechanical properties of natural muscle can be seen in Figure 2.7. With the use of a dynamic mechanical analyzer, Kornbluh, Pelrine et al. [21, 25] compared their properties in order to evaluate the DEs' potential use as artificial muscles. The specimen used for the biological benchmark was a cockroach leg muscle. Due to the insect's great mobility, this is considered a good comparative benchmark for robotic and biomimetic application. It can be seen that both materials possess similar compliance to that of natural muscle, although acrylic demonstrates slightly stiffer properties. Frequency also does not seem to greatly affect the variation in stiffness over a wide range of values. In the case of energy loss, however, the behaviour does not run parallel between the natural muscle and the synthetic alternatives. In both cases, damping properties seem to run far below those of muscle. For acrylic-based DE's, frequency also seems to play a greater role in its energy dissipation properties. This is not as much of a concern, since actuators can be fitted with additional damping mechanisms [3, 25]. Overall, silicones show lower dynamic viscoelastic response, which makes them suitable for higher frequency applications.

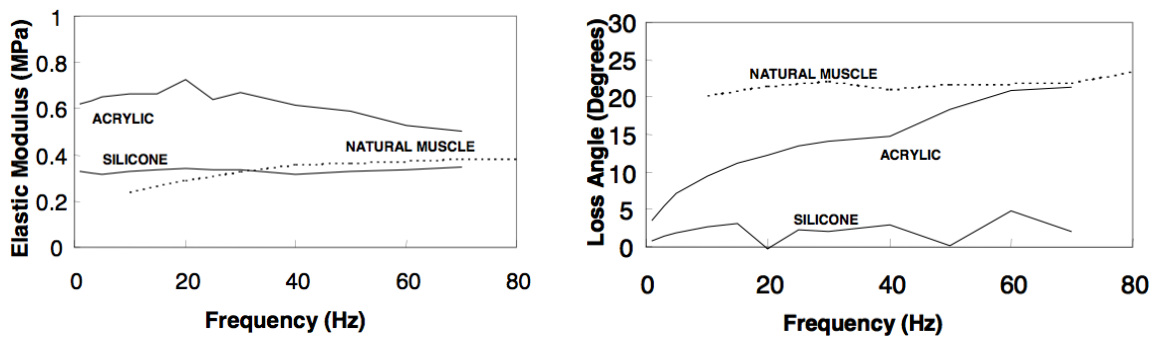


Figure 2.7: Comparison of stiffness and damping properties of acrylic and silicone DEs with respect to passive properties of natural muscle (adapted from [25])

The speed response of the film is also an important factor when considering actuator design. The electro-mechanical response of the DEs is mostly defined by the intrinsic properties of the material. This is due to the fact that their dielectric constant is typically not affected by the frequencies

ranging from 100 Hz to 100 kHz. It can therefore be concluded that actuating limitations (delay in response) are primarily governed by the speed at which the resulting electrostatic pressure (created by the electrodes) can propagate within the film. This speed can typically be controlled through design parameter modifications [21].

An experiment representing the speed of response for acrylic and silicone DEs (specifically: 3M™ VHB 4910 tape, and NuSil CF19-2186) was presented by Kornbluh and Pelrine [21], and is reproduced in Figure 2.8. The data represents the in-plane actuated strain of a circular stretched film of both materials. The materials were submitted to sinusoidal voltage waves in order to demonstrate their electro-mechanical response speed. It should be noted that these data are not definitive, but rather representative of the behavioural trends, since actuator size and configuration, among other factors, play a large role in the response speed.

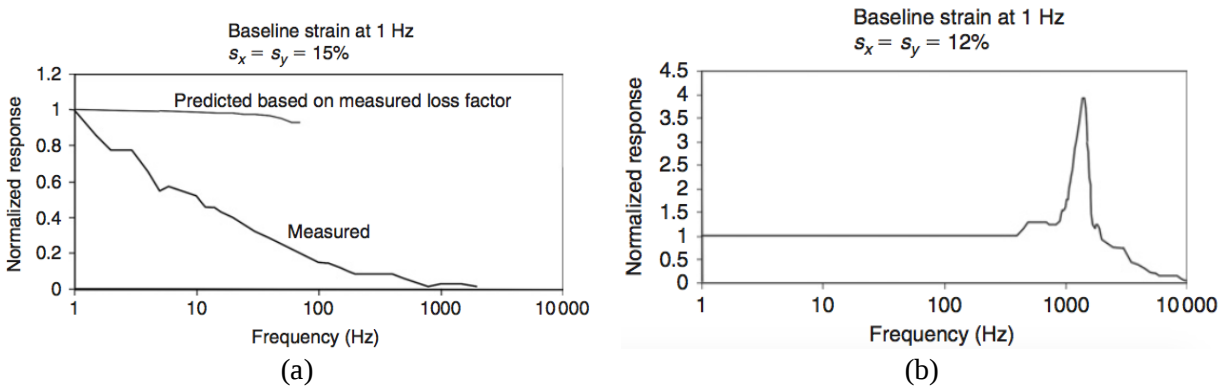


Figure 2.8: Frequency response of stretched DE films [21]
(a) Acrylic films, and (b) Silicone film

The silicone based film demonstrates a consistent response until roughly 400 Hz, and then reaches a peak value at 1425 Hz. This is attributed to the fact that, based on the actuator configuration, the film has an in-plane strain resonance at this frequency. It can therefore be suggested that the limiting factor of silicone-based DE actuators is directly associated with its mechanical resonance, which is governed by the material's elasticity and mass. The results for the acrylic based film do not demonstrate the same steady behaviour. There is a consistent decay in performance based on the frequency applied. It is suggested that, at large strains, this may be caused by the fact that electrical resistance of the surface electrodes may increase due to their deformation. It is also important to keep in mind that acrylic films have demonstrated higher performance when substantially pre-stretched. These factors may have a negative effect on the results of the current

experimental format, and should not be taken as a direct reflection of the film's general performance [21]. Overall, these results suggest that acrylic based dielectric elastomers have a greater dependence on frequency during electro-mechanical transduction, whereas silicones can be considered mostly consistent (until a certain resonance frequency).

Other time-dependant factors resulting from the viscoelastic nature of DEs, such as creep and stress relaxation, are significant properties that also need to be considered for the design, actuation, and modelling aspects of transducers. It is known that, for silicone elastomers, factors such as creep and stress relaxations are not particularly significant when under tension. Acrylics, however, show greater time-dependant behaviour, especially when considering the large pre-stretching required to enhance its performance [21]. Since there are less concerns regarding silicone elastomers' time-dependent viscoelastic responses, these properties will be further discussed specifically for acrylic elastomers in the next section of the report.

Dielectric elastomers are highly capacitive and typically operate at voltages ranging between 300V and 10 kV [4, 6, 26, 27]. As previously mentioned, the pre-stretching of these films has also proven to have a vital role in the actuation performance of acrylics and silicones [6, 20, 28, 29, 30]. Applying an initial pre-strain to the film (prior to activation) has shown an increase of its dielectric breakdown strength (resistance to the electric field) [6, 26, 28, 29, 31], as well as an increase in its mechanical efficiency and response speeds [6, 32, 33]. Although not yet confirmed, it is widely believed that the reason for early failure of DE films is the result of local defects within the material that arise during manufacturing and processing, or through cyclical loading. These defects are thought to reduce the dielectric strength of the DE, resulting in localized damage and/or global failure of the material. Other factors such as viscoelastic material properties, localized pull-in effects, and large leakage currents have also been proposed as factors that affect the electro-mechanical performance of these materials [6, 20, 26, 30, 33, 34, 35, 36, 37].

The pull-in effect is a phenomenon that occurs in electrostatic actuation. A positive feedback loop occurs when the electric field between the parallel plates (or electrodes) reduces the gap between them by exerting electrostatic forces. The decreased distance will lead to an increase in the system's capacitance, which results in an increase in charge and electric field. A further reduction in the gap will then follow, which results in the described positive feedback loop. Once the distance between the electrodes reaches a certain threshold, the actuator becomes unstable and

collapses [38]. In the case of a DE film, the reduction in thickness, paired with the increased electric field, results in failure since the field will surpass the material's dielectric breakdown strength.

When the film is pre-stretched, the mechanical stress-strain behaviour is offset from its original behaviour, which in turn will offset its breakdown strength. This will result in a more stable actuation [6]. The principle of pull-in effect of dielectric elastomers has been well illustrated by Brochu [6], and can be seen in Figure 2.9. The plot represents the contrast between the stress as a function of strain (or electric field at constant voltage for Maxwell stresses) for the unstretched state (beginning at origin O) and the pre-stretched state (beginning at origin O'). As can be seen, due to the mechanical change brought about by pre-stretching, both curves will be offset. This will inhibit a pre-mature breakdown due to the effects of pull-in. Additional frequency response improvement and viscoelastic property reduction have also been observed [6].

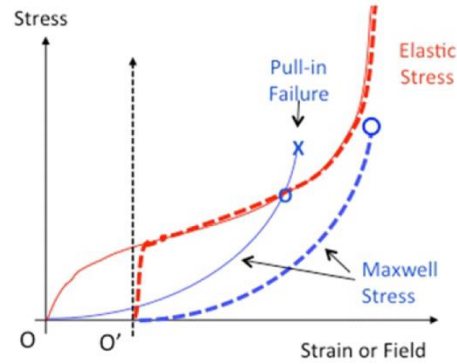


Figure 2.9: Effects of pre-strain on DE stress-strain behaviour and analogue exerted Maxwell stresses [6]

The effect of pre-stretching has also been found to have a theoretically optimal actuation range based on the force-stretch behaviour of the elastomer. Kofod [29] describes this concept through the mechanical behaviour of a DE with a biaxial pre-stretched condition. For a sample with a fixed pre-stretch along its width (λ_2), the mechanical tensile output-load along the orthogonal planar axis (λ_1 , i.e. the stretch along axis of actuation) demonstrates a “plateau region” occurring within a stretch ratio range of $3 \leq \lambda_1 \leq 5$. As previously seen in Figure 2.6, the elastomer's tensile response exhibits a change in slope progression, due to the strain-hardening of the material. Kofod describes that the fulcrum of the curve's slope-change seemed to always fall at a stretch ratio $\lambda_1 \approx 4$, irrespective of the fixed width pre-stretch λ_2 . Further analysis, through electro-mechanical modelling, suggested that this fulcrum represented an optimal zone, wherein the largest achievable

electro-mechanically induced deformations would occur. This led to the hypothesis that actuating structures should operate within the plateau region. From a mechanical standpoint, this was justified by the fact that (in this optimal zone) there is a maximum “softening” of the material (since its force-stretch tangential slope – or “instantaneous stiffness” – is quasi-zero). This enables the Maxwell stresses applied by the electrodes to achieve maximum actuation strains through the compression of the elastomer due to minimal mechanical resistance. It was concluded that pre-stretch would not greatly affect achievable actuation beyond this plateau region, and that the initial stretch ratios should therefore be tuned between $\lambda_1 = 3$ to 5.

2.3.3 3M™ VHB Polyacrylic Dielectric Elastomer

This thesis will focus on 3M™ VHB tape series. These dielectric rubbers have been selected for their large achievable stretch ratios (up to $\lambda = 4.8$ [39]), their off-the-shelf commercial availability, and their wide use in current actuator development [33]. The following section will discuss details of VHB tapes’ material properties.

3M™ company manufactures an elastomer adhesive tape class, dubbed VHB tapes [40]. Within this category of product, a specific version, namely the VHB 4905/4910 tape, has been coveted by researchers for its promising dielectric properties. A summary of pertinent tape characteristics from the product data sheet can be found in Table 2.4. Among all the VHB tapes manufactured by 3M™, this type has demonstrated the highest dielectric properties, and has thus made it the most appealing for the use of DE based actuators. It should be noted that both VHB 4905 and 4910 tapes are of identical material composition, however are structurally different (in thickness). Since the principles of electro-mechanical transduction rely heavily on elastomer thickness, they are therefore considered independent in this report.

VHB 4905/4910 tapes are sold in pre-manufactured rolls, that are lined with a protective polyethylene film (due to the tape’s double-sided nature). The material, when unrolled, is provided as a flat sheet. As can be seen in Figure 2.10, the results of uniaxial tensile testing agree with the general viscoelastic behaviour previously discussed for elastomers. Firstly, they demonstrate the elastomeric softening which occurs prior to the previously mentioned “plateau region”. Secondly, a clear hysteresis loop can also be observed in all cases, where the unloading curve noticeably does not return to the origin. The peak stress values created by the tensile load heavily depend on the

strain-rate applied, and the energy dissipation increases with the percentage deformation that is applied to the sample.

Table 2.4: 3M™ VHB 4910 tape series material properties and typical performance characteristics (adapted from [40])

	VHB 4905	VHB 4910
Tape Thickness (mm)	0.5 ± 15%	1.0 ± 10%
Density (kg/m ³)	960	
Tape Liner	Polyethylene film (red)	
Dielectric Constant ¹		
at 1 kHz	3.21	
at 1 MHz	2.68	
Dissipation Factor ¹		
at 1 kHz	0.0214	
at 1 MHz	0.0595	
Dielectric Breakdown Strength ² (V/μm)	25	
Volume Resistivity ³ (Ω·cm)	3.1 × 10 ¹⁶	
Surface Resistivity ³ (Ω/sq)	>10 ¹⁶	

¹ASTM D150 Test Standard

²ASTM D140 Test Standard

³ASTM D257 Test Standard

VHB tapes also exhibit large amounts of creep and stress relaxation behaviours. A general representation of these properties is displayed in Figure 2.11. The data were gathered from tensile uniaxial testing of VHB 4905 tape for static creep (at constant stress), and static stress relaxation (at constant strain). The creep response of the elastomer demonstrated a very large drop in stretch ratio (of over $\lambda = 1.5$) within a time-frame of 600 seconds. The same highly time-dependant behaviour was also observed in the case of stress relaxation. The material exhibited a large peak stress when first elongated. After being held, the stress decreased rapidly within the first few seconds of the relaxation process, and then slowly converged to a stress that is less than 50% of its original peak.

More detailed creep and stress relaxation behaviour of VHB 4910 tape has recently been studied by Sahu et al. [41], for cases of both static and cyclical uniaxial loading conditions. In their study, it was observed that static creep strain-rate increases with larger loads. In the case of cyclical creep, it was observed that failure of the material occurred at lower loads than when a monotonic

load was applied. The creep rate of the material does not change with every subsequent cycle, and all strains stabilise over time. In the case of static stress relaxation, it was observed that the stress of the material converged after approximately 1800s. It was also observed that stress relaxation rate increased with larger applied loads. For cyclical stress relaxation, similar to the cyclical creep, the material had a tendency to fail at lower loads than the static loading condition. By contrast, the relaxation rate decreased with every consecutive cycle.

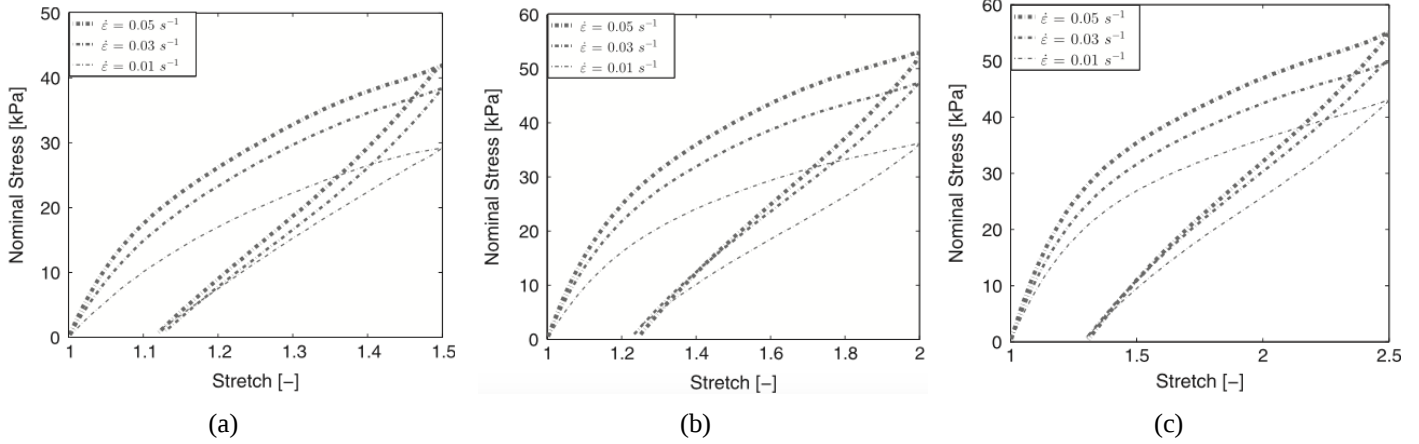


Figure 2.10: Sample load-unload experimental uniaxial tensile test results of VHB 4910 tape [42]
(a) $\lambda = 1.5$, (b) $\lambda = 2$, and (c) $\lambda = 2.5$

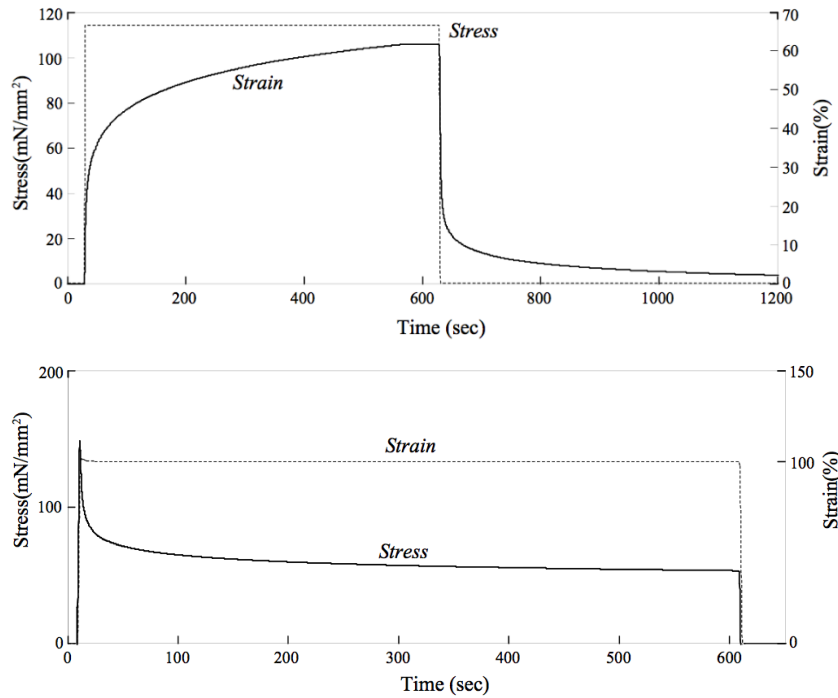


Figure 2.11: Creep (top) and stress relaxation (bottom) behaviour of VHB 4905 tape undergoing uniaxial tensile testing [43]

No multi-axis experimental results for VHB 4905/4910 tapes have been found in the literature to demonstrate the materials' behaviour under complex tensile loading. In most cases, the material was assumed to be isotropic based on its elastomeric structure. Plante et al. [31] stated previous experimental validation of the material's isotropy, with no further substantiation. 3M™ also published a material Poisson's ratio of 0.49 [40], implying that it exhibits properties within the typical range of isotropy. This value was not referenced with testing standards used, and was preceded with a disclaimer that the data published was not to be used for specification purposes. As previously stated, DEs (in this case, VHB tapes) will be pre-stretched for their use as an EAP. In most cases, this stretching will be applied biaxially. It is therefore of particular interest to quantify the materials' behaviour from a biaxial perspective, in order to validate the aforementioned mechanical properties based on uniaxial tests.

Electro-mechanical properties of VHB tapes are of great importance when implementing them as part of a dielectric elastomer actuator. In many cases, their behaviour has been evaluated specifically for an actuator's intended configuration, rather than as a general characterization. This is yet another reason for the need to develop global testing standards for such material characterization. An example of experimental results is provided in the following. Hossain et al. [44] recently documented a series of tests depicting VHB 4910 tape dynamic dielectric response. The results are representative of a biaxially pre-stretched film undergoing mechanical and electro-mechanically coupled loading conditions under uniaxial deformation. In all cases, a film was pre-stretched and clamped at a fixed stretch ratio of $\lambda_2 = 3$, and then elongated along the orthogonal axis (producing a biaxial strain condition) to a stretch ratio of $\lambda_1 = 4$ and $\lambda_1 = 5$. Voltages of 4 kV and 5 kV were applied to the samples. Load-unload tensile tests, single-step stress relaxation tests, and multi-step stress relaxation tests were performed for both mechanical and electro-mechanically coupled conditions.

Figure 2.12 presents a sample of the results for load-unload tests of two tests at $\lambda_1 = 4$, with 5 kV application, at two separate strain-rates. It can be seen that, in both cases, viscoelastic response of the material holds true to the previously discussed behaviour. It can also be observed that dielectric activation for this experimental setup begins at approximately $\lambda_1 = 1.5$. The difference in the hysteresis loops illustrate its relationship to the strain-rate. By observing the peak stress values in either situation, the gap between curves in Figure 2.12 (a) and in (b) increases with change in

testing condition. It should be noted that, as with all other presented behaviour, these experiments represent the dielectric response of a particular actuator configuration, and therefore do not provide explicit conclusions about the material's activation. Until standards, such as the ones proposed by Carpi et al. [45], are accepted for dielectric elastomer transducer characterization, experimental results are case specific and should be considered as qualitative.

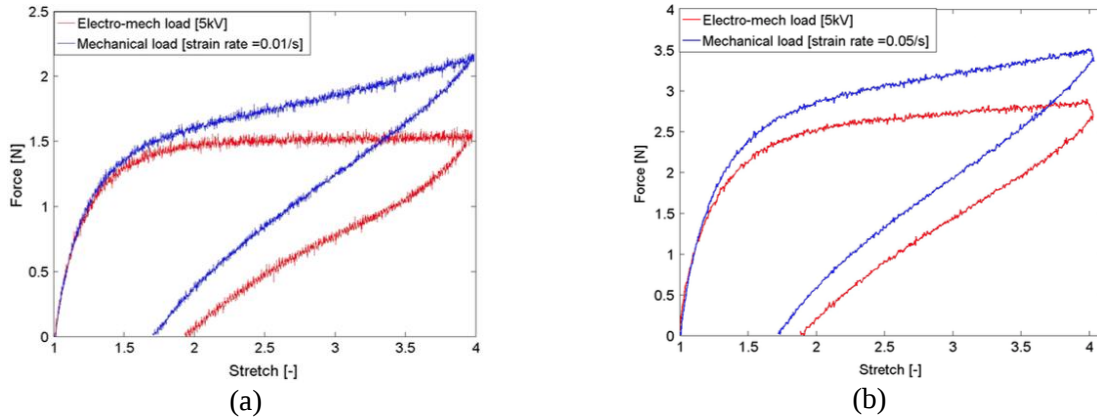


Figure 2.12: Load-unload test for mechanical and electro-mechanically coupled conditions [44] for $\lambda_2 = 3$ pre-stretched sample, elongated to $\lambda_1 = 4$ (a) at rate of 0.01 s^{-1} , and (b) at rate of 0.05 s^{-1}

Kofod et al. [26] have also reported a phenomenon named the “wrinkle limit” as part of their investigations on actuation responses of VHB 4910 tape. In their study, the elastomer was biaxially pre-strained at various x-y axes stretch ratio combinations in order to observe its behaviour under electro-mechanical coupling. They described a particular behaviour of the tape, where the membrane's surface started to wrinkle at higher voltages. In particular, all cases were noted to exhibit this wrinkle limit at a typical value of 5.0 kV. This effect was explained by the simple fact that the electrically induced stresses exceeded those of the elastic stresses required to deform the film. Limits such as this one should therefore be considered for both experimental and actuator design purposes.

2.3.4 Mechanical Modelling

To adequately design, predict, and optimize DE-based actuators, researchers have proposed several constitutive models to characterise the behaviour of these materials. To predict the electro-mechanically coupled behaviour of an actuator, the mechanical constitutive behaviour must first be studied. This relationship between the stress and stretch ratio provides the foundation to all further design and analysis of DE-based actuators. Being rubber-like materials, the elastic response of both acrylic and silicone based DEs is highly nonlinear, and therefore necessitates

more complex stress-stretch ratio characterization. Several hyperelastic strain energy functions have been proposed to characterize these types of materials, from both phenomenological and micro-mechanical considerations. Steinmann [46] and Hossain [47] have reviewed and compared twenty-five of these models, for the application in rubber-like material modelling. Among the surveyed candidates, they have demonstrated the accuracies of Neo-Hookean [48], Ogden [49], and Yeoh [50] models, which have been used by various research groups [35, 36, 37, 51, 52, 53] to model the mechanical and electro-mechanical response of DE films and actuators. The following will summarize an example of these types of hyperelastic modelling approaches, specifically for VHB polyacrylic rubber.

Mansouri et Darijani [53] proposed a phenomenological model, where an exponential framework for strain energy density functions is developed to characterize the behaviour of isotropic hyperelastic materials. These functions were constructed in terms of the first and second invariants of strain tensor, with a mathematical structure reflecting two material parameters. The goal of this approach was to provide a strain energy density that could characterize material behaviour while remaining as simple as possible. The group sought to develop their model based on previous comparative reviews, in published literature, regarding the effectiveness of various mathematical strain energy functions. It was found that, in considering all combinations of power-law, polynomial, logarithmic, and exponential functions, an exponential-exponential structure was most appropriate with regards to typical behaviour of elastomers and biological tissues undergoing finite deformation. Mansouri et Darijani argued that this more self-contained approach, relative to the standard conjecture-based methods, provided their model with greater mathematical justification. The addition of a second invariant was also understood to increase model accuracy when forecasting material behaviour. More specifically, it was shown to increase predictions for certain areas of deformation by $\sim 100\%$, and provided more accurate results for conditions of simple shear or pure torsion than the single-invariant alternatives.

The group fitted the model to eight rubber-like elastomers, and one sample of biological soft tissue. Among the group of polymers, VHB 4905 tape was selected as a candidate for analysis. The model was fitted to the experimental data, using the Levenberg-Marquardt method, and theoretical results were compared to experimental data by calculating the Residual Sum of Squares (RSS, where a perfect fit would yield 0). The RSS value was subsequently compared to 30 well-known

alternatives, to benchmark its successfulness. Figure 2.13 represents VHB 4905 model fitting for the proposed model, next to the 4-parameter Ogden model [49] and the 8-chain Arruda and Boyce model [54]. These were selected based on their favourable structure for uniaxial tensile modeling. The plots were shifted by $\lambda = 2$ to allow distinguishability. It can be seen that the Ogden model has difficulty with strain hardening at higher stretch ratios, whilst the Arruda and Boyce model is inaccurate during initial phases of tension. The newly proposed model, however, follows the trend more closely in all aspects of the experimental curve.

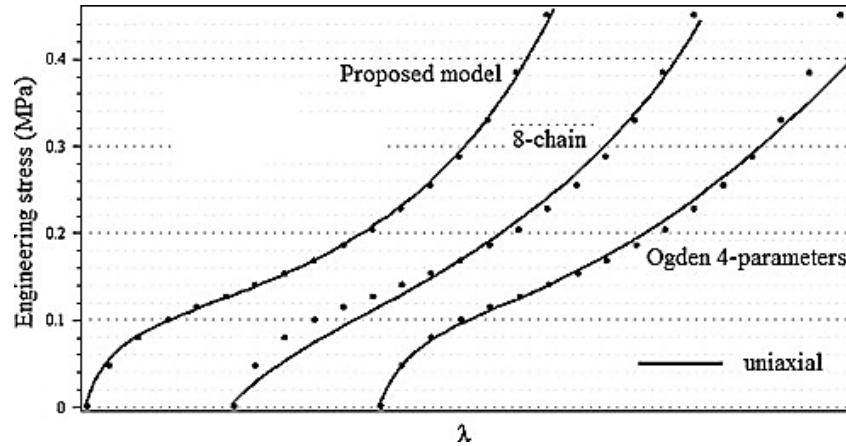


Figure 2.13: Proposed Mansouri and Darijani model for VHB 4905 tape uniaxial tensile test compared to two popular alternatives [53] where dotted lines represent experimental value and solid lines are theoretical simulation (experiments have been shifted $\lambda = 2$)

The model also proved more successful than the Fung model [55], by yielding an RSS value of 0.0001 for VHB 4905 tape fitting, relative to a value of 0.007 for Fung. This demonstrated the large impact of considering a second invariance as part of the model's structure. Finally, the model proved to be one of the most effective at predicting VHB mechanical behaviour relative to 12 other models. Among the other tested materials, the new phenomenological approach presented by Mansouri et Darijani [53] therefore proved effective at modeling VHB polyacrylic rubber's nonlinear hyperelastic behaviour under large uniaxial deformation, while remaining mathematically simple.

Although hyperelastic models provide good insight of the material's elastic behaviour in tension, they unfortunately neglect its time-dependant viscoelastic properties. This means that characteristics such as rate-dependant deformation, creep, stress-relaxation, and mechanical hysteresis are not considered. To include these behaviours as part of the constitutive models,

several groups [34, 42, 56, 57, 58] have adapted both hyper- and visco-hyperelastic models such as Mooney-Rivlin [48], Gent [59], and Bergström-Boyce [60] to predict the DE films/actuator mechanical behaviour. The following will summarize an example of these types of viscoelastic modelling approaches, specifically for VHB polyacrylic rubber.

Hossain et al. [44] have proposed a micro-mechanically motivated viscoelastic model to characterize the rate- and time-dependant mechanical behaviours of VHB 4910 tape. In this approach, a modified Bergström-Boyce viscoelastic model, in conjunction with a finite linear strain evolution law, was applied to a series of experimental results conducted by the group. The justification for the selection of a micromechanical model was two-fold. Phenomenological energy functions are typically used to characterize elastic behaviour, and have not proven very effective for the prediction of time-dependent mechanical response. In particular, successful attempts have assumed quasi-linear viscosity, which implies that material's relaxation function is independent of the deformation applied during relaxation tests. This may not hold for all materials, and therefore raises concerns. Moreover, phenomenological models tend to lack a direct physical representation of material parameters, as they draw their values through empirical relations. These disadvantages tend to make them mathematically complex for viscoelastic modelling, and difficult to implement in application and further development. The group stated their intent to extend the constitutive model to reflect electro-mechanically coupled behaviour of the dielectric elastomer. A micro-mechanical model was therefore deemed a superior choice for this reason.

The model's energy function contains volumetric and isochoric contributors. The latter was further subdivided into elastic and viscous portions. To find the material parameters through statistical mechanics, uniaxial tensile tests were conducted to quantify the parameters of these contributors. First, a series of stretch-relaxation tests were performed, to identify the ground-state elastic parameters. Specifically, a series of single-step and multi-step relaxation tests were performed, where the material was quickly stretched to different peak values, and left to rest for thirty minutes. Second, a series of loading-unloading experiments were performed at various stretch ratios and stretch rates, to identify the remaining viscous parameters. The model was then optimized using the built-in `lsqnonlin` fitting function in MATLAB, to yield a final set of material constants. Figure 2.14 represents the model's ability to replicate the experimental behaviour of VHB 4910 tape under the aforementioned loading conditions.

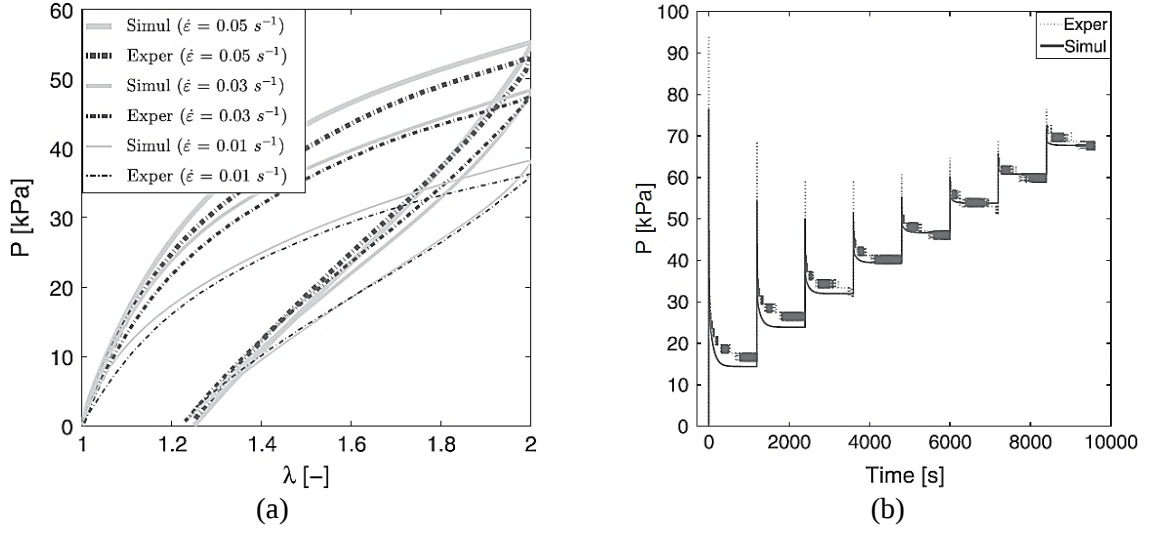


Figure 2.14: Proposed Hossain et al. model for VHB 4910 tape [42]
 (a) Various stretch rates to a max $\lambda = 2$, and
 (b) An 8-step stress-relaxation test at intervals of 20 mins

The group reported overall excellent model agreement with loading-unloading tests. As seen in Figure 2.14 (a), theoretical curves achieve accurate prediction of experimental data. They also reported good numerical agreement with the single- and multi-step relaxation tests, with small discrepancies when plotting the relaxation curves. This can be seen in Figure 2.14 (b). The model was therefore proven successful in portraying the complex mechanical properties of VHB elastomer.

Viscoelastic constitutive models yield high accuracy when describing static time-dependant responses such as stress relaxation and creep. They are also very effective in applications such as computational finite element modelling. Such alternatives are not, however, as practical for design purposes due to their high complexity, and lack of ability to effectively model continuous/alternating loading conditions. This is in-part due to the fact that the damping aspect of elastomers, particularly VHB tapes, is highly nonlinear and therefore difficult to represent analytically. For this reason, a novel visco-hyperelastic model was proposed by Lochmatter et al. [61], to provide a more straightforward approach to DE-based planar actuator design and analysis.

This alternative makes use of a three-dimensional network of fluid-filled cuboids, where their frame-segments are comprised of enhanced Kelvin-Voigt rheological model (also known as a Standard Linear Solid model). Each segment connecting the cuboids to their adjacent corner-nodes are comprised of a serial-spring, in series with a parallel spring-damper unit. The model

aimed to describe the mechanical behaviour of visco-hyperelastic elastomers to provide an investigative tool for actuators under continuous cyclical electro-mechanical activation. Its structure depends on three intrinsic parameters, namely the serial spring stiffness, the parallel spring stiffness, and the parallel damping coefficient. The group derived the model based on the relationships between external system stresses due to applied load, and corresponding internal hydrostatic pressure of the incompressible fluid due to cuboid deformation. The model was subsequently fitted to a tensile-creep-relaxation test sequence, and parameters were obtained for the constitutive model. Figure 2.15 illustrates the parameter fitting of the model, and its ability to demonstrate time-dependant behaviour of VHB 4910 tape.

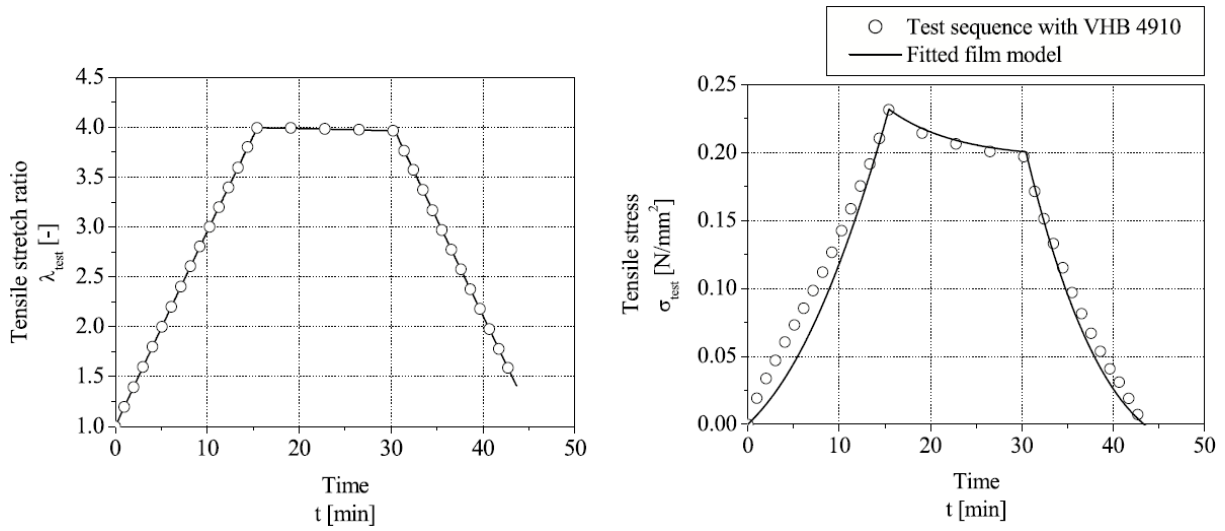


Figure 2.15: Proposed Lochmatter et al. hyper-viscoelastic model parameter fitting curve [61]

Lochmatter then adapted the model to simulate electro-mechanical actuation, and was able to retrieve predictions for actuator performance and efficiency. This demonstrated the mechanical model's potential to easily be implemented as part of an electro-mechanical framework, which attests to its relevance in DE actuator design.

Further development by Wang et al. [62] re-expressed this model with a dynamic energy dissipation parameter. The group introduced a rate-dependent frequency into the equivalent (lumped) modulus of the aforementioned Kelvin-Voigt segments. As the polymer's stress response is also dependant on stretch rate, this allowed the model to reflect the variations in mechanical response due to changes in rate of deformation. The group conducted a series of uniaxial tensile tests on samples of VHB 4910 tape at various stretch rates, while maintaining a

common maximum stretch ratio for all. The model was then fitted to the experimental data in two distinct optimization processes. The first portion consisted of a nonlinear parameter fitting to the individual experiments, which yielded values for each experiment's independent dynamic modulus (with respect to its distinct stretch rate). The complex moduli for all experiments were then run through a second nonlinear optimization, in which case the overall material parameters were found for the model, based on the change in stretch rates. To represent the variation in energy loss, relative to rate-dependant properties, the model also calculated a loss factor η , which was a function of the final material parameters and the dynamic stretch rate. This loss factor was used to determine a phase shift between the calculated stress and strain. This phase shift is what creates the hysteresis loop of the system. The results of this proposed modification to the original model are illustrated in Figure 2.16.

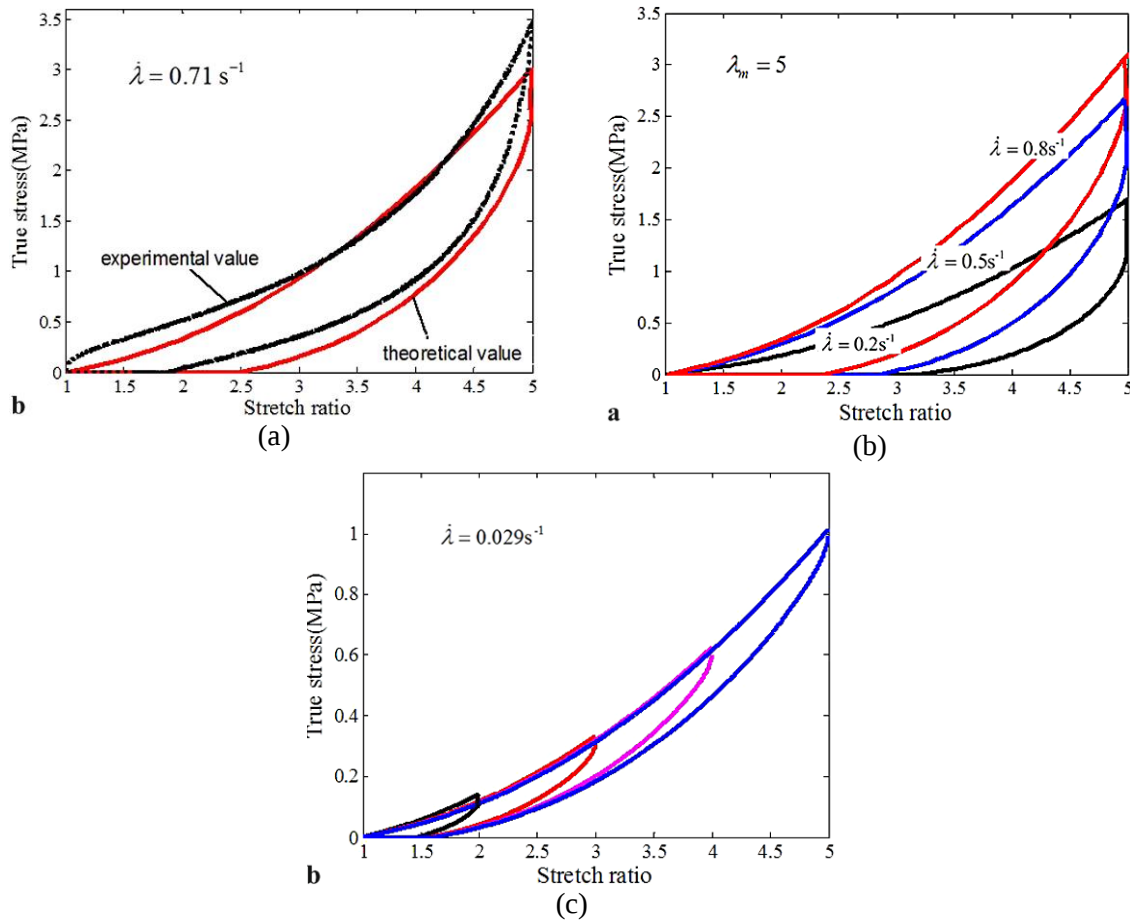


Figure 2.16: Proposed Wang et al. dynamic hyper-viscoelastic model for VHB 4910 tape [62] where model is (a) compared to experimental results, (b) plotted with various stretch rates, and (c) plotted with various peak-stretch ratios

It can be seen that the addition of a dynamic parameter enables the model to illustrate the rate-dependant visco-hyperelastic response of the VHB 4910 tape. Wang's new approach proved successful in agreeing with experimental values (Figure 2.16 (a)). It also demonstrated the ability to represent variations in energy loss and changes in peak stresses due to the effects of changing the kinematic parameters (Figure 2.16 (b) and (c) respectively). The model's mathematical structure is also more illustrative of mechanical behaviour, which is advantageous for the design and evaluation of DE actuators.

2.4 Actuator Design

2.4.1 Design and Considerations

Dielectric elastomer based actuators offer a wide range of configuration opportunities considering their highly flexible nature. As can be seen in Figure 2.17, the DE films can be arranged in a variety of shapes in order to produce electro-mechanical transduction, especially in the case of linear actuation. As previously described in Section 2.3.1, the configuration of the actuator is governed by the working direction selected. Similar to piezoelectric ceramic actuators, DE transducers can be stacked or folded to create multi-layered assemblies that take advantage of the thickness change while activated. Other options exploit the elastomers' large multidirectional strains, and work in the planar direction (as seen with the bowtie and spider configurations). In such cases, the elastomer needs to be fixed in a pre-stretched configuration by applying it to a rigid frame. Having these rigid mounts allows the designer to select the direction of motion, which provides a wide array of actuation opportunities, and do not limit it to a single linear path [2, 3, 4].

When designing an actuator, the material's mechanical and electronic limitations must both be considered. More specifically, the relationship between the achievable stroke length versus the produced axial force of the transducer must be taken into consideration. It is clear that the elastomer will have a maximum actuation strain, when completely unrestricted. However, the stroke length will decrease with respect to the amount of force it is resisting. This concept is explained by Kornbluh et al. [3] with a simplified equation. In this illustrative equation, the elastomer is assumed to be linearly elastic, and any mechanical constraints on the film are ignored.

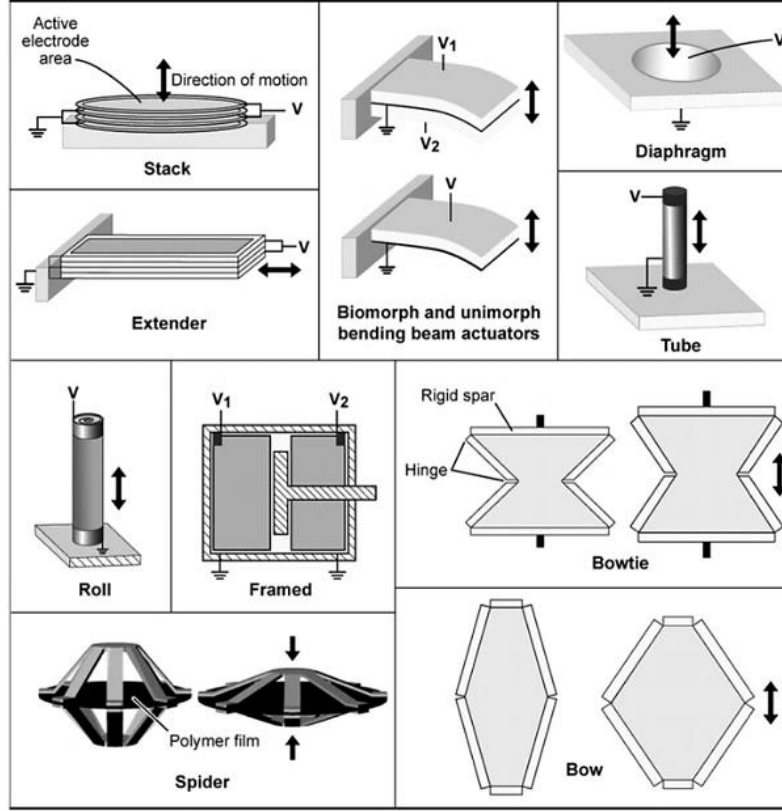


Figure 2.17: Selected representations of dielectric elastomer actuator configuration [4]

For a single layer of film, the electric field required to produce a certain force output at a specific stroke length [3] is:

$$\Delta l = \frac{l \left(0.5p - \frac{F_{load}}{wt} \right)}{Y} \quad (2.6)$$

where Δl represents the stroke of the actuator, l and w are the length and width of the film, t is the film's thickness, p is the effective pressure of the electrodes on the film (as given in (2.1)), and Y is the material's Young's Modulus. It has also been assumed that the polymer is incompressible and isotropic, therefore implying a Poisson's ratio of 0.5. A graphical representation of this relationship can be seen in Figure 2.18. From this graph, it can be noted that an actuator's overall displacement is inversely proportional to its force output, due to its mechanical and electrical limitations.

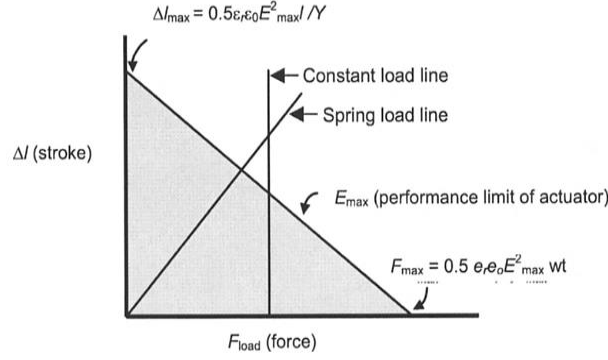


Figure 2.18: Force versus stroke outputs for simplified actuator model [3]

Both characteristics can theoretically be optimized by modifying certain design criteria, as can be seen in Figure 2.19. In the case where the actuator is actively deforming in the planar direction, the stroke length is governed by the plane's surface area. This implies that, by having a longer axial length (in the working direction), the actuator will have a greater deformation since more material will be displaced by a greater applied pressure (from larger electrodes). By contrast, to optimize the actuator with respect to the applied load, stacking multiple layers of film will provide a greater actuation force. This is evidently due to an increase in the working direction's cross-sectional area, which results in a higher tensile resistance. It will also provide a greater bending stiffness, which is an additional asset to the linear actuation design since thinner films tend to buckle under activation [16]. Similar logic can be applied to the case where the actuator is designed in thickness working direction. The principles are, however, reversed.

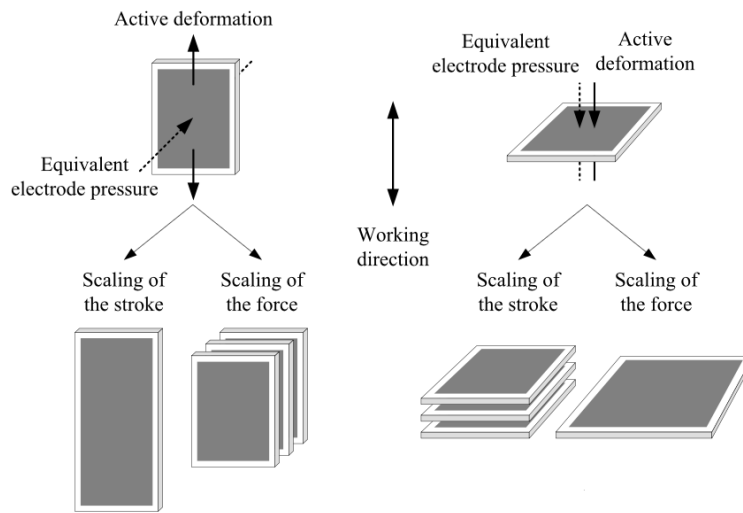


Figure 2.19: Parameter consideration for actuator stroke and force criteria [16] in planar working direction (left) and thickness working direction (right)

Another consideration for electro-mechanical transduction is the conductors that will apply the Maxwell pressures to the dielectric film's surfaces. Electrodes are typically selected based on the transducer's characteristics and objectives. In the case of actuation, structural compliance of the electrodes is paramount. They will be required to accommodate large-magnitude strains that are being achieved by the film. This implies that the electrodes must be able to stretch and contract in unison with the DE, in order to effectively transduce electrical energy into mechanical energy. A common alternative to satisfy these conditions is to apply a layer of conductive semiliquid or powder-based solution to the surfaces of the DE. Options such as silver/copper paint, carbon grease, and carbon/graphite powder have been used to create these conductive surfaces. Of these alternatives, carbon grease has been the most widely used solution thus far [2, 6, 7, 16, 36, 63]. This is due to its inexpensive, ready-made nature, as well as its ability to maintain good conductivity under very high strains. Similar qualities are found in the use of graphite and carbon powders. The disadvantage with grease, however, lies in the fact that it affects adhesion properties. In the case where an actuator may be multilayered, this may cause slippage between the sheets, thus impacting its performance. By contrast, powders have shown to lose conductivity with increasing strains, since the particles are spread apart and therefore lose contact [6, 64].

Other alternatives comprised of thin-film metal sheets have also been used as electrodes for DE based actuators. In particular, silver [65] and gold leaf [66] electrodes have been tested as viable options. In both cases, the metal leaves were applied to a compressed film, in order to create a corrugated membrane profile. This was done to allow the metal to expand after application. For either alternative, the actuation could only act in the direction of the corrugation, and maximum stretch ratios of $\lambda = 1.33$ and 1.22 respectively were achieved.

In recent works, more sophisticated electrodes were developed for use in DE actuators. A commercially available self-assembling nanostructured conductive film dubbed Metal Rubber™ has proven very successful, by demonstrating high conductivity while maintaining a low modulus of elasticity and achievable stretch ratios of up to $\lambda = 10$ [67, 68, 69]. This gold nanoparticle-rubber composite is applied by dipping a substrate into alternating baths of polyanion and polycation solutions, with attached gold clusters, to form a multilayered conductive film [13, 69]. Further developments have shined light on the effectiveness of nanofiber structures as compliant electrodes. Both polyaniline nanofibers and carbon nanotubes have shown very favourable

properties for this purpose. In particular, they have demonstrated unvarying conductivity at large strains, which reduces the electrode thickness required [70, 71]. Alongside being on par with carbon grease in terms of effectiveness, they have also shown a particularly interesting characteristic of “self-clearing” [72, 73]. This signifies that the electrode will burn off locally if an electrical short were to arise through the dielectric film. Self-clearing results in the effective prevention of elastomeric dielectric failure. An example of this property was demonstrated by Yuan et al. [73]. In the study, a pre-strained film of VHB tape with CNT electrodes was punctured using a cactus pin. The elastomer managed to still maintain very high actuation strains by recovering from the local failure through self-clearing effects. This type of fault-resistance in electrodes could prove extremely valuable for future developments of DE actuators, by increasing their resistance to dielectric breakdown, and increasing their overall longevity.

Several other design and operational factors also need to be considered when conceptualizing an actuator. Among others, features pertaining to the actuator itself such as force and response speed limits, controllability, reliability and durability, as well as environmental tolerances (e.g. humidity and temperature) will play a role in the design’s optimization. Operational factors, such as power supplies and driver circuits will also need to be considered as part of actuator implementation [3].

2.4.2 Currently Developed Actuator Configurations

Due to their promising characteristics and availability, dielectric elastomers have been exploited in a variety of configurations to produce actuators for multiple potential uses. The fields of biomimetics and soft robotics have shown a particular interest in these types of actuators, as they have demonstrated the ability to replicate the behaviour of biological muscle [3, 6, 9, 74]. To the author’s knowledge, only one commercially available DE-based actuator has been documented. The Universal Muscle Actuator [16], supplied by Artificial Muscle Inc., has not since been documented for real-world application. The company has been acquired by Parker Hannifin Corp., whom mention the use of the technology in various applications such as sensors, actuators, pumps and valves for medical devices, remote monitoring and industrial systems [75]. Aside from this, various research groups have also developed working prototypes using different configurations, to demonstrate these materials’ wide range of achievable motions. The scope of this report involves linear motion and will thus examine examples of this nature.

Actuators comprised of soft dielectric EAPs can be subdivided into two categories, based on their structure. The first group consists of non-pre-stretched configurations, where the DE is used at its original thickness. For this reason, these types of actuators are typically assembled in a stacked or folded geometry, since their working direction will be in the thickness direction (as seen in Figure 2.20) [76, 77, 78]. These configurations' working principle relies on the planar expansion of the polymer upon activation to induce a contraction of the total thickness of the actuator. This gives it a “shrinking” effect, which allows the actuator to resist external tensile forces.

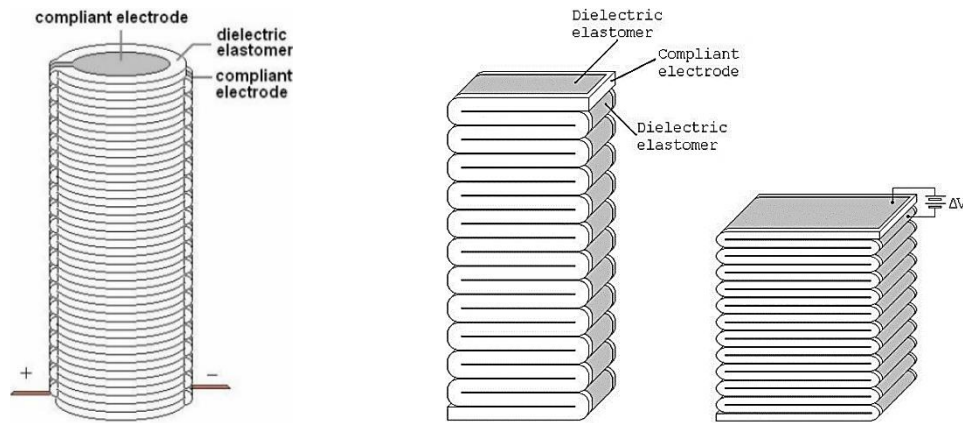


Figure 2.20: Stacked (left) and folded (right) DE linear actuators (adapted from [78])

Due to their relatively large manufactured thickness, VHB tapes are typically unfavourable for these types of configurations. Having such a large profile requires them to be pre-stretched in order to be activated. Pre-stretching requires the support of an external rigid frame to which the film can be fixed. To eliminate the dependence on rigid frame supports, additional pre-processing techniques have been developed and applied to acrylic-based DEs. This has allowed their use in stacked actuator configurations by modifying their core molecular structure, through the process of synthesizing Interpenetrating Polymer Networks (IPNs). In this method, the VHB tape is combined with an additional monomer to create an interlaced multi-polymeric network. It is first pre-stretched to a desired deformation, and then impregnated with the monomer additive. Once the VHB tape is released, it remains in pre-stretched form, without requiring an external rigid support [79, 80, 81]. An example of a stacked actuator, using VHB 4910 tape, can be seen in the works of Kovacs et al. (Figure 2.21) [77, 82]. The results of these prototypes have demonstrated remarkable potential in terms of their contractile strain, load-bearing abilities, and resistance to

fatigue. The requirement of material processing prior to assembly, however, brings an added factor of technical complexity to the production of these actuators.

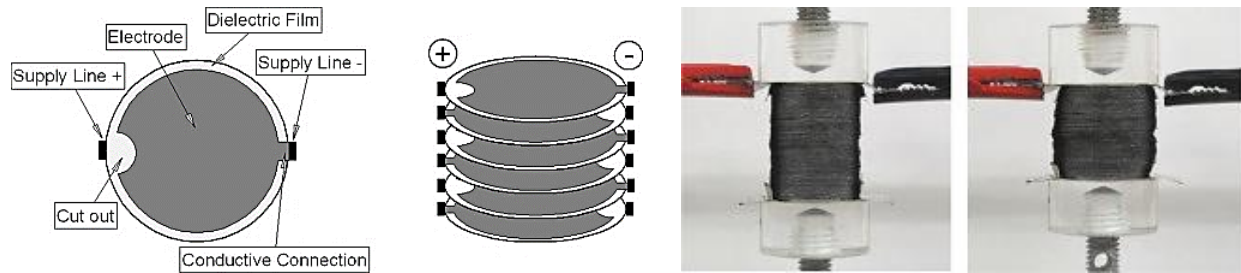


Figure 2.21: Stacked VHB-based IPN linear actuator (adapted from [77])

The second group of actuator configurations are comprised of pre-stretched DE membrane structures. As was illustrated in Figure 2.17, DEs can be exploited in multiple ways by using rigid outer frames to guide or limit their expansion degrees of freedom. The film will typically be stretched and adhered to the external (mobile) support, which will maintain the elastomer at a favourable thickness for activation. As opposed to their stacked counterparts, these actuator configurations work in the planar direction. The working principle relies on the planar expansion of the polymer upon activation, which will cause it to “relax”. This expansion, guided by the external support frame, will allow the actuator to apply external forces to its environment.

Possibly one of the most successful configurations of these types of actuators to date has been the rolled geometry. This configuration consists of a biaxially pre-stretched polyacrylic elastomer film, which is rolled around a compression-coil spring core (seen in Figure 2.22). The internal spring maintains the elastomer at a pre-stretched configuration along its axis of deformation, and is responsible for the stroke-extension of the actuator when the film is activated (and relaxes) [83, 84, 85, 86, 87].

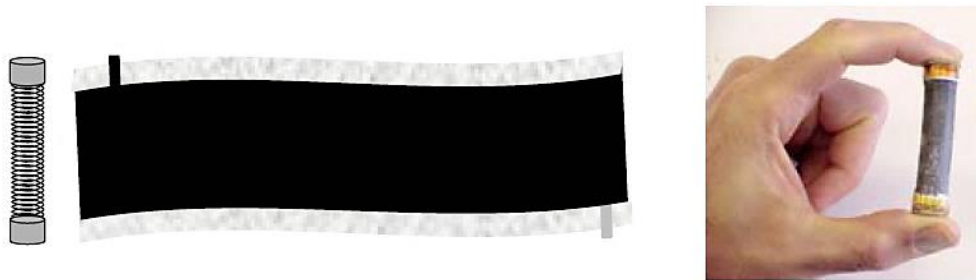


Figure 2.22: Rolled-configuration DE actuator [85]

This configuration has demonstrated very promising results, showing free stretch ratios of up to $\lambda = 1.35$ and forces ranging up to 33 N. It also provides parameter variability, by permitting its diameter and length to be modified according to desired application. In fact, perhaps one of the most informative examples of the potential abilities of DE technology as large-scale actuators was at 2005 EAP Arm Wrestling Competition. Kovacs et al. [84] described the construction and functioning of an arm wrestling robot based on a series of rolled VHB 4910 tape-based actuators. The robot managed to work against externally applied forces and return to its original position, which demonstrated an agonist–antagonist actuation mechanism that is favourable in applications for prosthetics and robotics. Its configuration can be seen in Figure 2.23.

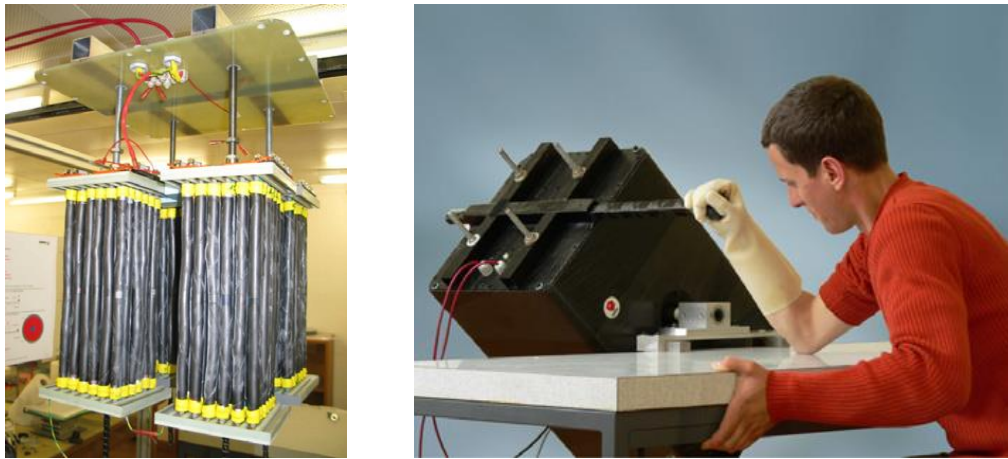


Figure 2.23: Arm wrestling robot based on VHB 4910 tape rolled actuators (adapted from [84])

The rolled configuration has also demonstrated the potential of being used in bending, through a different strategic electrode-pattern application. Their major pitfall is in the cylindrical configuration, which is difficult to manufacture. Due to its free-hanging edges, it also has a decreased biaxial deformation coupling. This signifies that the energy harnessed in the planar expansion is not fully exploited. The final examples of actuator configuration attempt to solve these downfalls through changes in structural supports.

Bow-tie and diamond-shaped actuators both consist of planar dielectric configurations which make use of a rigid perimeter with hinged connections. These actuators exploit the membrane's full biaxial deformation by coupling the longitudinal and lateral strains through a type of scissoring mechanism [88, 89]. Both structures can be seen in Figure 2.24.

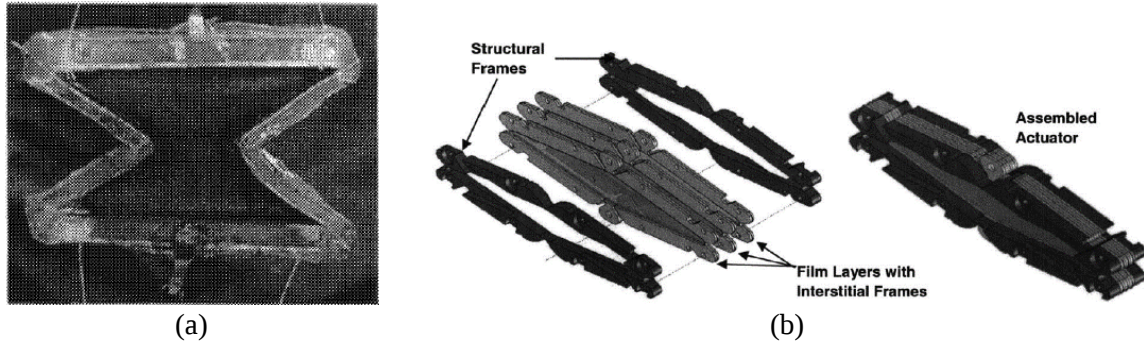


Figure 2.24: Planar DE actuator structures using rigid hinged frames for (a) Bow-tie configuration [88] and (b) Diamond-shaped configuration [89]

These types of actuators are ideal for VHB tape due to their planar configuration. This allows for a simple assembly, since the elastomer is manufactured in flat sheets and can remain so during pre-stretch and frame-application processes. In addition, the frame allows for full transfer of elongation along the axis of linear deformation, by taking advantage of the lateral expansion of the membrane during activation. As can be seen in Figure 2.24 (b), the structures also have the potential to be stacked in parallel and in series. This would allow the adjustment of both the total applied actuation force, as well as achieved elongation of the actuator assembly. Smaller multilayered models of these structures were tested and achieved elongations on the order of 30%, and achieving forces between 2 to 7 N. The bow-tie and diamond-shaped actuator configurations have proven to be light-weight, simple to manufacture, and parameterizable. With respect to the rolled actuators, however, their geometry possesses a larger footprint, which may affect their integrability.

CHAPTER 3

Dielectric Elastomer Experimental Evaluation

To properly characterize the 3M™ VHB tape behaviour, and then design an optimum actuator prototype, it is first paramount to understand its properties both from mechanical and electro-mechanical perspectives. The following chapter will thus present a comprehensive experimental evaluation of 3M™ VHB 4905 and 4910 tapes. It will first identify the critical parameters necessary to characterize the material's mechanical response. The chapter will also examine the electro-mechanical response of the material under variable experimental to provide optimization guidelines for prototype development.

3.1 Mechanical Property Testing

3.1.1 Equipment and Experimental Protocol

To characterize the mechanical behaviour of 3M™ VHB tape, a series of biaxial tests were performed. To achieve these experiments, CellScale's BioTester was used (as seen in Figure 3.1). The BioTester machine makes use of tungsten rakes to mount samples to its 23-N load cells. The rakes used for all experiments had a tine diameter of 305 μm , tine spacing of 1.0 mm and puncture depth of 1.9 mm. The BioTester machine acquires force and displacement data at a precision of 1 mN and 1 μm respectively, and will typically fluctuate within a range of 23 mN (0.01% of full scale) [90].

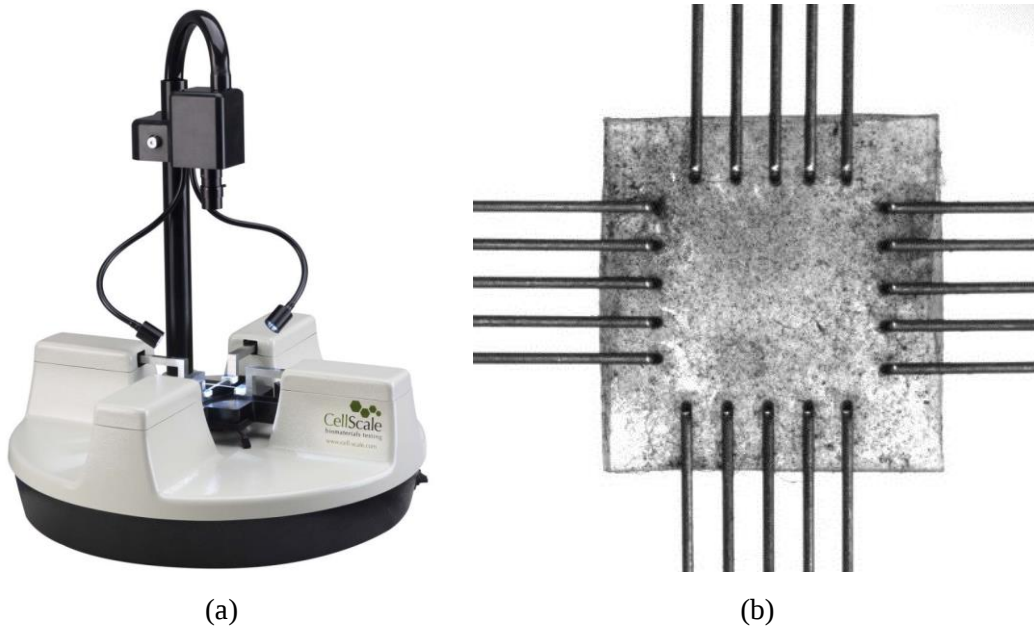


Figure 3.1: (a) CellScale BioTester [90] and (b) mounted specimen example

Samples for VHB 4905 and 4910 tapes were cut down to size and mounted to the rakes for tensile tests. A full description of this carefully planned procedure is described in Appendix A.1. Three types of experiments were conducted on both VHB 4905 and 4910 tapes: load-unload tensile testing, single-step relaxation testing, and multi-step relaxation testing. In all cases, experiments were biaxial, with equiaxial conditions (i.e. stretch ratios $\lambda_1 = \lambda_2 = \lambda$). The first series performed was load-unload tensile testing at six different stretch rates: 0.025 s^{-1} , 0.050 s^{-1} , 0.075 s^{-1} , 0.100 s^{-1} , 0.200 s^{-1} , and 0.300 s^{-1} . These tests consisted of a constant stretch-rate elongation phase

to a peak stretch ratio of $\lambda = 2$, followed by a mirrored release phase. Each experimental stretch-rate was repeated for 5 different samples.

The second series of experiments consisted of five single-step tensile isostrain tests. For each of these tests, the machine's maximum displacement velocity of 10 mm/s was used to reach stretch ratios of $\lambda = 1.2, 1.4, 1.6, 1.8, 2.0$. Once the specimens have reached their maximum elongation, they were then held for a period of 30 minutes to observe the time-dependant relaxation response of the material. The final set of experiments consisted of multi-step tensile isostrain tests. Similar to the single-step tests, this set involved a stretch-hold sequence. In this case, however, the elongations were performed in a 5-part incremental process on the same specimen. Each step began with a constant-rate stretch phase which enlarged the stretch ratio in single-unit increments (i.e. $\delta\lambda = +1$). This was then followed by a hold phase of 30 mins. Again, for each of the stretch phases, the machine's maximum displacement velocity was used of 10 mm/s. The sample reached a final total biaxial stretch ratio of $\lambda_{max} = 6$. In all cases, experiments were conducted at standard ambient temperature and pressure.

Sampling rates for data points and images, taken by the BioTester, need to have identical values in order to use the image tracking software. For the load-unload data and camera sampling, a frequency of 5 Hz was selected for tests between 0.025 s^{-1} and 0.075 s^{-1} , whereas a frequency of 15 Hz was selected for tests between 0.100 s^{-1} and 0.300 s^{-1} . These values were selected based on a combination of computing storage capacity, and CellScale's recommendations of 1 Hz for cycles > 5 seconds and 10 Hz for cycles < 5 seconds. It should be noted that the software has a maximum image output frequency of 15 Hz. For single-step and multi-step relaxation tests, output frequencies of 1 Hz and 0.1 Hz were selected, respectively, based on the duration of each test.

3.1.2 Image and Data Processing

CellScale's LabJoy image tracking software was used to evaluate the specimen's true stretch ratio for the biaxial load-unload tests. This additional step was taken as a precaution due to possible inaccurate representation of the material's deformation, based on grip displacements [91, 92]. The specimen has a tendency to deform around the tines, as seen in Figure 3.2, which results in a different total stretch ratio than input in the testing conditions. This is particularly true in elastomers such as VHB tapes, due to their stiffer and highly viscoelastic properties.

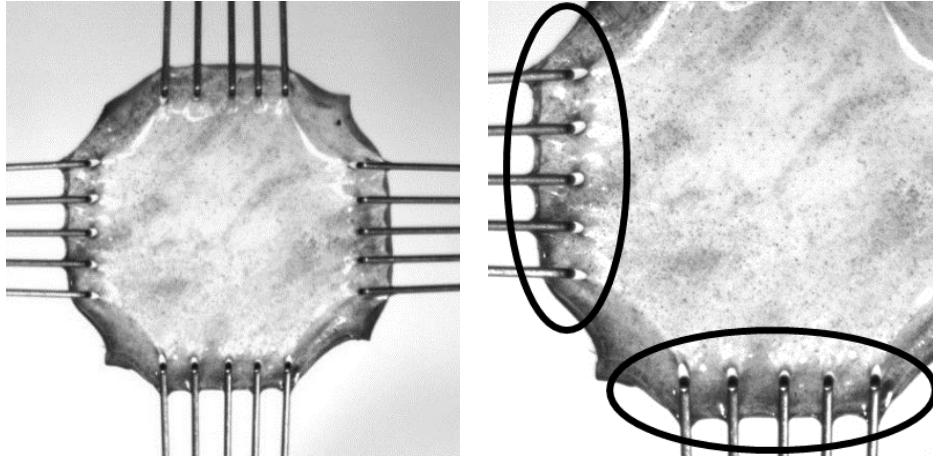


Figure 3.2: Example of material deformation around rake tines

To track the specimen's true displacement, methods similar to the ones reported by Labrosse et al. [91] were used, where a 9 by 9 node square grid was manually selected within the central portion of its surface. After running the tracking software, the localized stretch ratios were observed for each of the 64 square elements, and a single element was selected based on the region's most relatively homogeneous strain. An illustration of this process is depicted in Figure 3.3.

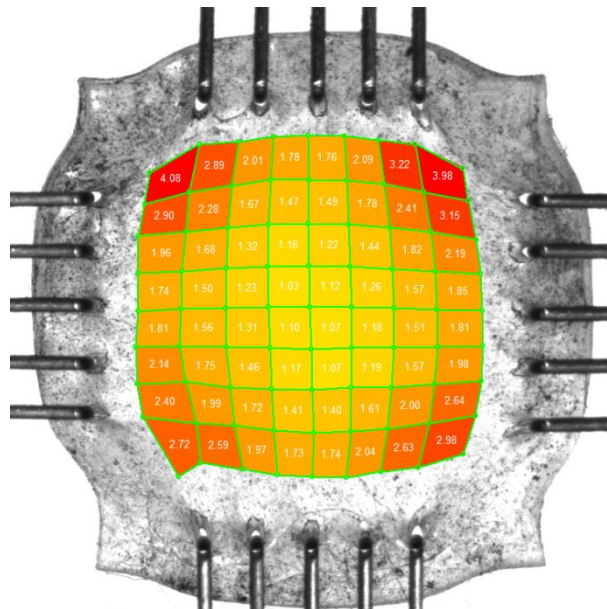


Figure 3.3: Example of image tracking for VHB 4910 tape biaxial tensile test representing E_1/E_2 principal strain ratios

It should be noted that extra care was taken through lighting adjustments and filtration techniques (with the LabJoy software's native camera-adjustment settings) to reduce every sample's innate reflectiveness, and minimize error during the tracking process. The displacement of all four nodes forming the chosen square element are then exported in terms of the x and y axis (i.e. x_1, y_1, x_2, y_2 , etc.) for further processing.

To determine the displacement of the element along either axis, a method of iso-parametric mapping was utilised. Similar to the method described by Humphrey [93] and Labrosse et al. [91, 94], this involves transformations between a quadrilateral element's nodal coordinates in (x, y) (or displacements in (u, v)) and a set of natural coordinates (r, s) , based on the reference coordinate system of its analogous parent geometry (as seen in Figure 3.4).

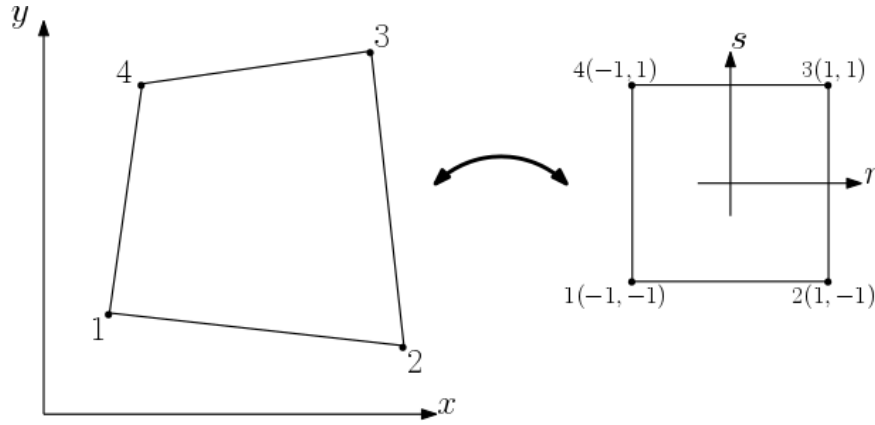


Figure 3.4: Iso-parametric mapping representation between nodal (left) and natural (right) coordinate systems

The variables of interest, for the current application of the method, are the displacements u and v of the quadrilateral element. This will provide values to compute the resulting deformation of the element, and thus the sample. The shape functions of the parent element can be expressed using Lagrange interpolation, which is expressed through the following general formula:

$$N_i = \frac{1}{4}(1 + rr_i)(1 + ss_i) \quad \text{for } -1 \leq r \leq 1 \text{ and } -1 \leq s \leq 1 \quad (3.1)$$

where N_i are the shape functions for the four nodes of the quad element. In (r, s) natural coordinates, knowing that the parent geometry has nodes $N_1(-1, -1)$, $N_2(1, -1)$, $N_3(1, 1)$, and $N_4(-1, 1)$, we have:

$$[N(r, s)] = [N_1 \quad N_2 \quad N_3 \quad N_4]$$

$$[N(r, s)] = \left[\frac{1}{4}(1-r)(1-s) \quad \frac{1}{4}(1+r)(1-s) \quad \frac{1}{4}(1+r)(1+s) \quad \frac{1}{4}(1-r)(1+s) \right]$$

To interpolate from the real geometry to the parent coordinate system, we have:

$$\varphi(r, s) = [N] \begin{Bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{Bmatrix} = [N] \{\varphi^e\} \quad (3.2)$$

where φ_i represents any nodal value in the real configuration. This means that the relationship described in (3.2) can either be applied to a coordinate value (i.e. x or y), or a displacement (i.e. u or v). Taking the partial derivatives of $\varphi(r, s)$ will yield:

$$\frac{\partial \varphi(r, s)}{\partial r} = \left[\frac{\partial N(r, s)}{\partial r} \right] \{\varphi^e\} \quad \text{and} \quad \frac{\partial \varphi(r, s)}{\partial s} = \left[\frac{\partial N(r, s)}{\partial s} \right] \{\varphi^e\} \quad (3.3)$$

where

$$\frac{\partial N(r, s)}{\partial r} = \frac{1}{4} \begin{bmatrix} -1+s & 1-s & 1+s & -1-s \end{bmatrix}$$

$$\frac{\partial N(r, s)}{\partial s} = \frac{1}{4} \begin{bmatrix} -1+r & 1-r & 1+r & -1-r \end{bmatrix}$$

X and Y are the coordinates of the initial reference geometry (i.e. the unloaded initial position of the quadrilateral element). For any displacement $w(X(r, s), Y(r, s))$, following the chain rule, its partial derivatives with respect to natural coordinates can be expressed as:

$$\frac{\partial w}{\partial r} = \frac{\partial w}{\partial X} \cdot \frac{\partial X}{\partial r} + \frac{\partial w}{\partial Y} \cdot \frac{\partial Y}{\partial r} \quad \text{and} \quad \frac{\partial w}{\partial s} = \frac{\partial w}{\partial X} \cdot \frac{\partial X}{\partial s} + \frac{\partial w}{\partial Y} \cdot \frac{\partial Y}{\partial s}$$

which can be represented in matrix form as:

$$\begin{Bmatrix} \frac{\partial w}{\partial r} \\ \frac{\partial w}{\partial s} \end{Bmatrix} = \begin{bmatrix} \frac{\partial X}{\partial r} & \frac{\partial Y}{\partial r} \\ \frac{\partial X}{\partial s} & \frac{\partial Y}{\partial s} \end{bmatrix} \begin{Bmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{Bmatrix} = [\mathbf{J}] \begin{Bmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{Bmatrix} \quad (3.4)$$

Inverting the equation, in order to solve for displacements of interest $\frac{\partial w}{\partial X}$ and $\frac{\partial w}{\partial Y}$, the following final equation is derived:

$$\begin{Bmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{Bmatrix} = \frac{1}{|\mathbf{J}|} \begin{bmatrix} \frac{\partial Y}{\partial s} & -\frac{\partial Y}{\partial r} \\ -\frac{\partial X}{\partial s} & \frac{\partial X}{\partial r} \end{bmatrix} \begin{Bmatrix} \frac{\partial w}{\partial r} \\ \frac{\partial w}{\partial s} \end{Bmatrix} \quad (3.5)$$

where $|\mathbf{J}| = \det[\mathbf{J}]$.

The system can then be solved for any value of r and s , with respect to the axis of interest. For instance, in the case of displacement u along the x-axis (knowing that $u_i = x_i - X_i$ by definition) the corresponding u_i values of all nodes would be substituted in φ_i . The equivalent stretch ratio would then be found, by definition of the deformation gradient tensor $\bar{\bar{F}} = \frac{\partial \vec{u}}{\partial \vec{X}} + \bar{\bar{I}}$. This therefore results in the following equality:

$$\begin{bmatrix} \lambda_1 & F_{12} \\ F_{21} & \lambda_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial X} + 1 & \frac{\partial u}{\partial Y} \\ \frac{\partial v}{\partial X} & \frac{\partial v}{\partial Y} + 1 \end{bmatrix} \quad (3.6)$$

The current thickness of the specimen h can be expressed with known quantities as $h = \frac{H}{J_{2D}}$, where H is the original specimen thickness. The determinant of the deformation gradient tensor must be equal to 1, due to incompressibility assumption:

$$[\bar{\bar{F}}] = \begin{bmatrix} \lambda_1 & F_{12} & 0 \\ F_{21} & \lambda_2 & 0 \\ 0 & 0 & \frac{1}{J_{2D}} \end{bmatrix} \quad (3.7)$$

which therefore results in $J_{2D} = \lambda_1 \lambda_2 = F_{12} F_{21}$. Following displacement tracking and calculations, the true stress acting on both axes of the specimen were calculated by introducing the Cauchy Stress tensor. This will apply the experimental forces f_1 and f_2 along the current cross-sectional areas of the specimen. Cauchy Stress tensor can be expressed as:

$$[\bar{t}] = \frac{1}{H} \begin{bmatrix} \frac{\lambda_1 f_1}{L_2} & \frac{F_{12} f_2}{L_2} & 0 \\ \frac{F_{21} f_1}{L_2} & \frac{\lambda_2 f_2}{L_1} & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3.8)$$

which yield the final equations for true stresses along both planar axes $\sigma_1 = \frac{\lambda_1 f_1}{H L_2}$ and $\sigma_2 = \frac{\lambda_2 f_2}{H L_1}$.

A full derivation of these equations can be found in Appendix A.2.

The image tracking was not used for the single-step and multi-step relaxation tests due to their very long duration. This led to the requirement of extensive processing power and time, which made the tracking difficult to achieve. Since these experiments aimed to investigate material mechanical behaviour, the grip displacement values were deemed sufficient to demonstrate the material's tensile behavioural trends. Should the data need to be used in later analytical applications, these experiments would need to be repeated at higher capture frequencies, and analyzed using the method described above with higher performing computational hardware.

A MATLAB code was written in order to process the previously described calculations, as well as plot the final data. In all cases, the data collected had a great level of noise, due to the load cell's high sensitivity and relative fluctuation. In order to reduce this noise, smoothing functions were applied to all experiments, to provide a more representative material behaviour. The full code can be found in Appendix A.3.

3.1.3 Results

3.1.3.1 Load-Unload Tensile Testing

The first type of tests performed on VHB 4905 and VHB 4910 tapes were a series of load-unload tensile tests, at 5 different stretch rates to maximum stretch ratio of $\lambda_{max} = 2$. These tests were performed in order to characterize the material's viscoelastic behaviour, biaxially, and quantify its mechanical properties using a constitutive model. These tests will also provide insight on the

materials currently assumed isotropic characteristics, as well as overall biaxial behaviour under tension. The tests were repeated for each stretch rate in order to provide a statistical significance to the results. All graphs for these experiments can be found in Appendix A.4.

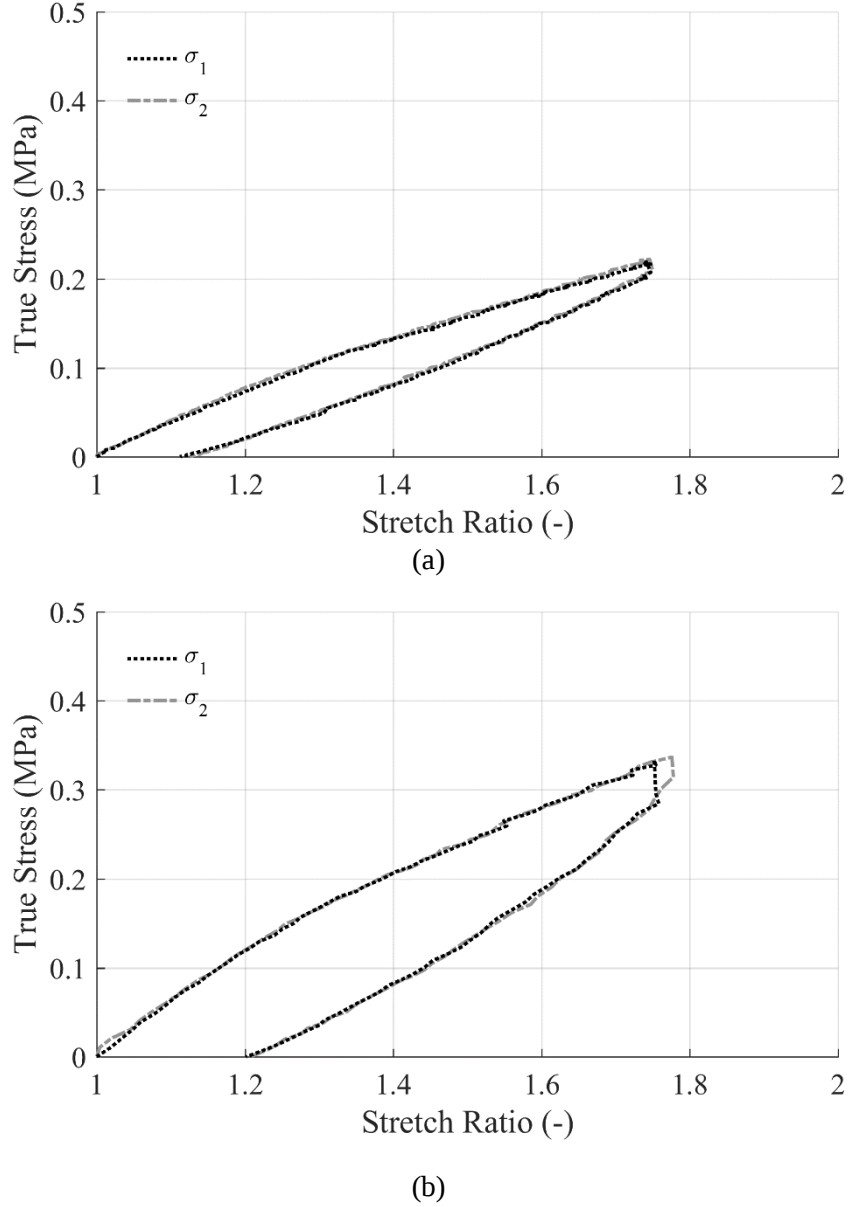


Figure 3.5: Comparison of biaxial tensile load-unload curves for VHB 4910 tape at different stretch rates for (a) $\dot{\lambda} = 0.025 \text{ s}^{-1}$ and (b) $\dot{\lambda} = 0.300 \text{ s}^{-1}$

Examples of the experimental results from these tests are displayed in the following section. Figure 3.5 depicts the data for VHB 4910 tape, being stretched at rates of (a) $\dot{\lambda} = 0.025 \text{ s}^{-1}$ and (b) $\dot{\lambda} = 0.300 \text{ s}^{-1}$. In both cases, the graphs show a clear offset between the stretch and release

curves. This phenomenon, otherwise known as a hysteresis loop, demonstrates an energy loss within the material during its elongation, which is a typical characteristic of viscoelastic material. Further analysis of the superimposed curves also shows an almost parallel behaviour of the stress versus stretch ratio of the material on both axes of tension. This similarity of the normal stresses confirms that the material behaves in a transversely isotropic manner.

The material's tensile response also exhibited proportional rate-dependant behaviour between tests. Due to the highly viscous nature of the elastomer, the energy loss is clear, particularly when noticing the differences in initial and final stretch ratio values. It can be seen that the stretch rate has a proportional influence on this loss, as the samples with greater rates all exhibited larger overall hysteresis. The peak stress increases by almost 60%, based on the variation of stretch-rate. In all cases, for both tape types, the peak stress exerted on the sample increased as the strain rate was accelerated. For VHB 4905 tape, the peak stresses ranged from 0.22 MPa to 0.42 MPa, whereas for VHB 4910 tape, their values increased from 0.19 MPa to 0.37 MPa. The overall achieved maximum stresses were larger for VHB 4905 tape for the simple fact that, with identical experimental parameters, the thinner tape will exhibit higher stresses due its smaller cross-section. It can therefore be concluded that VHB 4905 will in general have stiffer, more sensitive response to changes in kinematic parameters due to its thinner profile.

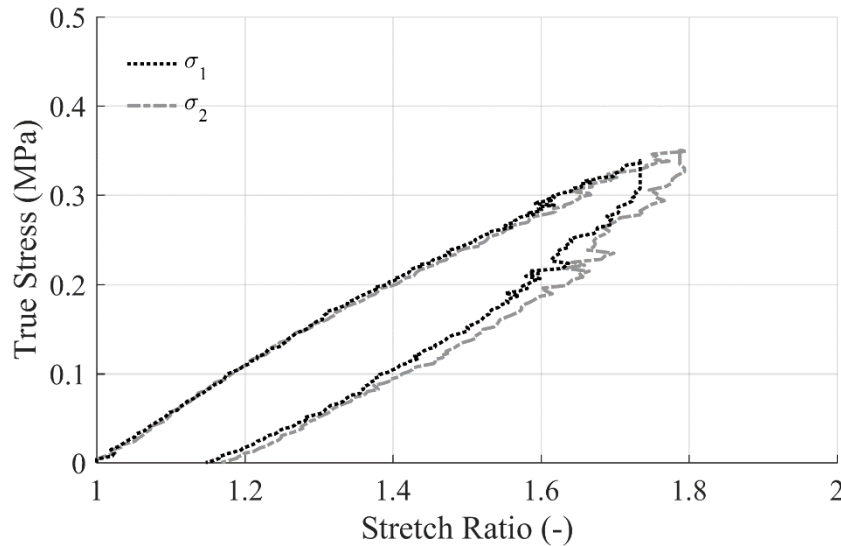


Figure 3.6: Biaxial tensile load-unload curve for VHB 4905 tape at $\dot{\lambda} = 0.100 \text{ s}^{-1}$

For VHB 4905 tape, the data outputs were similar in behaviour, however the noise of the sampling data was much larger. Figure 3.6 displays the data for a VHB 4905 tape load-unload test at a stretch rate of $\dot{\lambda} = 0.100 \text{ s}^{-1}$. As can be seen in this figure, the data still follows an expected hysteresis loop, however does not have a distinguishably smooth curve. Reasons for this lack of smoothness are explained below.

Overall, the results of the load-unload tensile testing followed the trends that have previously been discussed in literature. It should be noted that none of the experiments achieved a peak stretch ratio of $\lambda = 2$. Due to the polymer's high viscosity, combined with the attachment type used in experimentation, samples achieved peak elongations of $\lambda_{max} \approx 1.7 - 1.8$. Due to these relatively smaller total elongations, the curves displayed in experimental data did not reach the expected exponential behaviour typical of elastomers at high stretch ratios. This is most likely due to the fact that (at these smaller elongations) the material has not reached a point of strain-hardening, where polymeric chains are fully engaged after being “unwound”. Despite this fact, the VHB tapes still demonstrated viscoelastic response to a biaxial tensile load-unload cycle. They exhibited a proportional sensitivity to stretch-rate, through both their achieved peak stresses as well as their distinguishable energy loss. Both tapes also do not recover instantaneously to their original geometry, after being unloaded. In all cases, the samples remained much more relaxed on the machine, which resulted in an unloading curve that does not return to $\lambda = 1$ (as seen above). The viscoelastic behaviours observed in these tests agree with the previous uniaxial results in literature, and are all typical of rubber-like materials. They will need to be taken into consideration during the conceptualisation and design of actuators using VHB tapes. Further analysis of this data will be performed in Chapter 4, where a biaxial model will be proposed to characterize its behaviour under tensile testing.

The results for all experiments provided representative mechanical behaviour within sound accuracy. In all cases, the experiments' biaxial deformation fell within acceptable limits for equiaxial stretch ratios. Certain discrepancies can be noticed with respect to a portion of the experiments, particularly for VHB 4905 tape. These can be attributed to a variety of factors, including excessive noise during experimentation, accuracy of image tracking, and overall material deformation relative to the attachment points. As was previously mentioned, high amounts of noise were observed in all cases of experimentation, especially for the thinner tape samples.

This can be attributed to the BioTester's high load cell resolution (on the order of 1 mN), and the environment in which the experiments were conducted. The associated LabJoy software possesses additional filtering settings which could be used to decrease the effects of external interference. These settings were, however, not used for the current experiments to ensure all data is raw and untampered with. Post-experiment data smoothing did provide sufficient filtering to offer more consistent data in most cases, however, it would be favourable in future testing to conduct experiments in an environment with reduced noise. Another source of possible error relates to the attachment mechanism used by CellScale's BioTester. The rakes are fixed to the goosenecks by strong magnets. Although it has not been noticed visually, there is a possibility that these magnets may have lifted during certain portions of experimentation, which would cause periodic interferences during the loading process. This would explain the presence of higher interference for the thinner tape (with stiffer response), as well as the periodic interferences at the higher-rate experiments. It would be suggested, in future tests of these tapes (as well as other, stiffer materials using the BioTester), to add supplementary supports such as clamps on the rakes to prevent any unwanted lifting of the attachments during experimentation.

The image tracking did prove effective in the majority of cases for tracking of sample deformation. Certain inconsistencies in pixel tracking were observed due to two main reasons. The first factor involved photo clarity. As previously mentioned, all possible steps were taken before each experiment to adjust camera and native filtering settings through the software. It is clear, however, that further photo processing from an external editor would prove effective in assisting with image tracking. It would therefore be favorable, in future trials, to develop a photo editing algorithm that could enhance each experiment's photo-set to ensure optimal clarity of the carbon powder. This would also moderate the VHB tape's surface reflectiveness, which additionally played a great part in tracking inaccuracies. Furthermore, certain samples' image tracking was affected by the presence of unwanted particles attached to the tape's highly adhesive surface. Although great consideration was taken to prevent this from occurring, occasional fibers and larger particles would bind to the samples' surfaces, creating interference for the tracking software. These factors were infrequent, and typically did not greatly affect the overall success of the process. It would be suggested, however, that all future experiments (as well as all testing of VHB tape in general) be conducted in a cleanroom, to eliminate unfavourable particle interference.

3.1.3.2 Single-Step and Multi-Step Relaxation Tensile Testing

The second series of tests performed on both materials were split into two sub-categories: single-step relaxation tests, and multi-step relaxation tests. In both cases, the material was stretched at the machine's maximum actuator speed of 10 mm/s, to various peak stretch ratios, and then left to rest for a 30-minute time frame. These tests were performed in order to qualitatively characterize the material's time-dependant relaxation response under biaxial tensile loading. All graphs for these experiments can be found in Appendix A.4.

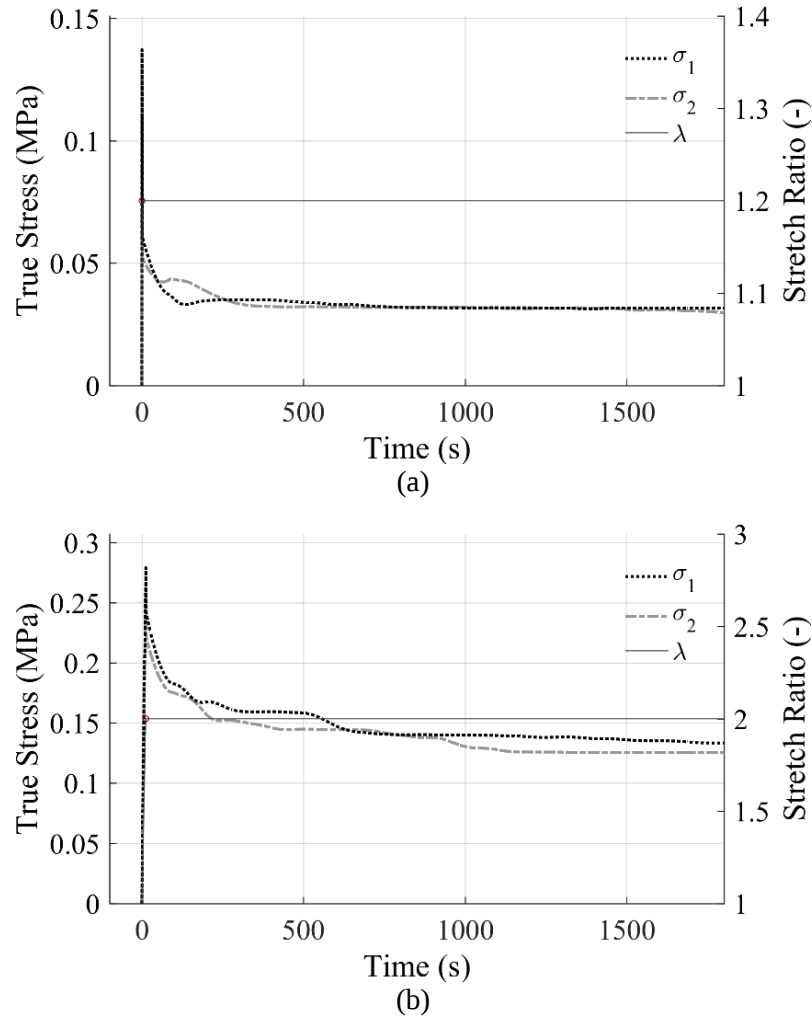


Figure 3.7: Comparison of biaxial tensile single-step stress relaxation curves for VHB 4910 tape at (a) $\lambda_{max} = 1.2$ and (b) $\lambda_{max} = 2$

An example of two single-step relaxation tests ($\lambda_{max} = 1.2$ and $\lambda_{max} = 2$), performed on VHB 4910 tape, can be seen in Figure 3.7. In both cases, it can be observed that the material has

an initial peak stress, which rapidly decreases within the first few seconds of the holding period. Over the course of the 30-minute relaxation, the material's stress converges to an almost constant state. The stress peak caused by the initial rapid-stretching phase is greater for the sample with the larger maximum stretch ratio, as expected. The difference between the peak stress and the final constant stress, as well as time required for convergence, also seem to be proportional to the maximum stretch ratio applied. Observing the curve produced by both axes (i.e. σ_1 and σ_2), an almost symmetrical convergence is noticeable, which suggests transverse isotropic stress-relaxation behaviour of the material. The same behaviour was observed for all experiments for VHB 4910 tape.

In the case of VHB 4905 tape, the trends remained the same, however all samples seemed to have demonstrated a slightly faster convergence. On average, the stress-relaxation period was roughly half of that of its counterpart. As can be seen in Figure 3.8, the single-step relaxation of a sample stretched to $\lambda = 2$ converges to a constant stress at around 900 seconds. This may be justified due to the material's smaller thickness, which may affect its time-dependant properties. VHB 4905 tape's experimental results also demonstrated much greater differences between the σ_1 and σ_2 curves. These differences in behaviour may be caused by inaccuracies in actuator positions readings relative to actual sample deformation. Further investigation using image tracking would provide a better representation of sample biaxial normal stresses, and would most likely resolve these discrepancies.

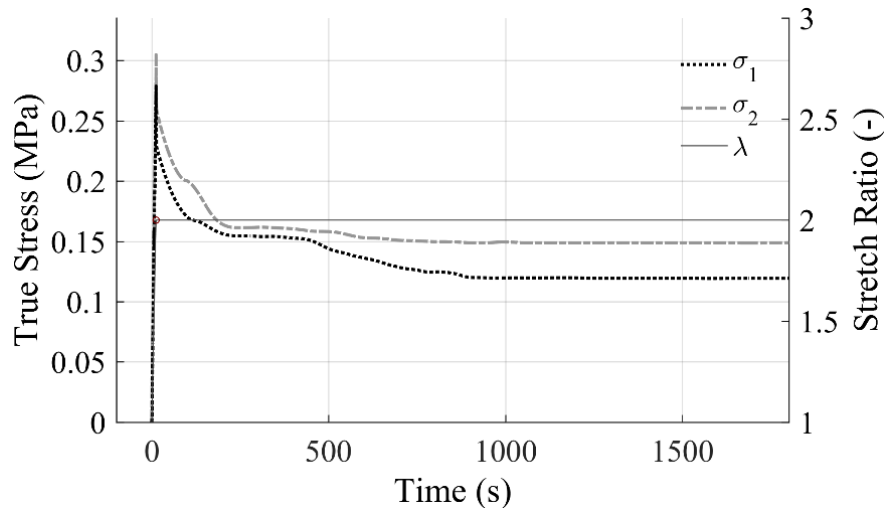


Figure 3.8: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 2$

Experiments for multi-step stress relaxation demonstrated comparable behaviour as the single-step relaxation tests. Figure 3.9 displays the data from a test performed on VHB 4910 tape. Similar to the previous examples, the material is shown to have a high peak stress at elongation, which rapidly relaxes within the first few seconds of the experiment. The 30-minute relaxation phases all demonstrate a convergence to constant stress, and all subsequent stretching phases still have a noticeable peak in induced stress. It was observed that, although small, each following peak had decreased in relative value to its corresponding previous converged relaxed stress. This suggests that prior stress relaxation may decrease the viscous nature of the material as it continues to elongate, despite it reaching stretch ratios where strain-hardening begins to occur.

The comparison between principle axes demonstrates a similar paralleled response to the single-step testing. Certain phases of Figure 3.9, more specifically steps $\lambda = 1.5, 1.6$, and 1.7 , seem to have a slight break in consistency. Due to the fact that these tests were evaluated based on actuator displacement, the output data assumed perfectly uniform deformation of the sample throughout experimentation. As was illustrated in Section 3.1.2, the rake attachments tend to deform the edges of the sample unevenly, which affects the true elongation of the sample relative to the machine's actuator locations. This may therefore be the cause for the inconsistencies in stress-curve collinearity. Similar irregularities were observed for the VHB 4905 tape. In order to draw a more definitive conclusion regarding the material's isotropy under stress relaxation, these tests would need to be performed and analyzed using the image tracking method. This would allow the results to better reflect the real deformation of the material.

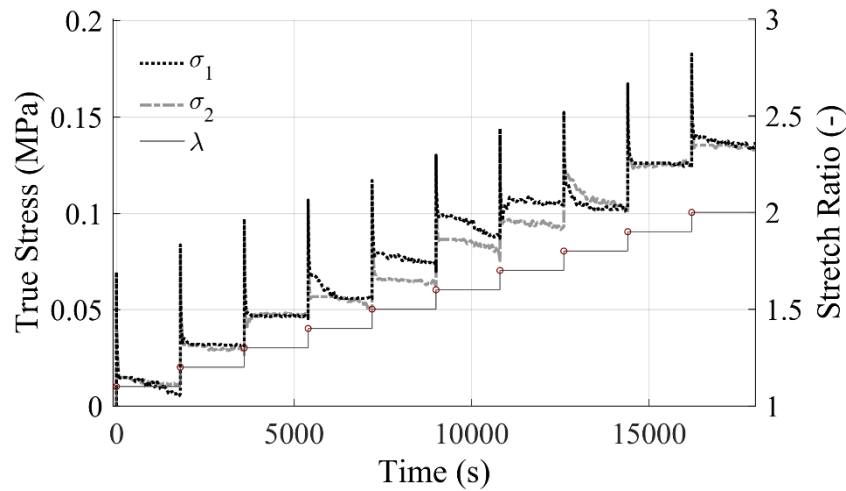


Figure 3.9: Biaxial tensile multi-step stress relaxation curve for VHB 4910 tape

Overall, the results of the single-step and multi-step relaxation tests both demonstrated trends that agree with typical time-dependant elastomeric behaviour, both in general and specific to findings in literature for VHB tapes under uniaxial tension. The stress-relaxation response was demonstrated through these experiments, and provided an overall stress-convergence time of 30 minutes or less. This data provides important information about the stress-relaxation response of both VHB tapes that could be applied to continuum based viscoelastic models, as discussed in literature. It also provides insight for design and manufacturing of VHB based devices. More specifically, it will help with the tape's biaxial pre-stretching, which has sometimes proven to be challenging due to VHB tape's tendency to tear when quickly extended to a desired stretch ratio.

3.2 Electro-Mechanical Property Testing

3.2.1 Equipment and experimental protocol

To characterize the VHB tapes electro-mechanically, a series of uniaxial tensile tests were performed at various biaxial stretch combinations. That is to say that the tapes were fixed at a predetermined lateral (width) stretch ratio, and elongated to various axial stretch ratios. For all future explanation, the axial direction of sample elongation will be referred to as λ_1 (i.e. x-axis in cartesian coordinates), and the lateral axis with respect to specimen elongation (width) will be referred to as λ_2 (i.e. y-axis). λ_3 will therefore be the thickness (or transverse axis) of the sample (i.e. z-axis). True biaxial electro-mechanical testing was unfeasible with the rakes. Their metal construction caused interference with the high voltages applied to the samples, and their small size did not allow for proper electrode application after mounting. The holes produced by the tines also created local defects in the DE that caused the samples to prematurely fail. In order to perform these tests with the CellScale BioTester, a set of 3D printed custom clamps (made of polylactide) were designed and retrofitted to the machine's actuator goosenecks. Their main structure can be seen in Figure 3.10.

These clamps consisted of independent top and bottom brackets (Figure 3.10 (a)) that were then joined by two machine screws and wing nuts. The connexion between the clamps and the goosenecks was achieved by creating a geometry that enveloped the hooks (Figure 3.10 (c)) that would otherwise house the rakes. A hole was made in the clamps, above the hook, to allow the

use of the BioTester's integrated magnet system, for additional support (Figure 3.10 (b) – Section view). A flange was also added to the base of the clamp, running parallel to the outer face of the goosenecks, to resist any inwards rotation during tensile testing. The surfaces of the brackets have been ribbed (along its width) in order to eliminate any slipping during experimentation. Full engineering drawings and specifications of the clamps can be seen in Appendix A.5.

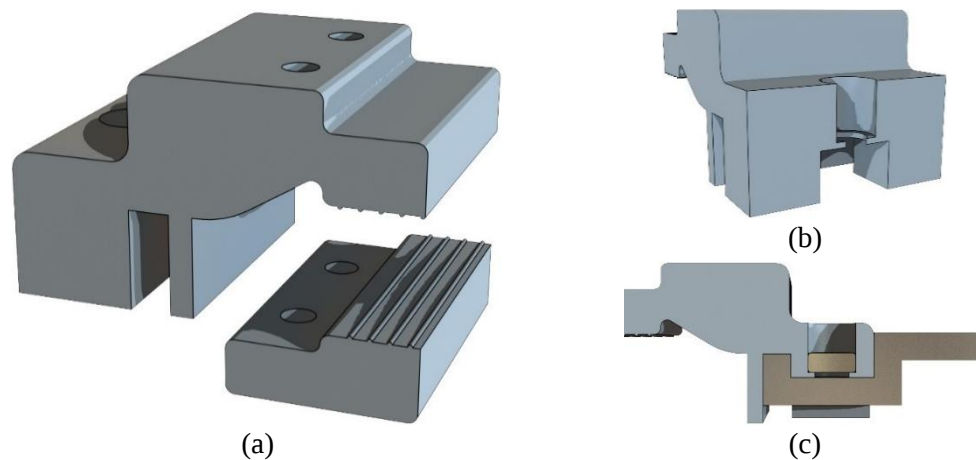


Figure 3.10: Rendering of custom clamps for biaxial testing machine
 (a) Side view of top and bottom clamp assembly,
 (b) back sectioned view demonstrating the cut-out for the gooseneck and magnet, and
 (c) side sectioned view with actuator's gooseneck and magnet

As previously explained in Chapter 2, VHB tapes require the application of electrodes on parallel surfaces in order to create the Maxwell stresses required for actuation. A common solution is to make use of conductive grease. This has been a popular alternative due to its inexpensive, off-the-shelf availability, its easy application, highly conductive nature, and proper compliance with the elastomer deformation. A carbon conductive grease by MG Chemicals (847-40G Carbon Conductive Assembly Paste [95]) was used for all experiments. The ready-made grease has a thick paste-like consistency, which affected the electrode's reliability during the experimental process. It was observed, during preliminary tests, that it had a tendency to clump up on the tape's surface, as well as dry up and flake off after long periods of time. This affected the electrode's evenness along the tape's surface, as well as created gaps between the electrode and the connection (to the voltage source) when the tape had stretched to large ratios. The grease was therefore diluted into a 3:1 solution of grease and motor oil, by weight, to decrease viscosity and maintain an even coating throughout each experiment.

To achieve a DC voltage of up to 5,000 V (which is the suggested limit in literature, to avoid elastomer wrinkling), a proportional step-up converter was utilized. The EMCO G50R DC to High Voltage DC (HVDC) converter was selected for its compact design, and maximum output capabilities. A summary of the converter's specifications, and input to output ratio are given in Table 3.1. It should be noted that, for all experimental data, ideal (lossless) conditions were assumed for the output of the converter. Voltage output from the power source was measured with a standard multimeter, and subsequently converted to the output high voltage using the ramp function derived from EMCO's specification sheet.



Figure 3.11: EMCO DC to HVDC converter [96]

Table 3.1: EMCO G50R DC to HVDC converter specifications [97]

Input Current (No Load)	<125 mA
Input Current (Full Load)	<300 mA
Output Voltage	0 to +/-5,000V
Output Current	0 to 0.3 mA
Ripple P-P	<2.0%
Output Voltage Ramp Function*	$V_{output} = \begin{cases} 0, & V_{in} < 0.7V \\ V_{in} \times 0.83, & V_{in} \geq 0.7V \end{cases}$

* (derived from graph provided by EMCO)

To filter the power supply output, a series of decoupling capacitors were added. These capacitors help suppress any high-frequency noise that could otherwise affect the components of the circuit, as well as the experimental data. The connection between the DC to HVDC converter and the electrode on the specimen was achieved using a combination of alligator clips and copper tape. The clips were clamped to one side of the copper strip, while the other side of the tape was connected to the electrode by painting the grease along its surface. Further details about this connection are described below, in the specimen preparation process. Figure 3.12 provides an illustration of the full experimental setup, including a closeup of the final sample assembly with electrodes in Figure 3.12 (b). A figure of the experimental circuit is depicted in Figure 3.13. Appropriate safety measures were taken throughout experimentation, to prevent any risk of electrical injury and equipment damage. All exposed connections and adjacent surfaces to the HVDC converter were covered with rubber sheets and electrical tape prior to testing. All metal components of the CellScale BioTester that came near the alligator clips were shielded by rubber sheets and electrical tape, to prevent any short circuiting of the load-cells.

Throughout experimentation, safety goggles and safety gloves (rated up to 12 kV) were worn, and all experiments were performed standing over an insulative switchboard mat (rated up to 17 kV).

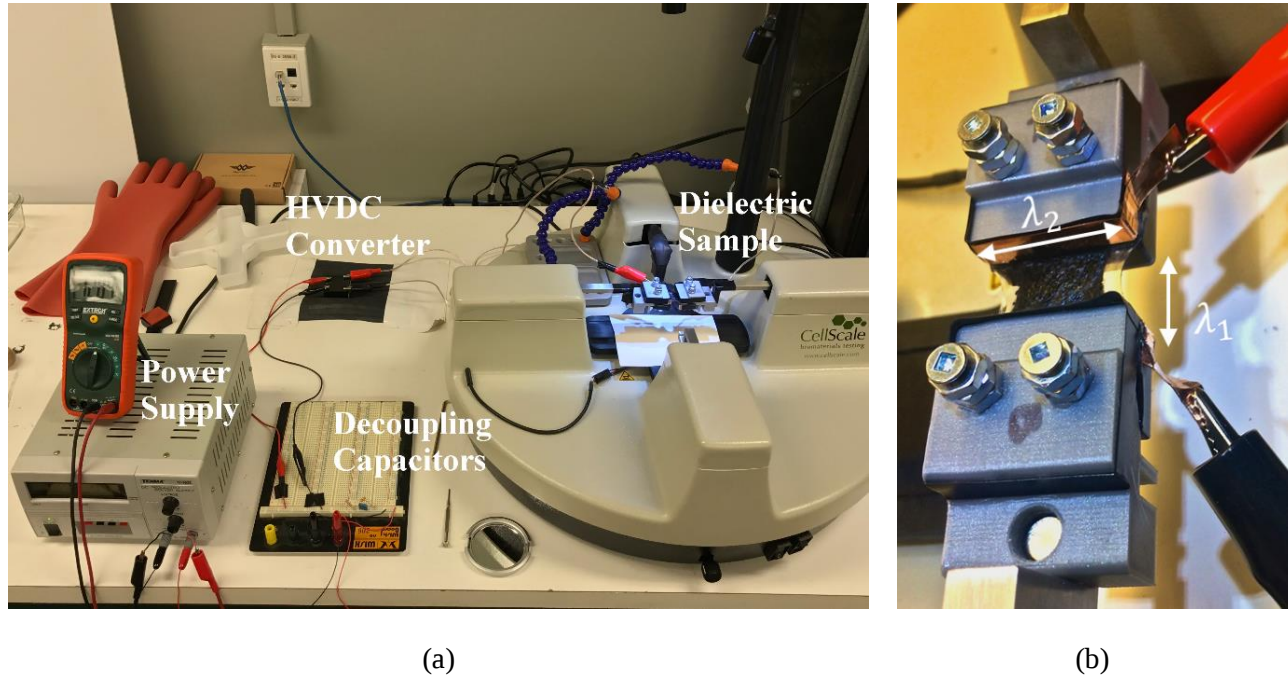


Figure 3.12: Uniaxial electro-mechanical experimental setup
(a) Power source, amplifying circuit and BioTester
(b) Closeup of sample and alligator clip connections

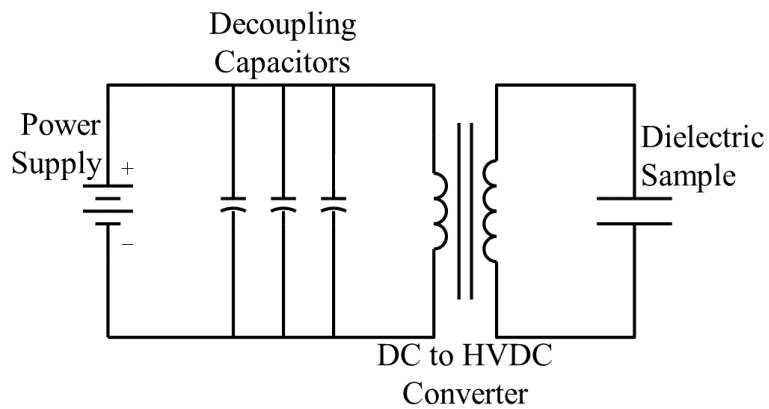


Figure 3.13: Electro-mechanical experimental circuit diagram

Samples tested were pre-stretched along the clamp's width (λ_2), at various fixed stretch ratios, in order to evaluate material electroactive behaviour for different parameter combinations. To accomplish this, tape samples were cut and manually stretched from an initial, pre-determined

width that would equate to the desired stretch-ratio based on clamp width dimensions. For example, knowing that the width of the clamps is of 30 mm, a VHB sample of 10 mm in width was cut and stretched to achieve a fixed pre-stretch of $\lambda_2 = 3$ (200% strain).

After several testing protocol iterations, a series of strategic preparation steps were rigorously developed and followed for the experimental setup in order to ensure sample consistency between experiments. It should be noted that the following was performed using nitrile powder-free gloves. This was done to ensure no finger grease was transmitted to any adhesion surfaces during the preparation process, which would otherwise greatly affect the proper binding of the samples. Clamp edges were first covered with a layer of electrical tape, followed by opposing copper-tape electrodes. Their inner-surfaces were then lined with a piece of VHB 4905 tape, to create an adequate bonding site for the samples. This also helped minimize any excessive compression or possible specimen damage during testing. Samples were then cut to size and stretched to the desired experimental stretch ratio using acrylic sheets as side-grips for stretching. Clamps were assembled and tightened using wing nuts. The unpainted samples were left to rest for 30 minutes in order to allow internal stresses to converge prior to testing. An illustration of a fully assembled unpainted sample is shown in Figure 3.14.

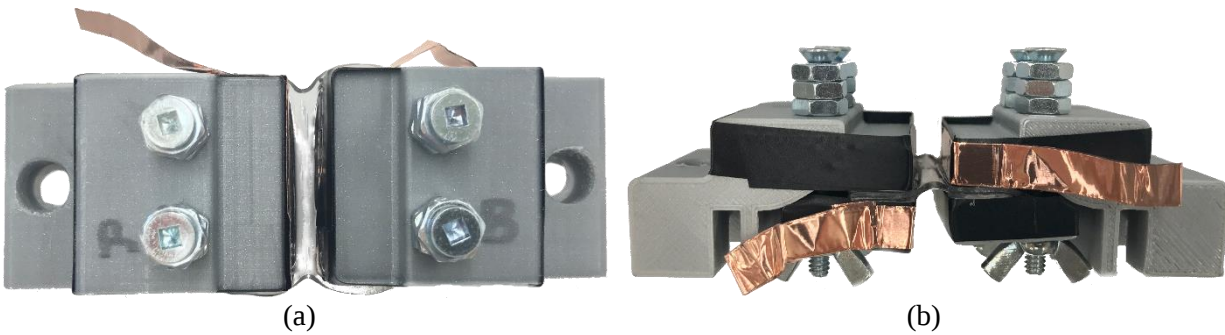


Figure 3.14: Fully assembled uniaxial electro-mechanical testing specimen (excluding grease electrodes)
(a) Top view, and (b) Side view with copper connection electrodes

The electrodes were then painted onto the surfaces of the sample using a fine-tipped paintbrush. The sample assembly required slight stretching during the painting process, due to the small-scale nature of the assembled experimental specimen. The electrode surface area covered the entirety of the VHB tape samples, with a 2-mm edged left unpainted on either of the free-standing edges. It was observed during experimentation that, if the electrodes were painted to the edge, the grease would eventually bleed over (while being extended) and make contact with the opposing surface.

This led to the breakdown of the material and failure of the experiment. The unpainted edge was therefore essential to the reliability of the experiments.

Due to the stretching of the specimen during the painting process, slight deformation of the membrane occurred, which led to the buckling of the film between the two clamps when brought back to $\lambda_1 = 1$. This led to grease smudging and possible contact between electrodes, which tarnished the sample prior to testing. To prevent this, all sample assemblies requiring an undeformed initial position were installed onto the machine at a stretch ratio of $\lambda_1 = 2$, and then slowly brought back to their original, un-stretched dimension using the BioTester's manually controlled Actuator Control jog arrows. A detailed description of all sample preparation steps can be found in Appendix A.6.

The image tracking software was ineffective for these experiments (which will be further explained in Section 3.2.2). The results therefore relied on the actuator positions recorded by the software. It was thus necessary to ensure that the gooseneck/clamp positions listed on the LabJoy software reflected their true relative distances. The 3D printed clamps used for these experiments were designed based on the dimensions taken from the gooseneck hooks and rake dimensions. Despite these considerations, the final shape of the clamps was slightly imperfect with respect to the CAD-specified dimensions. This is due to plastic swelling during printing and subsequent surface finishing procedures. Several measurements between the clamp faces were therefore taken and averaged, with the help of a Vernier caliper, to find that a clamp distance of 5 mm translated to a distance of 4.445 mm in the software. When manually bringing the specimens back to an un-stretched state, this discrepancy in positions was taken into consideration.

Two experiments were conducted on both VHB 4905 and 4910 tapes: multi-step isostrain incremental voltage testing, and load-unload electro-mechanical tensile testing. As was mentioned previously, experiments were uniaxial with a fixed pre-stretch in the lateral direction (λ_2). Three pre-stretched states were selected for each material: VHB 4905 tape was tested at $\lambda_2 = 1.5, 2$, and 2.5 pre-stretched sample states, whereas VHB 4910 tape was tested at pre-stretched states of $\lambda_2 = 2, 3$, and 4 . The difference in strains between the two tapes was selected based on their respective thicknesses. Since VHB 4905 tape's thickness is half that of VHB 4910 tape, its dielectric behaviour was assumed to also be active at half of the imposed parameters for VHB 4910 tape testing. Preliminary experimental investigation demonstrated that this was justified.

In fact, testing the VHB 4905 tape at similar stretch ratio conditions to VHB 4910 tape caused it to catastrophically fail (through dielectric breakdown) in almost every case. This observation therefore reinforced the correlation between dielectric activation and sample thickness.

The first test series performed were multi-step isostrain voltage application tests. Similar to the multi-step tests of Section 3.1.1, these experiments involved a 5-part stepwise stretch-hold sequence. Once the material had reached its converged relaxed stress state, the isostrain phase was followed by an incremental voltage application to the sample's electrodes. Each step began with a constant-stretch-rate elongation phase, with the machine's maximum displacement velocity of 10 mm/s. VHB 4905 tape samples were elongated in increments of 2.5 mm (i.e. $\delta\lambda_1 = +0.5$ increments), whereas VHB 4910 tape samples were elongated in increments of 5 mm (i.e. $\delta\lambda_1 = +1$ increments). Following the stretch phase, a hold phase of 30 mins was added, to allow for stress relaxation of the material. A voltage was then applied to the sample. The power supply was increased in 2-volt increments, starting from 4V, and ending at 12V. These voltages translate to an idealized amplified output voltage range of 1.7 kV to 5 kV applied to the specimen, based on manufacturer's specifications for the HVDC converter. The voltage application phase ended with a 0V-resting period, to allow the circuit to discharge prior to the next stretch phase. Each voltage application duration was set to 2 minutes, to allow enough time to increase the voltage on the power source between each step. This was also done to give sufficient time for the system to fully charge after each increment. Due to the power source's analog-knob type interface, precise voltages for each increment were difficult to achieve. With the use of a multimeter, the power source's output voltage was therefore measured for every increment. A voltage ranging between +0.00V and +0.04V of the desired value was accepted. The tape samples reached a final maximum stretch ratio of $\lambda_1 = 3.5$ for VHB 4905 tape, and $\lambda_1 = 6$ for VHB 4910 tape.

During the experiment, it was observed that the grease solution would sometimes shift slightly from the edges of the specimen, after it had relaxed to constant stress. To ensure proper connection throughout the experiment, the edges of the electrodes (that came into contact with their respective copper foil connection) were repainted at the end of the relaxation period.

The second series of experiments consisted of load-unload cyclical electro-mechanical tensile testing. These tests involved a constant-rate elongation phase, followed by a mirrored release phase. For each of these trials, a constant stretch rate of $\dot{\lambda}_1 = 0.050 \text{ s}^{-1}$ was selected as a common

parameter for all experiments. After preliminary testing, this rate seemed to provide a reasonable velocity whilst not exhibiting high risk of sample failure. Every configuration of λ_2 pre-stretched specimen ran through two experiments, for two separate (ideally identical) samples. The first involved a load-unload test with no voltage applied, and the second repeated the same test for a different sample with a voltage application of 5 kV. Tensile load-unloading was repeated 10 times for one trial. This cyclical testing was deemed necessary, as a preconditioning step of the experiment, to ensure comparison between the inactive and electrically active samples would be representative of their electro-mechanical behaviour rather than possible viscoelastic effects. As was mentioned in Chapter 2, the viscoelastic nature of the elastomer affects its load-unload consistency. If it is loaded cyclically, the peak stresses eventually converge to a consistent repeatable value, which provides a constant (converged) representation of the material behaviour. Allowing the stress curves to converge under cyclical loading therefore decreased the risk of experimental discrepancies between similar samples for comparison. In both cases, samples were started at a non-zero initial stretch ratio, due to a curling effect noticed during sample installation after painting. Starting at a zero position almost always led to premature breakdown of samples once the voltage was initially applied. This was due to strong interferences caused by the sample's inability to return to a flat configuration after having been stretched for electrode application. VHB 4905 tape was started at a position of $\lambda_1 = 1.5$, and VHB 4910 tape was started at of $\lambda_1 = 2$. Samples were brought to various peak maximum stretch ratios based on optimal conditions that will be discussed in Section 3.2.3.

It should be noted that, in the case of the samples undergoing cyclical load-unloading with no voltage, all steps described in Appendix A.6 were still followed. This was done to ensure consistency between the zero-voltage samples and the electrically active samples. Clamps were covered in electrical tape and copper electrodes. The specimens were also stretched to $\lambda_1 = 2$ for a 10-minute period in order to simulate the same straining of the sample during the painting process. No grease was applied, however, since it is assumed that the electrodes do not affect the mechanical behaviour of elastomer, due to the grease's high compliance. Manufacturing specification also quote a very high resistance to oils and greases [40], which confirms that the carbon grease electrodes will not greatly affect the molecular integrity of the VHB tapes during experimentation. Finally, alligator clips were also attached to the overhanging copper flap; however, no voltage was applied to the sample.

3.2.2 Data Processing

The displacement of the samples for the following experimental data was taken directly from the BioTester actuator readings. Image tracking was ineffective due to the dark, reflective surface created by the grease coating on the tape. In an attempt to create contrasting reference points on the sample's surface, corn starch was generously dusted on the grease prior to testing. Unfortunately, the tracking software was unable to find reference points with this technique. The powder also eventually dissolved within the grease, for tests performed over long periods of time. Future testing could potentially make use of a similar technique, using an insoluble white powder. Images would need to be processed to reduce grease reflectiveness. Their negatives would then need to be taken, in order to provide the LabJoy software with black reference points, rather than white. Alternatively, a different algorithm could be developed to track the white powder. Issues pertaining to grease-to-film relative motion would need to be taken into consideration.

A MATLAB code was written to plot the final data. Force versus stretch ratio of the samples were plotted, since the cross-section of each sample was inconsistent along its axis of elongation (due to the inward curves created by the pre-stretched configuration of the samples). Similar to the biaxial tensile testing, the data collected had a high level of noise, due to the load cell's sensitivity and movement of custom clamps on the goosenecks. All experimental data were therefore smoothed, to provide a more quantitative electro-mechanical behaviour of the VHB tapes.

3.2.3 Results

3.2.3.1 *Electro-Mechanical Multi-Step Isostrain Tests*

The first type of tests performed on both tapes was a series of stepwise stretch-relaxation tests, followed by an incremental voltage application to the sample. These tests were performed in order to characterize the material's static dielectric response under various stretch-ratio combinations. The purpose of these observations was to determine at which biaxial stretch ratio combination the largest drop in force would occur.

A visual representation of the concept behind this investigation can be seen in Figure 3.15. Considering a dielectric film that is in force equilibrium, under an isotonic uniaxial load (along axial direction - Figure 3.15 (a)). Upon activation of the electrodes, Maxwell stresses would induce a relaxation of the elastomer, thereby reducing its internal membrane tension. Assuming purely linear motion, a drop in this force would interrupt the equilibrium of the system, causing an

elongation of the elastomer (since now $F_{elastomer} < F_{external}$ - Figure 3.15 (b)). This elongation would progressively increase the tension within the elastomer, until new force equilibrium state is reached (Figure 3.15 (c)). Through this concept, it is evident that a larger drop in force, due to dielectric activation, would result in a larger displacement of the elastomer to reach a new state of equilibrium. Finding a biaxial stretch ratio combination, for which the drop of force along the x-axis is largest, is therefore of great interest when trying to optimize the elongation of a linear dielectric based actuator. This holds particularly true for the novel actuator sought through this thesis.

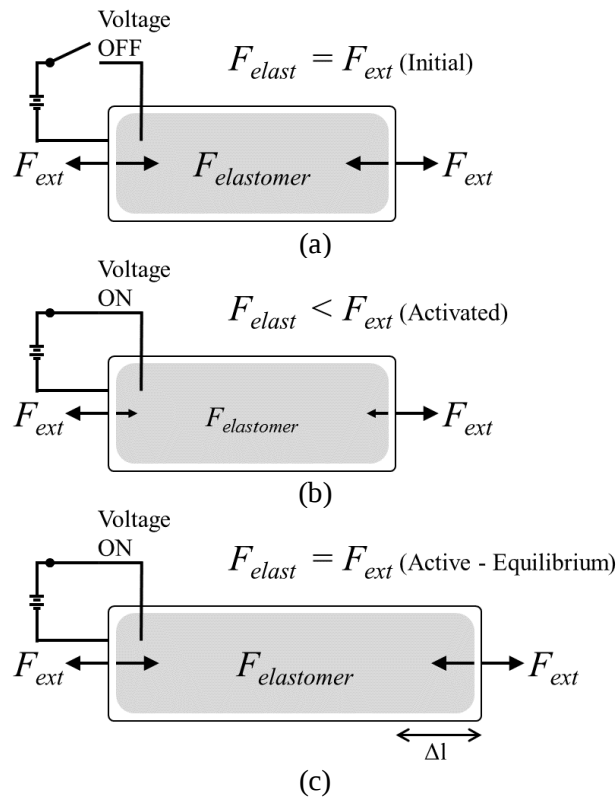


Figure 3.15: Theoretical actuation mechanism of DE film due to change in force equilibrium

In Chapter 2, Kofod [29] findings were presented, suggesting a performance plateau at a stretch ratio of $\lambda_1 = 4$. A very common combined biaxial stretch of $\lambda_1 = \lambda_2 = 4$ has been used for VHB 4910 tape based actuators in the literature. This biaxial stretch combination was therefore presumed as the optimal thickness threshold for dielectric actuation. Knowing that the effects of Maxwell stresses on the elastomer are directly related to the material's thickness, one can derive similar stretch ratio combinations equating to this optimal thickness. By utilizing the relationship

earlier described, thickness of the elongated sample h is equal to $h = \frac{H}{\lambda_1 \lambda_2}$. In other words, for VHB 4910 tape $\lambda_1 \times \lambda_2 = 16$. By this logic, the ratio combinations of cases applying to the present experimental parameters were derived as in Table 3.2. It should be noted that, for the reasons described in Section 3.2.1, optimal biaxial stretch ratios for VHB 4905 tape is considered half of that for VHB 4910 tape. In other words, for VHB 4905 tape $\varepsilon_{optimal} = (\varepsilon_x = \varepsilon_y) = 150\%$ (which translates into $\lambda_1 = \lambda_2 = 2.5$, keeping in mind that $\lambda = \varepsilon + 1$).

Table 3.2: Theoretically derived optimal biaxial stretch ratio combinations for dielectric activation

λ_2 (lateral)	λ_1 (axial)	
	VHB 4905	VHB 4910
1.5	4.17	10.7
2	3.13	8.0
2.5	2.50	6.4
3	2.08	5.3
3.5	1.79	4.6
4	1.56	4.0

In general, diminishing the thickness is expected to result in greater force drops for the isostrain experimental setup. This is due to the simple fact that a thinner elastomer sample, combined with increased Maxwell stresses should result in an overall greater electro-mechanical expansion. The inversely proportional relationship between Maxwell pressures and sample thickness was earlier illustrated in (2.1), where $p = \varepsilon_r \varepsilon_0 \left(\frac{V}{t}\right)^2$. It can be noted, however, that the suggested theoretical optimal combinations in Table 3.2 exceed the operational range recommended by Kofod [29] (where $3 \leq \lambda_1 \leq 5$ for VHB 4910 tape, and assumed $2 \leq \lambda_1 \leq 3$ for VHB 4905 tape – which is half that of VHB 4910 tape). Experiments were therefore kept within proximity of these suggested optimal ranges. The results of all experiments can be found in Appendix A.7.

An example of experimental data for a test performed on a sample of VHB 4910 tape at fixed width pre-stretch of $\lambda_2 = 3$ is shown in Figure 3.16. Each step is plotted separately, and the load-cell force readings are color coded in alternating black-grey sequence representing the voltage increment period (e.g. 4V, 6V, 8V, 10V, 12V, and 0V power-source output, respectively). It should be noted that these graphs also contain the transitional stages where voltage was increased

between each increment. In order to quantify the final force for each step, the MATLAB code computed the mean value for the middle $\frac{1}{3}$ of each portion of the curves. That is to say that, for each 2-minute voltage increment, the forces for the middle 40 seconds were averaged and considered as being the fully achieved activation.

In Figure 3.16, there is a clear decrease of force at every phase of the experiment. The majority of the steps also demonstrate a proportional relationship between the voltage applied and the force decrease. In some of the experiments, a reoccurring inconsistency occurred at the third step of the experiment (in this case at $\lambda_1 = 4$). Despite this fact, the final maximum voltage still induced an overall distinguishable force drop.

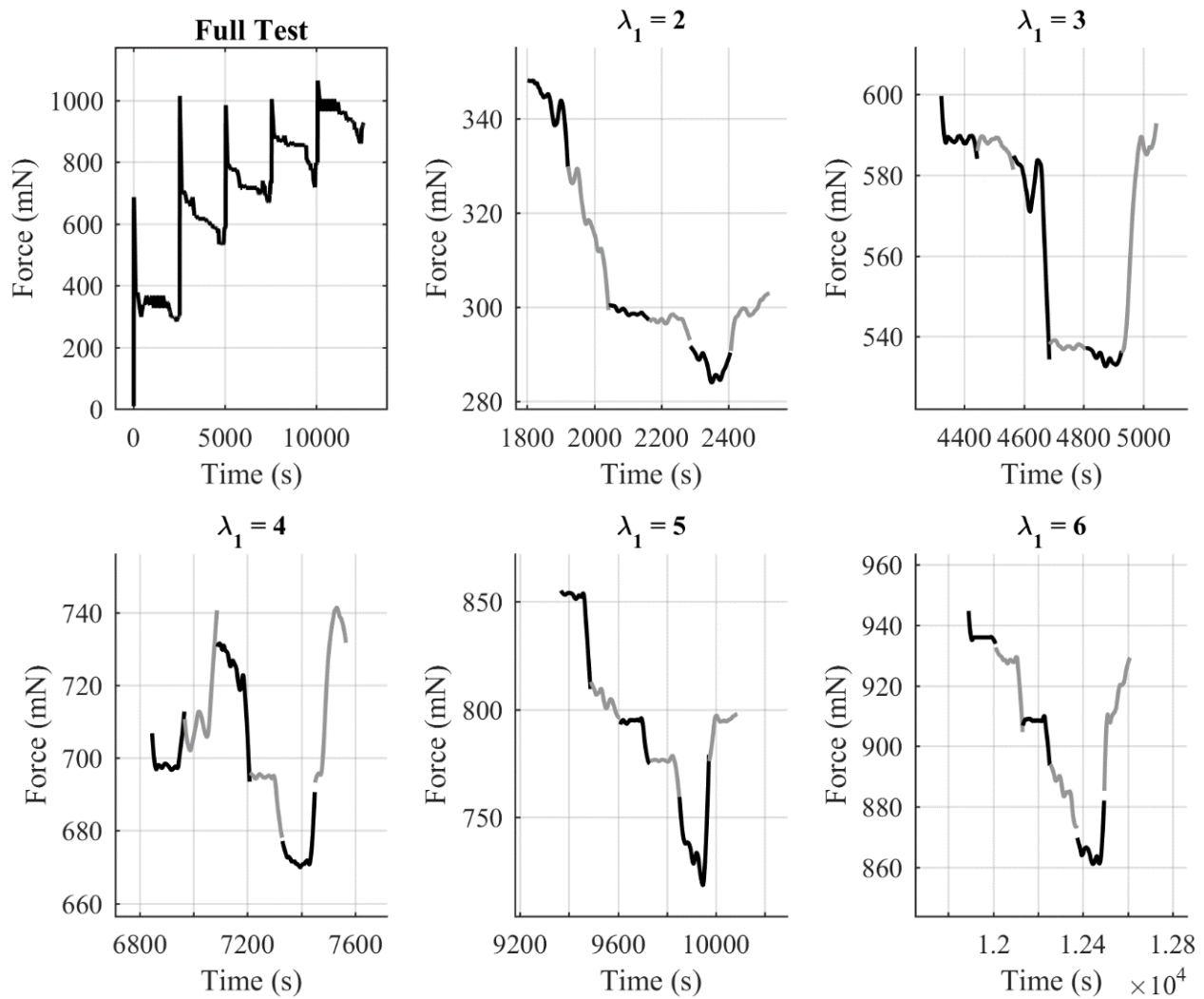


Figure 3.16: Multi-step isostrain electro-mechanical test for VHB 4910 tape at fixed $\lambda_2 = 3$

All other experiments demonstrated similar behaviour, where the maximum voltage output created the largest drop in force. Some irregularities were observed at the first step of the experiment. This was attributed to the fact that some samples were slightly curled during this initial phase, which meant that they were not in tension at the time of voltage application. The curling was a result of the stretching of the material while electrodes were being applied. For this reason, the values of force drop at the initial testing conditions for all samples were not considered to be representative.

The following Table 3.3 and Table 3.4 list the initial and final forces recorded for the steps of each experiment. The overall force drop is also displayed in both millinewtons as well as a percentage relative to the initial force. It can be seen that (excluding all first steps), in the majority of cases, a clear proportionality between sample thickness and force drop can be concluded. The values in some cases, however, do not differ greatly between each step, which suggests that the maximum force drop could be similar for two scenarios with biaxial stretch ratios that are close in magnitude. For example, VHB 4910 tape values for $\lambda_2 = 4$ seem to converge around the $3 \leq \lambda_1 \leq 5$, which fall in line with the predicted plateau-region performance peak of Kofod [29]. Certain discrepancies can be noted in various places, however, which do not seem to follow any specific trend. With the exception of VHB 4910 tape at $\lambda_2 = 4$, all other cases fall in line with the predicted optimal peak values specified in Table 3.2 (taking into consideration the limits imposed based on suggested experimental ranges previously discussed).

A final test was performed on VHB 4910 tape, where stretch ratios that exceeded the suggested operating range were applied. This experiment was performed to rule out the possibility that dielectric response of the elastomer was not affected by its strain-hardening, and was rather even higher when stretch ratios surpassed the recommended range. As can be seen from Table 3.5, although the maximum drop did not occur at the theoretical optimum, the other changes in forces decreased past that point, with the exception of the final value. This implies that over-stretching the elastomer beyond this point may have no benefits. In other words, it has surpassed the plateau region for optimum actuation. This is perhaps due to the elastomer being extended past a point of further deformability, as was suggested in the literature. That is to say that the stiffness within the elastomer has exceeded a point where it can further be compressed by external electromagnetic forces of the electrodes.

Table 3.3: Biaxial stretch ratio combination comparison for dielectric activation of VHB 4905 tape under isostrain condition

VHB 4905							
		$\lambda_2 = 1.5$		$\lambda_2 = 2$		$\lambda_2 = 2.5$	
λ_1	Stretch Ratio	Force (mN)	Force Drop (mN)	Force (mN)	Force Drop (mN)	Force (mN)	Force Drop (mN)
1.5	0 Volts	66		37		118	
	12 Volts	60.39	5.61 (8.50%)	26.87	10.13 (27.38%)	62.76	55.24 (46.40%)
2	0 Volts	325		330		278	
	12 Volts	282.46	42.54 (13.09%)	195.98	134.02 (40.61%)	155.86	122.14 (43.93%)
2.5	0 Volts	534		435		362	
	12 Volts	386.66	147.34 (27.59%)	324.17	110.83 (25.48%)	216.74	145.26 (40.13%)
3	0 Volts	594		509		382	
	12 Volts	474.25	119.75 (20.16%)	355.04	153.96 (30.25%)	314.74	67.26 (17.60%)
3.5	0 Volts	698		564			
	12 Volts	526.78	171.22 (24.53%)	388.41	175.59 (31.13%)		

Table 3.4: Biaxial stretch ratio combination comparison for dielectric activation of VHB 4910 tape under isostrain condition

VHB 4910							
		$\lambda_2 = 2$		$\lambda_2 = 3$		$\lambda_2 = 4$	
λ_1	Stretch Ratio	Force (mN)	Force Drop (mN)	Force (mN)	Force Drop (mN)	Force (mN)	Force Drop (mN)
2	0 Volts	346		348		319	
	12 Volts	278.38	67.62 (19.54%)	284.96	63.04 (18.11%)	306.76	12.24 (3.84%)
3	0 Volts	709		602		538	
	12 Volts	689.866	19.134 (2.70%)	533.24	68.76 (11.42%)	476.15	61.85 (11.50%)
4	0 Volts	933		717		668	
	12 Volts	853.35	79.65 (8.54%)	670.63	46.37 (6.47%)	589.00	79 (11.83%)
5	0 Volts	1063		856		742	
	12 Volts	994.65	68.35 (6.43%)	725.03	130.97 (15.30%)	672.20	69.8 (9.41%)
6	0 Volts	1247		936		872	
	12 Volts	1107.88	139.12 (11.16%)	861.88	74.12 (7.62%)	715.29	156.71 (17.97%)

Overall, this series of experiments demonstrated an evident static dielectric response of the VHB tapes at all stretch ratio combinations. The observed force-drop demonstrated a proportionality to reduction in thickness, with reasonable agreement to the optimal stretch ratio combinations suggested above. Due to the small variations seen in some tests, further investigation would be necessary to confirm the repeatability of these results. These trends will be taken into consideration and further investigated during the prototype development in Chapter 5.

Table 3.5: Biaxial stretch ratio combination comparison for dielectric activation of VHB 4910 (over-stretched)

VHB 4910			
$\lambda_2 = 3$			
λ_1	Stretch Ratio	Force (mN)	Force Drop (mN)
4	0 Volts	874	158.33 (18.12%)
	12 Volts	715.67	
5	0 Volts	978	107.14 (10.96%)
	12 Volts	870.86	
6	0 Volts	1073	89.55 (8.35%)
	12 Volts	983.45	
7	0 Volts	1127.5	36.13 (3.20%)
	12 Volts	1091.37	
8	0 Volts	1381	124.01 (8.98%)
	12 Volts	1256.99	

Several factors involving the limitations of the current testing setup have been taken into consideration as possible causes for experimental discrepancies. Perhaps the most contributing issue during experimentation involved the sample's edge deformation due to the free boundaries. The clamped experimental setup induced inward bowing along the membrane plane (i.e. x-y plane), which resulted in an unevenly distributed biaxially strain geometry. This greatly affected the experiment's ability to produce representative results based on the ideal experimental stretch ratio combinations. However, this was a limitation of the current experimental apparatus. Due to their metallic construct, the rakes were deemed unsafe to use next to such high voltages. Piercing the dielectric film also generally induces premature dielectric breakdown, which would prove very challenging for testing. In future experiments, it would be favourable to use a biaxial clamping system, with a cruciform specimen. This would enable the specimen to properly be stretched along both planar axes, while not interfering with the electrostatic charges of the electrodes. This clamping method would also provide a consistent biaxial strain along the entirety of the sample.

Further inconsistencies involving variable sample sizes may have also caused inaccuracies in final data. As was mentioned earlier, extra care was taken to ensure sample dimensions and pre-stretch application were as consistent as possible. Due to the very small nature of the samples, it is clear that greater risk of human error was present and may have caused inaccuracies in specimen assembly. This was also a challenge with regards to the application of the electrodes.

Despite attempting to apply a consistent geometry for all samples, it was nearly impossible to replicate exact electrode shape. This changed the surface area that applies Maxwell stresses onto the membrane, which would ultimately affect its “relaxing” effects. In general terms, both of these variations would typically be considered marginal. In the current experimental setup, however, the slightest changes in sample and electrode geometries can have substantial impact on the final data due to its small-scale nature.

High failure rates of these experiments (on the order of 1 success to 5 failures) led to the selection of a single experiment per configuration. In future research, it would be favourable to repeat these experiments multiple times to provide statistical significance to the results. This would allow the calculation of standard deviation, and therefore illustrate the consistency of this experimental procedure. Alternatively, the experiments could be conducted on a much larger scale. This would reduce the impact of the aforementioned variables, as their relative effects would have been substantially diminished with respect to the overall scale of the specimen.

3.2.3.2 Electro-Mechanical Load-Unload Cyclical Testing

The second type of tests performed on both tapes was a series of electro-mechanical load-unload cyclical tests. These tests were performed at various width (λ_2) pre-stretch ratios, in order to characterize the material’s dynamic dielectric response under various stretch ratio combinations. All results for these experiments can be found in Appendix A.7.

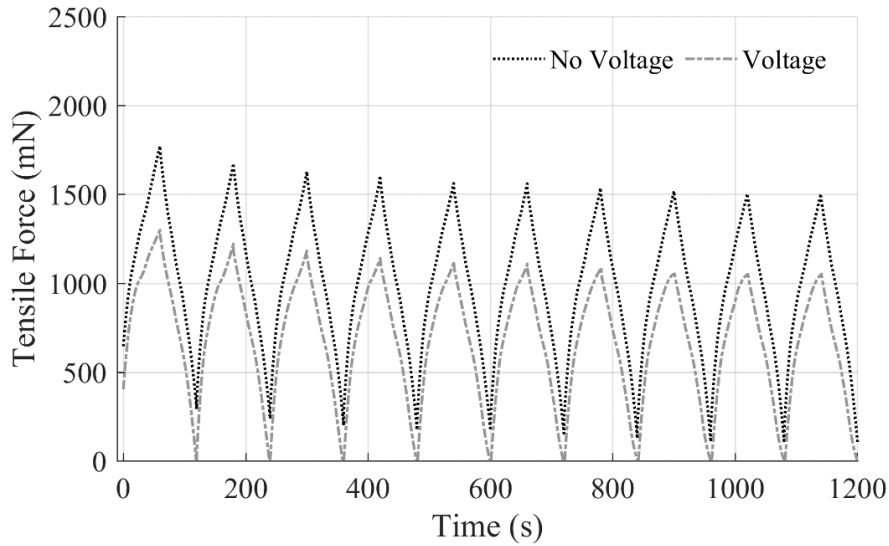


Figure 3.17: Cyclical electro-mechanical load-unload test for VHB 4910 tape at fixed $\lambda_2 = 3$ for $2 \leq \lambda_1 \leq 5$

The purpose of the cyclical testing was to allow the viscoelastic mechanical behaviour to converge prior to the analysis of the force-displacement response. As described in Section 2.3.2, the geometry of elastomer's load-unload curve will gradually diminish when submitted to cyclical tensile tests, due to material softening. As can be seen in Figure 3.17, over a period of 10 cycles, the forces converge to an accepted state of reproducibility. For the results of this section, only the last cycle is considered.

Examples of experimental data for a test performed on a sample of VHB 4910 tape at fixed width pre-stretch of $\lambda_2 = 3$, with a stretch range of $2 \leq \lambda_1 \leq 4$ is shown in Figure 3.18 (a). It can be observed that there is a clear shift of the hysteresis loop between the mechanical and electro-mechanically coupled conditions. Since the experimental setup did not allow for the test to begin at a stretch ratio of $\lambda_1 = 1$, no conclusions can be drawn regarding the point at which the electromagnetic forces take effect. It is clear from the results, however, that it has already affected the tape's dynamic response after $\lambda_1 = 2$. By also observing the geometry of the curve of the loading portion, it can be seen that there is a slight increase in slope curvature, with respect to the no-voltage curve. This can be explained by the simple fact that, as the loading occurs, the tape becomes thinner, which increases the applied Maxwell pressures on the film. It should be noted, however, that there doesn't seem to be a significant change in the overall energy dissipation of the polymer due to electro-mechanical coupling. The hysteresis loop remains within the same order of magnitude. This implies that the applied Maxwell stresses have no effect on the viscoelastic behaviour of the material, and is supported by the fact that the material is, in theory, remaining molecularly unchanged despite being electro-activated. It is simply being further compressed by the presence of opposing electrodes, which should have no discernable effects on its intrinsic material properties.

To compare the force variations due to electro-mechanical coupling, relative to the overall deformation of the film, a second series of tests was performed where samples were extended to stretch ratios reflecting the theorized optimal combinations (previously listed in Table 3.2), keeping in line with the suggested operational range. Figure 3.18 (b) provides a comparison to the previous curve, where a VHB 4910 tape sample at a fixed width pre-stretch of $\lambda_2 = 3$ was elongated within a range of $2 \leq \lambda_1 \leq 5_{(optimal)}$. As can be seen in the plot, there is a noticeable change in force variation between the mechanical and electro-mechanical conditions when

increasing the total elongation. For all cases of this nature, the gap between the peak values was larger when the elongation reached the greater stretch ratio combinations (compared to the cases where the samples were stretched to a smaller value). It can also be seen that the slope of the loading curve demonstrates a proportionally greater decay in those cases. This can be explained by the same logic as before, that the effects of electro-mechanical coupling are increased due to a smaller achieved thickness from greater elongation.

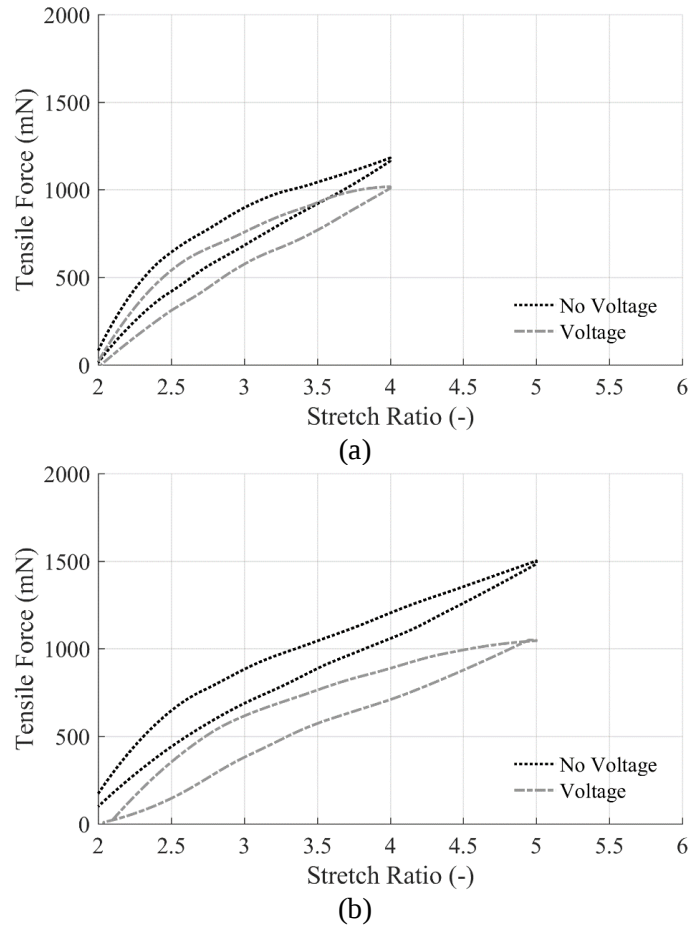
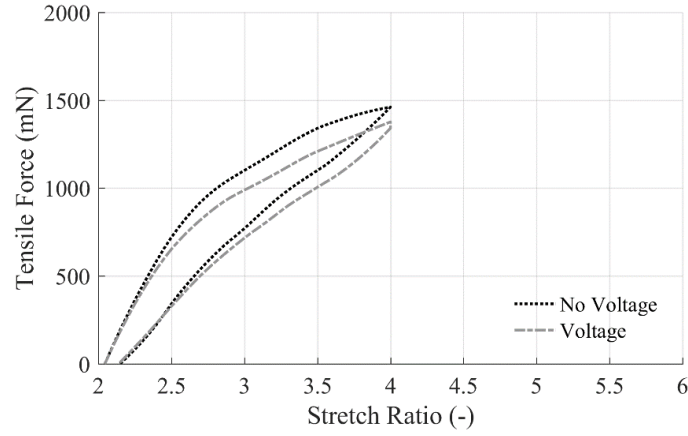


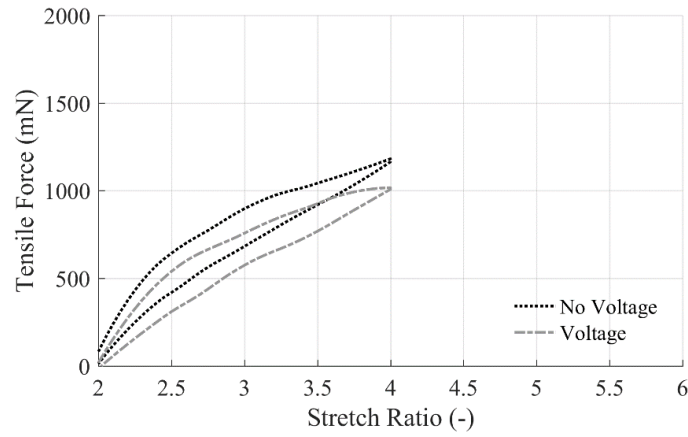
Figure 3.18: Comparison of electro-mechanical load-unload curves for various elongations of VHB 4910 tape at fixed $\lambda_2 = 3$ for (a) $2 \leq \lambda_1 \leq 4$ and (b) $2 \leq \lambda_1 \leq 5$

The dynamic dielectric response of the tapes also demonstrated a variation depending on the fixed lateral (λ_2) pre-stretch ratio along the y-axis. As can be seen in Figure 3.19, the difference in forces for each scenario is larger as the width pre-stretch increases. This type of behaviour is in agreement with the previous two examples, in that the dielectric activation of the film is inversely proportional to the film thickness. By applying a greater pre-stretch, the thickness of the tape

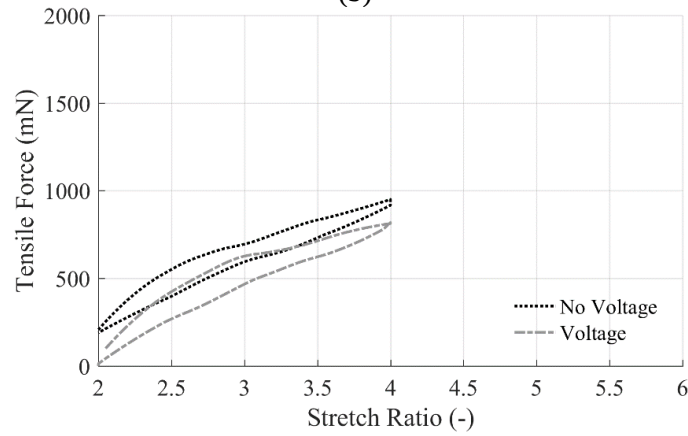
begins at a smaller initial value. This leads to a greater thinning of the elastomer during the axial (λ_1) elongation, which results in a larger application of Maxwell stresses on the DE.



(a)



(b)



(c)

Figure 3.19: Comparison of electro-mechanical load-unload curves for various fixed width stretch ratio of VHB 4910 tape at $2 \leq \lambda_1 \leq 4$ for (a) $\lambda_2 = 2$, (b) $\lambda_2 = 3$, and (c) $\lambda_2 = 4$

It should be noticed that, in spite of the offset of the curves in the cases of $\lambda_2 = 3$ (Figure 3.19 (b)) and $\lambda_2 = 4$ (Figure 3.19 (c)), the difference in peak stress values are not as considerable in comparison to the case of $\lambda_2 = 2$ (Figure 3.19 (a)). This may be explained by the earlier discussed concept of the plateau region (in Section 2.3.3). When nearing this region of the elastomer's tensile properties, the material's stiffness will reach a fulcrum resulting in similar electro-mechanical properties.

Overall, this series of experiments demonstrated a clear dynamic electro-mechanical response of the material, under various stretch ratio combinations. The change in loading curve values was evident in all cases, and also demonstrated a proportional drop when increasing the stretch ratios to their hypothesised optimal combinations. These observations, along with the ones from the previous sections, will be taken into consideration during the prototype development.

Similar to the experiments for static electro-mechanical tests, several discrepancies in the experimental process may have affected the accuracy of the data. Problems involving inconsistent sample cross-sectional area due to unfavourable lateral deformation were present for these samples. This was again due to the current clamped experimental configuration, which left the lateral edges free to bow inwards. Variations in sample and electrode geometries may have also played a role in the differences of results. In this case specifically, the comparative samples for baseline mechanical and activated electro-mechanical tests were not identical. This may have led to differences in the tensile mechanical behaviour between the samples, irrespective of the dielectric activation. Due to the cyclical nature of the current experiments, grease electrodes tended to crumble and flake after the first several loading cycles. This, along with the difficult task of applying a voltage manually at a specific point in an experimental process, prevented the same sample from being used for both mechanical and electro-mechanical testing. In future experiments, a sturdier type electrode would allow the same sample to be used, mitigating any variations in specimen sizes. It would also be of great value to integrate a computer-controlled voltage application mechanism, through the incorporation of a micro-processor. This would allow the voltage application to be both timed and precise, increasing experimental accuracy. The automation of voltage application for both isostrain and dynamic experiments of this chapter would ensure that activation was properly synchronized with the experimental protocol. It would also remove the risk of human error due to the analog knob on the power supply.

CHAPTER 4

Dielectric Elastomer Constitutive Modelling

An imperative step for designing an actuator based on smart materials is to characterize these materials constitutively. This will provide the essential foundation for the development of design parameters and help to predict the behaviour of the proposed actuator. The following chapter will thus present a constitutive visco-hyperelastic model to characterize VHB tapes from a mechanical perspective. The model presented will first be validated from a uniaxial tensile perspective, and subsequently extended to a biaxial experimental condition.

4.1 Mechanical Model

The model proposed by Wang et al. [62] is a visco-hyperelastic constitutive model based on an enhanced Kelvin-Voigt model, as shown in Figure 4.1. The spring-damper element model was first proposed by Lochmatter et al. [61] as a suitable general description of VHB tape's characteristic viscoelastic mechanical behaviour.

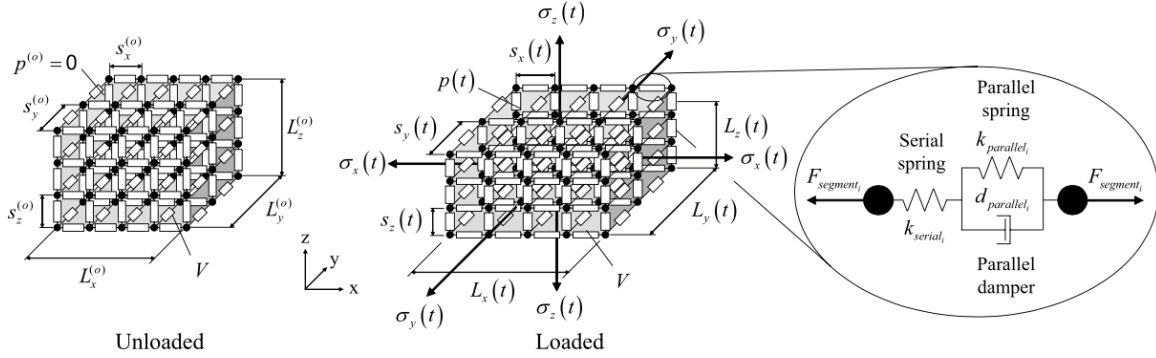


Figure 4.1: Representation of dielectric elastomer model and enhanced Kelvin-Voigt element [61]

In the model illustration, it can be seen that the polymer is analyzed within a three-dimensional micro-level framework. The film is divided into cuboid elements, each consisting of individual segments comprised of an enhanced Kelvin-Voigt element. This element is comprised of a serial spring of stiffness k_s , and a parallel spring-damper element with coefficients of k_p and d_p respectively. The cuboids are further described as being filled with an incompressible fluid, which will exert a hydrostatic pressure p on their walls when deformed. The combination of the segments' spring-damper configuration and the incompressible fluidic cuboid cores ensure that the model represents VHB's visco-hyperelastic properties in all three principal directions. It additionally ensures the mechanical coupling of the spatial deformation due to incompressibility. Three main assumptions are made for this model:

- The segments of the cuboid elements are mass-free, which implies a neglect of internal wave propagation
- The cuboid geometry is maintained under deformation, which is a requirement for laterally compliant boundary conditions
- Only uniformly distributed normal loads are considered, discounting all shearing effects

The film is broken down into a large number of N_i segments (i.e. $N_i \gg 1$), where $i = 1, 2, 3$ (or x, y, z). The sample's global dimensions are represented by $L_i^{(0)}$ and L_i , as the initial (undeformed) and final deformed lengths respectively, in all three directions of space. Similarly, each cuboid's dimensions are represented as initial and deformed lengths $s_i^{(0)}$ and s_i . When loaded, the net true stresses exerted on the film can be derived across the cuboid walls, and expressed as:

$$\sigma_i = \lambda_i \sigma_{system_i} - p, \quad i = 1, 2, 3 \quad (4.1)$$

where λ_i is the stretch ratio of the deformed geometry, defined by $\lambda_i = L_i/L_i^{(0)}$. Under the assumption that deformation of coaxial segments of all cuboids is equal, this implies that $\lambda_i = s_i/s_i^{(0)}$ as well. σ_{system_i} are the nominal (or “engineering”) stresses of the spring-damper segments of the uncoupled frameworks, and p is the previously mentioned hydrostatic pressure exerted on the cuboid walls.

Based on the enhanced Kelvin-Voigt model presented in Figure 4.1, the spring-damper element's modulus can be expressed as a single equivalent parameter:

$$E_{eq_i} = \frac{E_{s_i} \left(E_{p_i} + D_{p_i} \frac{d}{dt} \right)}{\left(E_{s_i} + E_{p_i} \right) + D_{p_i} \frac{d}{dt}}, \quad i = 1, 2, 3 \quad (4.2)$$

where (with respect to the stiffness and damping coefficients k_{s_i} , k_{p_i} , and d_{p_i} for segment in direction i) the serial modulus of elasticity, and parallel moduli of elasticity and viscosity-loss are $E_{s_i} = k_{s_i}/s_i^{(0)}$, $E_{p_i} = k_{p_i}/s_i^{(0)}$, and $D_{p_i} = d_{p_i}/s_i^{(0)}$ respectively. Lastly, d/dt represents the differential operator with respect to time. By observing this equivalent modulus, it can be assumed that E_{eq_i} does not depend on the number of segments or the geometry and dimensions of the film, which thereby implies that it directly reflects the material's inherent mechanical property.

To provide a more explicit physical representation of the material's dynamic response, the current model is expressed in the frequency domain as a complex modulus. Letting $d/dt = j\omega$ in (4.2), the new complex modulus can be expressed as:

$$E_{eq_i}^* = \frac{E_{s_i}(E_{p_i} + j\omega_i D_{p_i})}{(E_{s_i} + E_{p_i}) + j\omega_i D_{p_i}}, \quad i = 1, 2, 3 \quad (4.3)$$

where ω_i is the angular frequency of the alternating stress (or strain) applied to the system, in direction i .

The use of an angular frequency implies that the material undergoes harmonic motion. This type of movement control is difficult to perfectly achieve in experimental conditions. To simplify the experimental conditions, the material was tested through a rudimentary ramp load-unload tensile test (uniaxially or biaxially), at a constant stretch rate. This uniform motion is then approximated to be the first half-cycle of the harmonic motion, as can be seen in Figure 4.2.

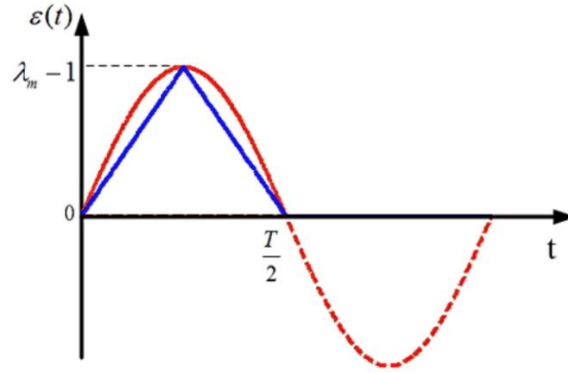


Figure 4.2: Approximation of harmonic motion based on uniform tensile motion [62]

Based on this approximation, the experimental angular frequency can be expressed as:

$$\omega_i = \frac{2\pi}{T_i} \approx \frac{\pi \dot{\lambda}_i}{2(\lambda_{m_i} - 1)}, \quad i = 1, 2, 3 \quad (4.4)$$

where $\dot{\lambda}_i = d\lambda_i/dt$ is the stretch rate, and λ_{m_i} is the maximum achieved stretch ratio during the cycle.

Finally, the system's nominal stress σ_{system_i} in each direction can be represented as:

$$\sigma_{system_i} = E_{eq_i}^* \varepsilon_i = E_{eq_i}^* (\lambda_i - 1), \quad i = 1, 2, 3 \quad (4.5)$$

where ε_i is the strain in direction i .

For the case where the strains are both periodically and dynamically changing based on time and angular frequency, ε_i can be expressed as $\varepsilon_i = \varepsilon_{m_i} e^{j\omega t}$ (or $\varepsilon_i = \varepsilon_{m_i} \sin(\omega t)$) where ε_{m_i} is the strain amplitude. Applying this relationship to (4.5), under the assumption that the stresses and strains vary at the same frequency, with a certain phase shift δ_i , the nominal stresses can then be expressed as:

$$\sigma_{system_i} = |E_{eq_i}^*| \varepsilon_{m_i} e^{j(\omega_i t + \delta_i)}, \quad i = 1, 2, 3 \quad (4.6)$$

where $|E_{eq_i}^*|$ is the magnitude of the complex modulus (i.e. the absolute modulus), and δ_i denotes the lag angle of the strain relative to the stress. Through general conventions for complex numbers, the absolute modulus can be expressed as:

$$|E_{eq_i}^*| = \frac{|E_{s_i}(E_{p_i} + j\omega_i D_{p_i})|}{|(E_{s_i} + E_{p_i}) + j\omega_i D_{p_i}|}$$

$$|E_{eq_i}^*| = \frac{E_{s_i} \sqrt{(E_{p_i}^2 + \omega_i^2 D_{p_i}^2)}}{\sqrt{(E_{s_i} + E_{p_i})^2 + \omega_i^2 D_{p_i}^2}}, \quad i = 1, 2, 3 \quad (4.7)$$

The variable η is a measure of a viscoelastic material's intrinsic damping property, which is defined by the ratio between the imaginary and real parts of the complex modulus [97]. This value can be used to illustrate the internal energy dissipation of the elastomer. From this, the lag angle is derived as:

$$\delta_i = \arctan \eta_i = \arctan \frac{\text{Im}[E_{eq_i}^*]}{\text{Re}[E_{eq_i}^*]}$$

$$\delta_i = \arctan \left(\frac{E_{s_i}^2 D_{p_i} \omega_i}{E_{s_i}^2 E_{p_i} + E_{s_i} E_{p_i}^2 + E_{s_i} D_{p_i}^2 \omega_i^2} \right), \quad i = 1, 2, 3 \quad (4.8)$$

The lag angle δ_i creates a phase shift between the stress and the strain of the system. This shift in the otherwise overlapping curves will create the enclosed hysteresis curve, which will represent the expected mechanical response of a viscoelastic material. The area under the loop will demonstrate the internal energy dissipation of the elastomer. A representation of the lag between the stress and strain of a load-unload tensile test (i.e. a half-cycle of a sinusoidal harmonic motion)

is illustrated in Figure 4.3. Having derived these equations, the parameters of (4.7) can now be determined by fitting the model to experimental data. It will then be possible to analyze the dynamic behavior of the DE film quantitatively, at various stretch rates.

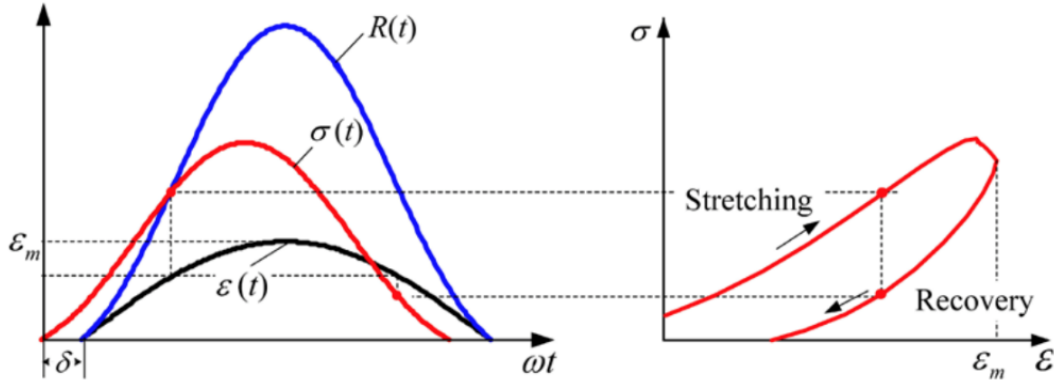


Figure 4.3: Stress-strain curve relationship in load-unload tensile testing: lag angle representation and resulting hysteresis loop [62]

4.2 Uniaxial Consideration

Under uniaxial tensile loading, the film is being elongated along a single axis. This implies free boundary conditions along the other two axes. For the case presented, the axis of elongation will be taken along $i = 1$ (x-axis). Since the material will only be characterized along this direction, an additional assumption of isotropy will need to be made. In other words, the moduli of elasticity and viscosity loss can be expressed uniformly as $E_{s_i} := E_s$, $E_{p_i} := E_p$, and $D_{p_i} := D_p$, and it will then follow that the dynamic complex modulus $E_{eq_i}^* := E_{eq}^*$ for $i = 1, 2, 3$. Assuming an ideal uniaxial tension along direction $i = 1$, the true stress from (4.1) can be expressed as:

$$\sigma_1 = \lambda_1 \sigma_{system_1} - p = \sigma_{ext} \quad (4.9)$$

where σ_{ext} is the external load applied to the system, at a stretch ratio of λ_1 . Since the two other axes have free boundary conditions, their true stresses will necessarily be zero, (i.e. $\sigma_2 = \sigma_3 = 0$). It follows that the net stress equations for both axes must also be equal to zero:

$$\sigma_i = \lambda_i \sigma_{system_i} - p = 0, \quad i = 2, 3 \quad (4.10)$$

It is known that, from the incompressibility condition, $\lambda_1\lambda_2\lambda_3 = 1$ throughout any deformation of the film. In the present case of uniaxial loading $\lambda_2 = \lambda_3$, which will result in a relationship between the three axes of $\lambda_2 = \lambda_3 = \lambda_1^{-1/2}$. The mechanical deformations for all three directions are coupled by the hydrostatic pressure p . Using (4.10), in conjunction with the newly found stretch ratio relationship, the pressure is expressed in terms of λ_1 :

$$p = \frac{\sigma_{system_i}}{\lambda_1^{-1/2}}, \quad i = 2, 3 \quad (4.11)$$

Taking the value of σ_{system_i} from (4.5), p can be further developed as:

$$p = \frac{E_{eq}^*(\lambda_i - 1)}{\lambda_1^{-1/2}} = \frac{E_{eq}^*(\lambda_1^{-1/2} - 1)}{\lambda_1^{-1/2}}, \quad i = 2, 3$$

$$p = E_{eq}^*(\lambda_1^{-1} - \lambda_1^{-1/2}) \quad (4.12)$$

Finally, taking the same equation to find σ_{system_1} in (4.9), and equating the hydrostatic pressures for $i = 1$ and $i = 2$ (or 3), yields to the final expression for stress along axis of deformation:

$$p = E_{eq}^*(\lambda_1^{-1} - \lambda_1^{-1/2}) = E_{eq}^*(\lambda_1^2 - \lambda_1) - \sigma_1$$

$$\sigma_1 = E_{eq}^*(\lambda_1^2 - \lambda_1 - \lambda_1^{-1} + \lambda_1^{-1/2}) \quad (4.13)$$

The strain of the system, in the direction of uniaxial deformation, will change over time, and can thus be expressed as

$$\varepsilon_1(t) = \lambda_1(t) - 1 = \varepsilon_m e^{j\omega t} \quad (4.14)$$

and the system's equivalent stretch ratio, considering the coupling of all three directions, can be synthesized as

$$R(t) = \lambda_1(t)^2 - \lambda_1(t) - \lambda_1(t)^{-1} + \lambda_1(t)^{-1/2} \quad (4.15)$$

Then, (4.13) can be expressed in terms of time:

$$\sigma_1(t) = E_{eq}^* R(t) = |E_{eq}^*| e^{j\delta} \cdot R(t) \quad (4.16)$$

In order to correlate the experimental values to this equation, only the variables' sizes are considered, such that:

$$|\sigma_1| = |E_{eq}^*| (\lambda_1^2 - \lambda_1 - \lambda_1^{-1} + \lambda_1^{-1/2}) \quad (4.17)$$

This equation can now be fitted to the experimental data, which represents the absolute sizes of the stress and stretch ratios under continuous changes.

4.2.1 Method

To characterize both tapes with the proposed model, a series of uniaxial tests were performed. As with the biaxial tests, discussed in Chapter 3, six stretch rates were selected as experimental parameters: $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$, 0.050 s^{-1} , 0.075 s^{-1} , 0.100 s^{-1} , 0.200 s^{-1} , and 0.300 s^{-1} . In all cases, the sample was stretched to a maximum ratio of $\lambda_{max} = 7$, and each stretch rate was repeated for 5 experiments in order to provide more statistically significant data.

The tests were performed using the same CellScale BioTester tensile machine, equipped with the custom clamps used in Section 3.2. Methods similar to the electro-mechanical experiments were used. The inner surfaces of the clamps were first lined with VHB 4905 tape. The clamps were then set to a 5-mm distance from each other, in the bench vice, using both a ruler, and acrylic spacer. Strips of 10 mm wide elastomer were then cut and carefully placed centered to the clamps' widths, ensuring that their edges were parallel to those of the clamps' outer edge. Clamps were then assembled, tightened, and installed on the actuator goosenecks.

Displacements were taken from the actuator position values in the experimental outputs, rather than using the image tracking. Despite adjusting camera settings and lens fittings, the output images did not provide sufficiently precise photos. This led to large discrepancies in the surface reference markers (carbon powder), and rendered the images impossible to analyze for deformations.

A MATLAB code was developed to process the experimental data. Using the equations previously derived in this section, in combination with preprogrammed sub-functions within the MATLAB

interface, the experimental data was fitted to the uniaxial model using the Levenberg-Marquardt (L-M) method. This first round of optimization provided the individual experiments' dynamic moduli with respect to their independent angular frequencies. A second optimization was then run in order to find global parameters for the materials. In this second round, also using the L-M method, the individual angular frequencies were related to their respective complex moduli by finding a set of constants for all cases. This yielded a set of final parameters that apply to all stretch-rates for the materials.

The program contains 6 general steps, as seen in Figure 4.4. Steps 0, 3 and 6 are confined within the main function of the program, whereas steps 1, 2, 4, and 5 are contained in separate functions that are called from outside of the main function. Note that Steps 0 through 3 are repeated for each individual uniaxial test. Steps 4 through 6 are applied to all experiments combined. A detailed description of these steps can be found in Appendix B.1.

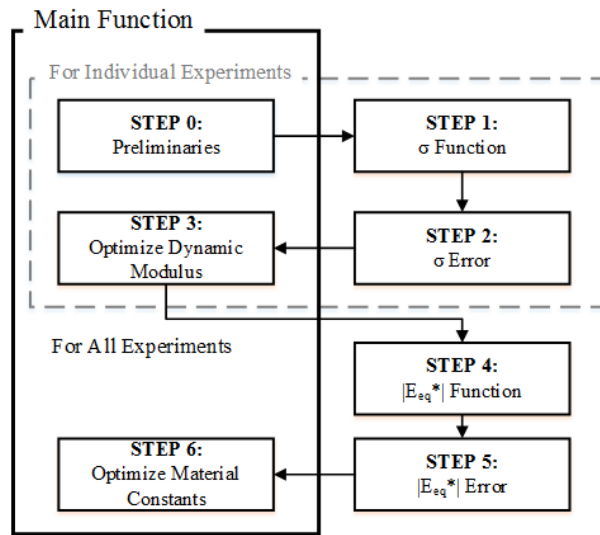


Figure 4.4: MATLAB optimization algorithm bloc diagram

4.2.1.1 Detailed Flow Chart

Figure 4.5 illustrates a detailed interpretation of the nonlinear optimization program, where the values of each variable can be followed through the process. It is important to note the two separate optimization processes, i.e. the upper portion which is applied to each experiment individually, and the lower portion which is applied to all experiments simultaneously (by utilizing the averaged dynamic modulus values obtained for each set of repeated stretch rate experiments).

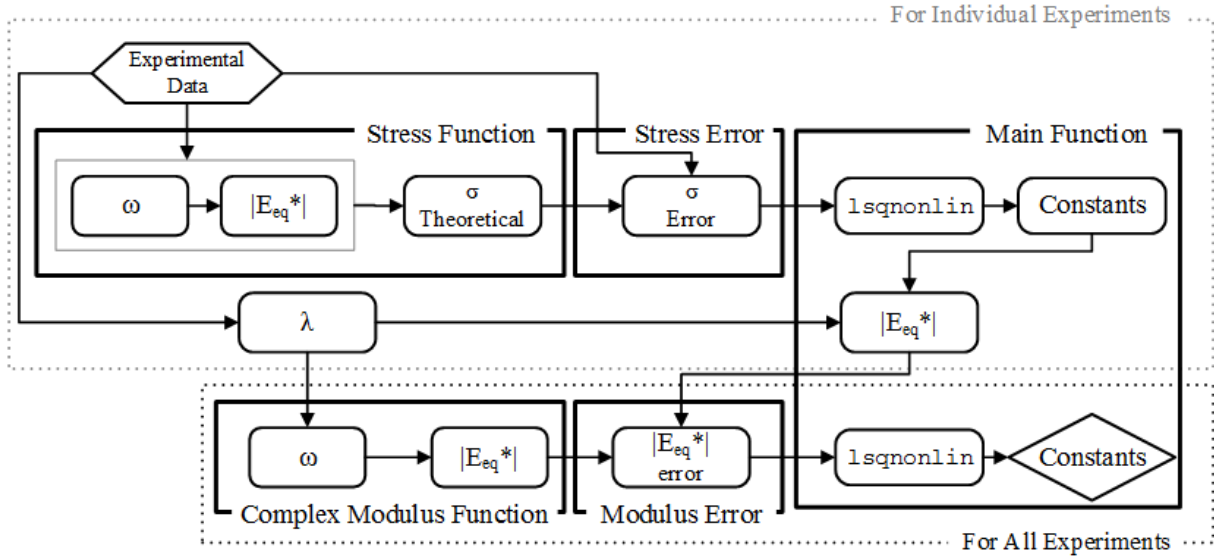


Figure 4.5: MATLAB optimization algorithm flow chart for uniaxial model

4.2.2 Results

The results of the mechanical model, under uniaxial consideration, have been subdivided into three sections. The first portion will comment on the accuracy of the optimization for the individual experiments. The second portion will illustrate the program's capacity to retrieve a general set of constants for the overall model, considering all stretch rates. The final section will demonstrate the model's accuracy in reproducing and predicting material behaviour, based on experimental data and varying kinematic parameters.

4.2.2.1 Experimental Curve Fitting

The first portion of the program's optimization process is to fit the mechanical model to each individual test, in order to find their corresponding dynamic modulus. An illustration is shown in Figure 4.6. This figure contains a loading curve example for an experiment at a rate of $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$, accompanied by the fitted curve obtained using the nonlinear optimizer of Step 3. It can be seen that, for both VHB 4905 and VHB 4910 tapes, the model is able to fit its polynomial (4.17) to the loading response of the elastomer. The behaviour of the material under uniaxial loading is clearly nonlinear, as expected, which the model is capable of reproducing. A strong proportional correlation between stretch rate and induced stress was also observed in the uniaxial experimental, which echoes the viscoelastic behaviour previously seen for biaxial testing of Chapter 3.

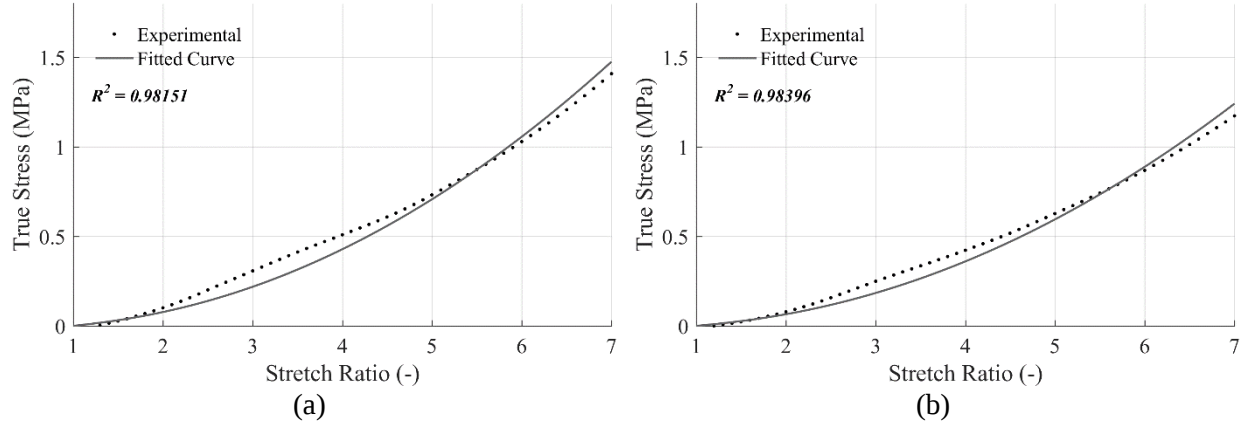


Figure 4.6: Example of curve fitting for individual uniaxial tensile experiments at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$ for (a) VHB 4905 tape trial and (b) VHB 4910 tape trial

Further quantitative investigation was conducted, by determining the sample standard deviations between similar tests for both the angular frequency and dynamic complex moduli calculated. To quantify the goodness of fit, coefficients of determination R^2 were calculated for all curves, and then averaged for similar stretch rate groups. The results for both can be found in Table 4.1 and Table 4.2, for VHB 4905 tape and VHB 4910 tape respectively. The values for all experiments can be found in Appendix B.3

It can firstly be noted that, in the majority of cases, the standard deviation for angular frequency is nearly zero. As mentioned earlier, due to the inability to use image tracking on the samples for uniaxial testing, the elongation was based on actuator position during the experiment. This means that the sample elongation data is a representation of the ideal deformation based on the experimental protocol programmed into the LabJoy software. As was demonstrated in Chapter 3, the VHB tape exhibits a significant amount of deformation around the fixtures due to its high viscoelastic response. This means that the stretch ratio values are not illustrative of the actual elongation of the elastomer. The level of accuracy with respects to the achieved maximum stretch ratio (and resulting achieved harmonic angular frequency) is therefore unrepresentative of the results' repeatability, but rather a reflection of the BioTester's ability to accurately replicate consistent actuation and record experimental data. Cases where the angular frequency was not equal for all tests were the result of discrepancies in the output data recorded by the software. More specifically, not all experiments reached a full $\lambda_{1max} = 7$. A small portion halted at a value slightly less than the desired maximum elongation (e.g. in one sample programmed at

$\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$, a maximum stretch of $\lambda_{1_{max}} = 6.968$ was achieved). This inconsistency in experimentation can only be attributed to the software itself, since the stretch ratios recorded are a direct reflection of the machines' actuator locations (which are strictly controlled by the software). The slight variations in experimentations were ultimately considered negligible, seeing as the current uniaxial model was solely tested to validate repeatable results, consistent with the findings of Wang et al [62].

Table 4.1: VHB 4905 tape averaged angular frequencies and optimized dynamic complex moduli for 5 uniaxial tensile experiments

Experimental Stretch Ratio $\dot{\lambda}_1 (\text{s}^{-1})$	Averaged Angular Frequency $\omega_1 (\text{rad s}^{-1})$	Standard Deviation (rad s^{-1})	Averaged Complex Modulus E_{eq}^* (MPa)	Standard Deviation (MPa)	Average R^2 Value
0.025	0.006545	8.674×10^{-19}	0.03026	0.001328	0.97322
0.050	0.01309	0	0.03199	0.001279	0.97517
0.075	0.01965	2.532×10^{-05}	0.03479	0.001366	0.97789
0.100	0.02618	1.735×10^{-18}	0.03447	0.001209	0.97718
0.200	0.05236	0	0.03787	0.0009323	0.97686
0.300	0.07864	0.0002298	0.04022	0.001562	0.97658

Table 4.2: VHB 4910 tape averaged angular frequencies and optimized dynamic complex moduli for 5 uniaxial tensile experiments

Experimental Stretch Ratio $\dot{\lambda}_1 (\text{s}^{-1})$	Averaged Angular Frequency $\omega_1 (\text{rad s}^{-1})$	Standard Deviation (rad s^{-1})	Averaged Complex Modulus E_{eq}^* (MPa)	Standard Deviation (MPa)	Average R^2 Value
0.025	0.006545	0	0.02620	0.001747	0.97448
0.050	0.01309	0	0.02850	0.001166	0.97467
0.075	0.01964	2.453×10^{-18}	0.02831	0.0002710	0.97376
0.100	0.02618	0	0.03091	0.001836	0.97499
0.200	0.05236	0	0.03606	0.002524	0.97334
0.300	0.07880	0.0005711	0.03860	0.0006976	0.97424

A second remark can be made with respect to the computed dynamic complex moduli, their variation with respect to change in stretch rate, and their overall standard deviation between similar tests. There is a clear proportional relationship between the stretch rate applied to the sample and the computed modulus of elasticity. This correlation falls in line with expectations, and attests to the material's viscoelastic nature. From a physical perspective, increasing tensile stretch rate will induce greater sample resistance due to the viscous response of the elastomer. This variation will

translate into overall stiffer dynamic properties of the material. From the analogous mathematical perspective, the current model's dynamic modulus relies on the three parameters drawn from the enhanced Kelvin-Voigt model (the serial modulus of elasticity (E_s), the parallel modulus of elasticity (E_p), and the viscosity loss modulus (D_p)), as well as the angular frequency (ω). It can be noted that the only variable within (4.7) is the angular frequency, which is directly proportional to the stretch rate based on equation (4.4). As seen in equation (4.7), the absolute value of the complex modulus $|E_{eq}^*|$ has a proportional relationship with the ω value, which implies that an increase in stretch ratio should indeed result in an increase in stiffness. Irregularities in this proportionality were noticed in the results of both VHB tapes. For either tape type, the results of the third stretch rate (that is $\dot{\lambda}_1 = 0.075 \text{ s}^{-1}$) resulted in “off-trend” values. In the case of VHB 4905 tape, its value fell above the trendline of the increasing degrees of stiffness, whereas in the case of VHB 4910 tape, the opposite outcome was observed, where its magnitude fell below the expected trend. These inconsistencies of proportionality are more discernable when plotted, and will be illustrated in the following section on parameter fitting (Figure 4.7).

The values of standard deviation for each set of experiments can also be noted as being higher, reaching values in the order of one-thousandth of a megapascal. This larger variability in parameters may reflect the slight inconsistencies during experimentation. Despite the great level of effort taken to ensure samples were cut to identical sizes, variations in sample width were inevitable due to human error. Similarly, sample application to the clamps may have had inconsistencies when considering if the sample was both centered on the clamp's surfaces, and if its edges were perfectly aligned with the axis of elongation. Due to the small-scale nature of the experimental setup, these otherwise small inconsistencies cannot be overlooked. Changes in sample dimensions and alignment would result in a change in stress values. The assumption of sample consistency, combined with the inability to use the image tracking, considerably decreases the data's accuracy. In spite of these factors, the averaged values were still sufficiently representative to provide an overall definable behaviour of the material, and allowed the model to be fitted for global parameters.

The values of complex moduli between the two types of VHB tapes also demonstrated a clear difference in magnitude. Even though the tapes are identical in composition, the current model is “trained” based on experimental data. This therefore suggests that a difference in values is to be

expected, due to their dissimilar thicknesses, resulting in different mechanical behaviours. From a physical standpoint, the sample cross-section of the VHB 4905 tape is half of the VHB 4910 tape. As was illustrated in Chapter 3, this signifies that, for the same amount of elongation, the VHB 4905 tape will have a significantly smaller cross-sectional area resisting the applied force during tensile loading. This will result in a higher applied stress (and therefore perceived higher stiffness). An analogous justification can be drawn using the current model's structure. Referring to Figure 4.1, the difference in thicknesses between both tapes can be represented as a difference in the number of cuboid segments along its transverse axis (i.e. thickness). When elongated in tension, the VHB 4905 tape will have less total thickness to deform in order to uphold the incompressibility condition. This will lead to a greater change along the transverse axis for the same stretch ratio, which will result in a greater internal hydrostatic pressure p . Thus, the VHB 4905 tape will exhibit stiffer response. This contradicts (and therefore disproves) the previous observation that, due to E_{eq_i} 's independence from the dimensions of the film, it should thereby be a direct reflection of material properties. It should be noted that, despite the material's identical composition, the model will need to be considered for both VHB tapes independently, with different global parameters.

Lastly, the goodness of fit for the stress-stretch ratio curves is demonstrated by the R^2 value. This provides the exactness between the theoretical and experimental values of the first optimization. It can be noted that, in all cases, the averaged coefficients are above 0.97 (or 97%). This signifies that the polynomial fitting of Step 3 has a relatively high accuracy and reliability. Figure 4.6 illustrates this accuracy more visually. The model tends to demonstrate a slightly greater overall nonlinear behaviour, due to its exponential nature. This can be explained for two reasons. Firstly, as was illustrated in the literature, elastomers have a tendency of demonstrating a material softening during the early stages of elongation, which then shifts to a strain-hardening exponential curve. The model's mathematical structure, being of simple exponential form, is therefore limited to representing the material behaviour as a pure exponential curve. This is a fundamental limitation of the model. Additionally, the experimental data may have shown a slightly less nonlinear behaviour due to some inaccuracies in elongation measurements. Had the sample deformation been retrieved from image tracking rather than actuator position, the values would have reflected the sample's true deformation.

4.2.2.2 Parameter Fitting

The second portion of the program's nonlinear data fitting optimizes the parameters of the dynamic modulus for all cases simultaneously. An example of this curve fitting is illustrated in Figure 4.7. This figure demonstrates the averaged complex moduli with respect to their individual angular frequencies (including their standard deviations), and the optimized theoretical curve based on these values.

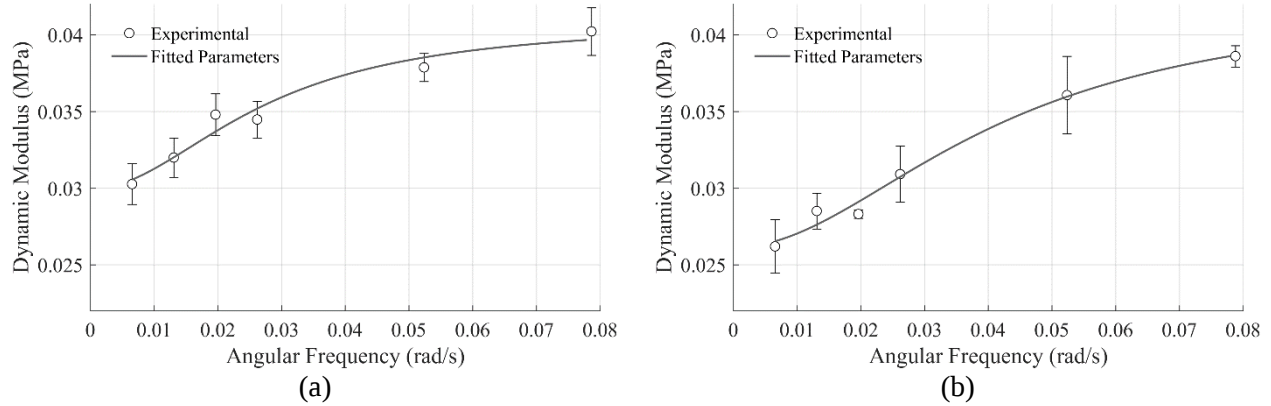


Figure 4.7: Curve fitting for averaged dynamic moduli and angular frequencies under uniaxial loading for (a) VHB 4905 tape and (b) VHB 4910 tape

As previously discussed, the dynamic moduli obtained from the first optimization contained certain outliers with respect to the expected mechanical behaviour. Due to these off-trend values, the `lsqnonlin` function was unable to fit the parameters for an exact fit, despite attempting to modify the weights within the error function. It can be seen that the curve crosses at a minimum through the delimitations of the error bars for the majority of the point. The final values for spring and damper moduli of both VHB tapes can be found in Table 4.3.

Table 4.3: Final optimized spring and damper moduli for VHB 4905 and VHB 4910 tapes under uniaxial tensile consideration

Model Constants	VHB 4905	VHB 4910
Serial Spring Modulus E_s (MPa)	0.04086	0.04221
Parallel Spring Modulus E_p (MPa)	0.1121	0.06859
Parallel Damper Modulus D_p (MPa s ⁻¹)	5.191	2.363

By comparing both cases it can be seen that the model's serial-spring modulus remains similar in stiffness for both VHB 4905 and 4910 tape samples. The constants, however, differ in the parallel

spring-damper region of the enhanced Kelvin-Voigt model. In both cases, the values for parallel spring and damper moduli drop to almost half the value for the thicker tape. This can be explained by the same logic as previously elaborated, with regards to stiffer response for VHB 4905 tape. Keeping in mind that the model has now been shown to not directly reflect the material's composition, the thinner elastomer sample exhibits a higher viscous response due to its smaller cross-sectional area. This property is governed by the spring-damper region within the mechanical model. The parameter difference between the two tapes is therefore consistent with their mechanical behaviours.

4.2.2.3 Model Plotting

To evaluate the model's ability to represent visco-hyperelastic behaviour, the above-listed final parameters for both VHB tapes were used to plot load-unload curves under various conditions. To test the model's accuracy at replicating experimental data, the values for all experimental tests for a same stretch rate were averaged and plotted next to a theoretical curve of the same stretch rate. The data calculated from the model parameters were zeroed prior to plotting, since the phase shift applied (to represent the energy dissipation) creates an initial stress value greater than zero. Figure 4.8 illustrates two examples of these comparisons for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ and $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$ respectively. All theoretical versus experimental plots for uniaxial model consideration can be found in Appendix B.4.

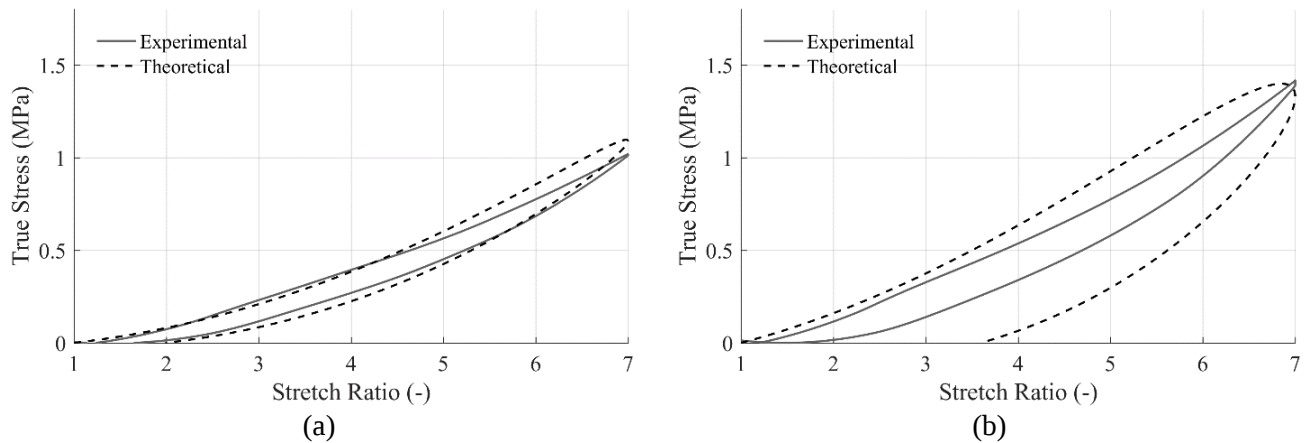


Figure 4.8: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at (a) $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ and (b) $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$

The model has demonstrated the ability to replicate the loading portion of the experimental data within good agreement. In all cases the peak stresses of the theoretical values fell within

reasonable limits of the achieved experimental values. It was observed, however, that as the stretch rate increases, the hysteresis loop of the theoretical data tends to exceed that of the experimental data. The hysteresis loops also seemed to have a greater variability between stretch rates for the VHB 4910 tape. This can be attributed to the differences in parameters found for the stiffness and viscous loss moduli of both tapes.

It can be observed that in both cases, the loss factor η found from the model reaches a certain maximum. This phenomenon is illustrated in Figure 4.9 for VHB 4910 tape, and is representative of the elastomer's change in internal dissipation characteristics due to changes in kinematic testing parameters.

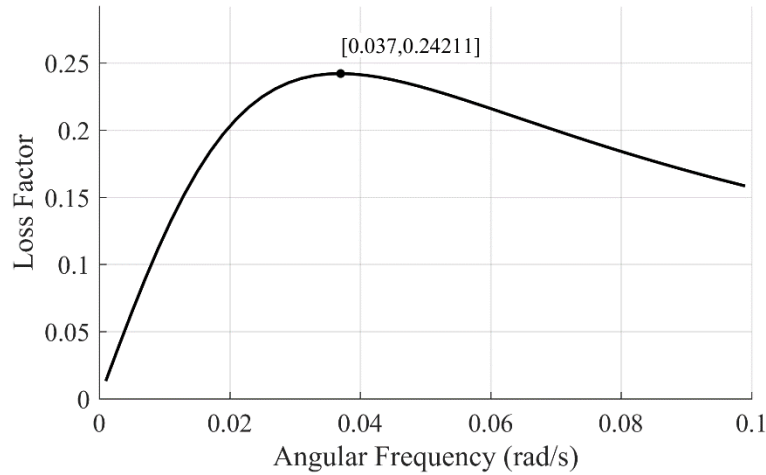


Figure 4.9: Distribution of loss factor variation with respect to angular frequency in VHB 4910 tape under uniaxial tensile loading

This peak in value is explained through the physical principles at a macroscopic level. At lower angular frequencies, the polymeric chains within the elastomer are able to adjust to the elongation of the film. This results in a hyper-elastic rubbery response with low internal thermal energy losses. As the frequency is increased, these chains will gradually lose their ability to “keep up” with the deformation, thus increasing the loss factor, and resulting in a viscoelastic response. At a certain peak value, the frequency will reach a threshold where the internal macrostructure will no longer be capable of adapting to the deformation, which will lead the polymer to exhibiting behaviour similar to its properties in glassy state. This will cause the loss factor to decrease, as the polymer's internal dissipation will be minimized [62, 98]. Based on (4.4), it is clear that any change to either the stretch rate or the maximum stretch ratio will affect the variation in energy

dissipation. This is because angular frequency of the system is a product of both these values. The peak dissipation values for VHB 4905 and VHB 4910 tapes are found to be at 0.025 rad/s and 0.037 rad/s respectively. The differences between the two materials can again be explained by the fact that the VHB 4905 tape, having a thinner profile, demonstrates a higher sensitivity to variations for the same set of parameters.

In order to demonstrate these changes in internal dissipation, as well as illustrate variable visco-hyperelastic response, the model was additionally plotted while modifying one of two kinematic experimental variables (i.e. stretch rate or maximum stretch ratio). Figure 4.10 provides an example of both tape models elongated to $\lambda_{max} = 3, 5, \& 7$, at a constant stretch rate of $\dot{\lambda} = 0.025 \text{ s}^{-1}$. These stretch ratios were selected arbitrarily, within the limits of the parameters used for model fitting, as illustrative examples.

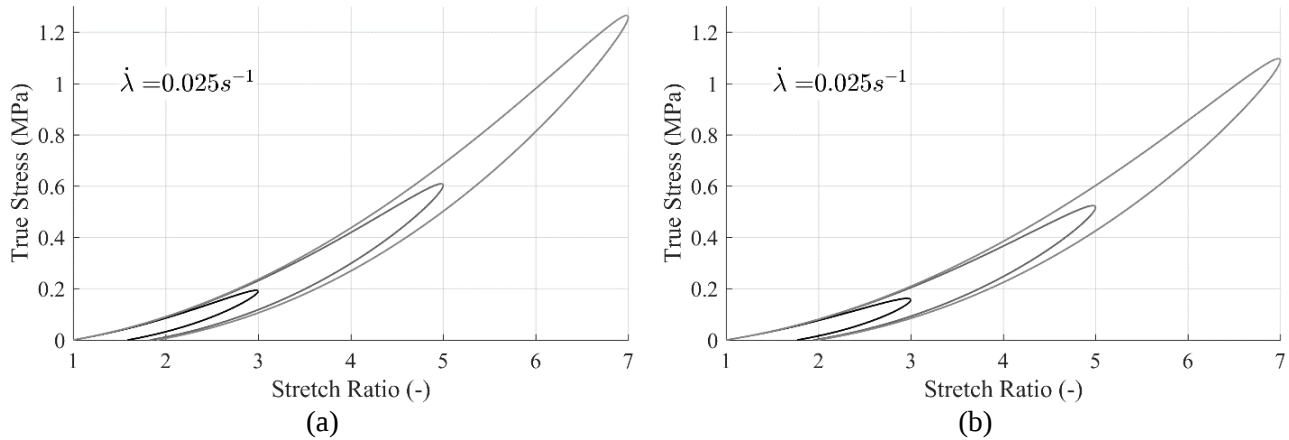


Figure 4.10: Theoretical plot of uniaxial tensile test at various maximum stretch ratios ($\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$) for (a) VHB 4905 tape and (b) VHB 4910 tape

It can be seen that the model has the ability to accurately portray the effects of maximum elongation on the mechanical behaviour of the material. In both cases, the nonlinearity of the true stress increases proportional to the maximum stretch ratio, and the VHB 4905 tape reaches higher peak stresses due to its stiffer overall response. The change in internal dissipation is also reflective of the expected behaviour based on a change in maximum elongation, in that the dissipation varies minimally since the stretch rate remains the same among all cases.

The final set of plots, depicted in Figure 4.11 represent the model under varying stretch rates of $\dot{\lambda}_1 = 0.040 \text{ s}^{-1}, 0.090 \text{ s}^{-1}, \& 0.130 \text{ s}^{-1}$. All three rates were set to elongate to a maximum

stretch ratio of $\lambda_{max} = 7$. These stretch rates were also selected arbitrarily, within the limits of the parameters used for model fitting, as illustrative examples. Similar to the previous figure, the change in kinematic testing variables results in a change of behaviour that is representative of the material's viscoelastic response. In both cases, the model dynamically changes its response with respect to the variation in stretch rate, by increasing the total stress resulting from the applied tensile force.

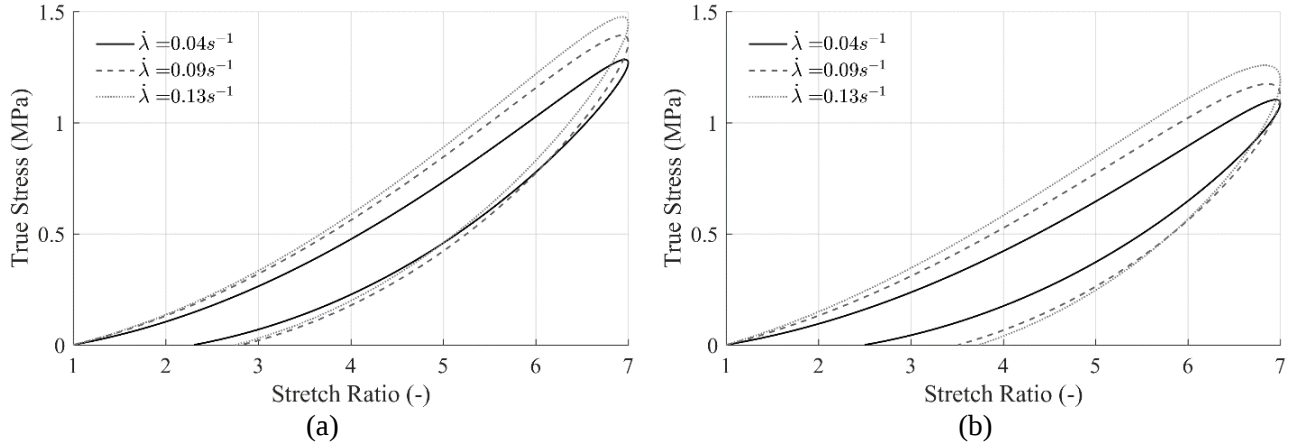


Figure 4.11: Theoretical plot of uniaxial tensile test for various stretch rates at $\lambda_{max} = 7$ for (a) VHB 4905 tape and (b) VHB 4910 tape

The variation in loss factor can also be distinguished. In the case of the VHB 4905 tape, the stretch rates and maximum stretch ratio combinations fall within the limits surrounding the peak value for the loss factor (i.e. $\omega_1 = 0.01047 \frac{rad}{s}$, $0.02356 \frac{rad}{s}$, & $0.03403 \frac{rad}{s}$ respectively). The hysteresis observed increases between the first two samples, and then decreases once the third stretch rate surpasses the maximum internal dissipation point (previously illustrated in Figure 4.9). For the case of the VHB 4910 tape, all three angular frequencies fall below the peak loss factor, and therefore display an increased energy loss as the stretch rate increases. Figure 4.11 (b) also demonstrates a clearer depiction of the model's tendency to exceed VHB 4910 tape's internal energy dissipation. The theoretical curves show much larger losses than any experimental values of the uniaxial tests.

The hysteresis loop of this model is the product of applying lag angle δ (from (4.8)), which directly relies on the model parameters (i.e. spring and damper moduli). It will thus greatly vary depending on their weights with respect to one another. For example, an increase in the magnitude for the

parallel modulus of elasticity (E_p) would result in an overall decrease in loss factor (and lag angle), since its value is only contributing to the denominator of the equation in (4.8). Looking back at the parameter values in Table 4.3, VHB 4905 tape has roughly double the value for its parallel modulus of elasticity (E_p) with respect to VHB 4910 tape. It therefore demonstrates a loss factor range of $0 \leq \eta \leq 0.156$, whereas VHB 4910 tape reaches a maximum loss factor value of $\eta = 0.242$. The difference in the tapes' internal energy dissipation variation is still representative of experimental findings, as the thinner VHB 4905 tape shows lower overall hysteresis for all cases. The energy loss for VHB 4910 tape, however, are much greater than those observed in experimentation.

The values of the parameters were optimized based on the algorithm within the `lsqnonlin` function, and are therefore difficult to control. The fault lies in the model itself. The simple nonlinear mathematical structure, on which the parameters are fitted, is less conformant and precise relative to other more complex visco-hyperelastic models. This limitation, however, is compensated by the model's straightforwardness in comparison to its alternatives. A solution to reduce error would be to gather further experimental data and optimize over a broader set of stretch rates. The current experimental parameters for uniaxial analysis were selected to reflect those of the biaxial testing, which were set based on the limitations of instrumentation. In the case of the VHB 4905 tape, the successfulness of the model can be attributed to its smaller thickness. Under the same kinematic parameters, the thinner tape was able to demonstrate a wider range of mechanical behaviour due to its higher sensitivity to applied loads. Having a narrower profile gave the VHB 4905 tape a greater viscous response over a smaller array of stretch rates, which allowed the model to obtain a more representative behaviour. For the VHB 4910 tape, a larger gamut of stretch rates would provide the optimization with a broader range of mechanical variations to fit the parameters with. In essence, providing the model with a wider spectrum of experimental stretch rates would allow it to be trained more precisely.

The current uniaxial visco-hyperelastic model, based on the enhanced Kelvin-Voigt rheological model, has thus demonstrated the potential to be effective at predicting the mechanical behaviour of VHB dielectric elastomer. Through the use of a dynamic modulus and simple mathematical structure, it has proven relatively accurate at predicting the material's dependence on stretch rate and maximum elongation. Aside from obvious errors due to experimental discrepancies and data

fitting, the model also made the assumption that the material deforms under harmonic motion. It is clear that the uniform linear (ramp) motion of the actual experimental data will affect the accuracy of the model. The effect of this assumption can, however, be deemed negligible based on the overall successfulness illustrated in this section. It can therefore be confirmed that the dynamic visco-hyperelastic model presented by Wang et al. [62] provides a straightforward alternative which is greatly representative of DE film's mechanical response.

In most cases, however, the real-life applications of these elastomers will involve stretching the film along both of its principle axes during design assembly. Many actuator geometries (e.g. the bow-tie actuator) will exhibit biaxial motion during activation, which will affect its mechanical behaviour differently than a simple uniaxial tensile scenario. The following section will thus present a modified dynamic visco-hyperelastic model which will attempt to characterize the VHB elastomer under biaxial tension. This novel perspective will provide a more suitable constitutive model for design purposes, by relating the effects of both stretch ratios λ_1 and λ_2 with the normal stresses produced on either axis. It will also provide the groundwork for further development of a biaxial electro-mechanical model, that would be used for further interpretation of dielectric actuation.

4.3 Biaxial Consideration

Under biaxial tensile loading, the film is being elongated along both x and y axes (" λ_1 and λ_2 "). This implies a free boundary condition only along only its thickness (z-axis). Due to the loads applied on axes $i = 1, 2$, the moduli for either axes will be processed independently, by using similar methods presented in Section 4.1. An assumption of isotropy will need to be introduced for the biaxial model as well, in order to allow mathematical derivations with a solvable number of unknown variables. In other words, the complex modulus $E_{eq_i}^* := E_{eq}^*$ for $i = 1, 2, 3$. Taking an ideal biaxial tension along directions $i = 1, 2$, the true stress from (4.1) can be expressed as:

$$\sigma_i = \lambda_i \sigma_{system_i} - p = \sigma_{ext_i}, \quad i = 1, 2 \quad (4.18)$$

where σ_{ext_i} are the external stresses applied to the system, at stretch ratios of λ_1 and λ_2 . The thickness will have free boundary conditions, and its true stress will necessarily be zero ($\sigma_3 = 0$). It follows that the net normal stress equation is:

$$\sigma_3 = \lambda_3 \sigma_{system_3} - p = 0 \quad (4.19)$$

From the incompressibility condition, a relationship between the three stretch ratios can be drawn, as $\lambda_3 = 1/(\lambda_1 \lambda_2)$. Following the same correlation of equal hydrostatic pressures for all axes (as previously derived in Section 4.2), and recalling that a nominal stress for a free boundary can be expressed as $\sigma_{system_i} = E_{eq_i}^* \varepsilon_i = E_{eq_i}^* (\lambda_i - 1)$, p can be expressed as:

$$p = \frac{E_{eq}^* (\lambda_3 - 1)}{\lambda_1 \lambda_2} = \frac{E_{eq}^* [(\lambda_1 \lambda_2)^{-1} - 1]}{\lambda_1 \lambda_2}$$

$$p = E_{eq}^* [(\lambda_1 \lambda_2)^{-2} - (\lambda_1 \lambda_2)^{-1}] \quad (4.20)$$

Due to the change in loading conditions, the currently proposed model will make use of the generalized Hooke's law for biaxial loading to express nominal stresses along $i = 1, 2$. This will allow the nominal stresses to reflect the overall deformation of the elastomer in terms of both λ_1 and λ_2 . Neglecting the effects of shear, based on the previously stated assumptions, the system nominal stresses (for assumed isotropic material) can therefore be expressed as:

$$\begin{Bmatrix} \sigma_{system_1} \\ \sigma_{system_2} \end{Bmatrix} = \frac{1}{1 - \nu^2} \begin{bmatrix} E_{eq}^* & \nu E_{eq}^* \\ \nu E_{eq}^* & E_{eq}^* \end{bmatrix} \begin{Bmatrix} (\lambda_1 - 1) \\ (\lambda_2 - 1) \end{Bmatrix} \quad (4.21)$$

where Poisson's ratio $\nu = 0.49$ for both VHB 4905 and VHB 4910 tapes (provided by manufacturer) [40]. Inserting (4.21) to (4.18), and equating the hydrostatic pressures will give the final expression for normal stress along axes of deformation:

$$p = E_{eq}^* [(\lambda_i \lambda_j)^{-2} - (\lambda_i \lambda_j)^{-1}] = \frac{\lambda_i E_{eq}^*}{1 - \nu^2} [(\lambda_i - 1) + \nu(\lambda_j - 1)] - \sigma_i$$

$$\begin{cases} \sigma_1 = \frac{\lambda_1 E_{eq}^*}{1 - \nu^2} [(\lambda_1 - 1) + \nu(\lambda_2 - 1)] + E_{eq}^* [(\lambda_1 \lambda_2)^{-1} - (\lambda_1 \lambda_2)^{-2}] \\ \sigma_2 = \frac{\lambda_2 E_{eq}^*}{1 - \nu^2} [(\lambda_2 - 1) + \nu(\lambda_1 - 1)] + E_{eq}^* [(\lambda_2 \lambda_1)^{-1} - (\lambda_2 \lambda_1)^{-2}] \end{cases} \quad (4.22)$$

The strain of the system, in both directions of deformation, will change over time, and can thus be expressed as

$$\varepsilon_i(t) = \lambda_i(t) - 1 = \varepsilon_{m_i} e^{j\omega_i t}, \quad i = 1, 2 \quad (4.23)$$

Then, (4.22) can be expressed in terms of time:

$$\begin{cases} \sigma_1(t) = \frac{\lambda_1(t) E_{eq}^*}{1 - \nu^2} [(\lambda_1(t) - 1) + \nu(\lambda_2(t) - 1)] + E_{eq}^* [(\lambda_1(t) \lambda_2(t))^{-1} - (\lambda_1(t) \lambda_2(t))^{-2}] \\ \sigma_2(t) = \frac{\lambda_2(t) E_{eq}^*}{1 - \nu^2} [(\lambda_2(t) - 1) + \nu(\lambda_1(t) - 1)] + E_{eq}^* [(\lambda_2(t) \lambda_1(t))^{-1} - (\lambda_2(t) \lambda_1(t))^{-2}] \end{cases} \quad (4.24)$$

In order to correlate the experimental values to this equation, only the variables' sizes are considered, such that:

$$\begin{cases} |\sigma_1| = |E_{eq}^*| \left[\frac{\lambda_1}{1 - \nu^2} ((\lambda_1 - 1) + \nu(\lambda_2 - 1)) + ((\lambda_1 \lambda_2)^{-1} - (\lambda_1 \lambda_2)^{-2}) \right] \\ |\sigma_2| = |E_{eq}^*| \left[\frac{\lambda_2}{1 - \nu^2} ((\lambda_2 - 1) + \nu(\lambda_1 - 1)) + ((\lambda_1 \lambda_2)^{-1} - (\lambda_1 \lambda_2)^{-2}) \right] \end{cases} \quad (4.25)$$

This equation can now be fitted to the experimental data for both axes, and represents the absolute values of the stress and stretch ratios under continuous changes.

4.3.1 Method

In order to characterize the material with the newly proposed model, the data from the biaxial tests, presented in Chapter 3, were utilized. The program described in Section 4.2.1 was modified in order to reflect the changes made to the model for biaxial consideration. The updated equation for stress (4.25) was added to its respective function, and the process was modified to simultaneously optimize both axes independently, based on the data acquired. The MATLAB code for the biaxial

analytical model can be found in Appendix B.2. A flowchart representing the program is displayed in Figure 4.12.

It should be noted that, due to the large deformation of the samples around the tines of the BioTester, the maximum achieved stretch ratio fell below the desired $\lambda_{1,2max} = 2$ (as illustrated in Chapter 3). The angular frequency of each experiment was therefore calculated to reflect the actual maximum stretch ratio and stretch rate, with the help of the data provided from the image tracking.

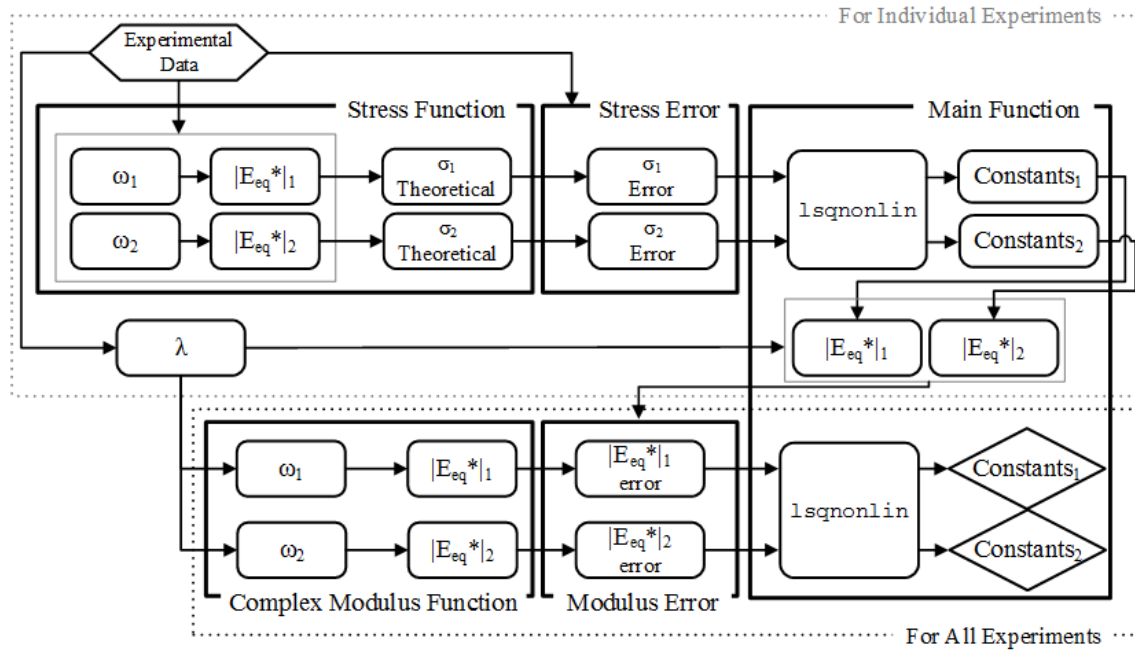


Figure 4.12: MATLAB optimization algorithm flow chart for biaxial model

4.3.2 Results

Similar to the uniaxial model, the results of the newly proposed biaxial model have been subdivided as follows. The accuracy of the optimization for individual experiments will first be examined. The program's capacity to retrieve a general set of constants for the overall model will then be discussed. Lastly, the model's accuracy in reproducing experimental data, and abilities to predict the effect of variations in kinematic parameters will be illustrated with a series of simulations.

4.3.2.1 Experimental Curve Fitting

For the proposed biaxial model, the complex modulus is obtained for either axis independently, despite the assumption that the material is isotropic. Achieving this allowed the results for both

axes to be compared to verify whether the assumption is in fact supportable. An example of these curve fittings is illustrated in Figure 4.13.

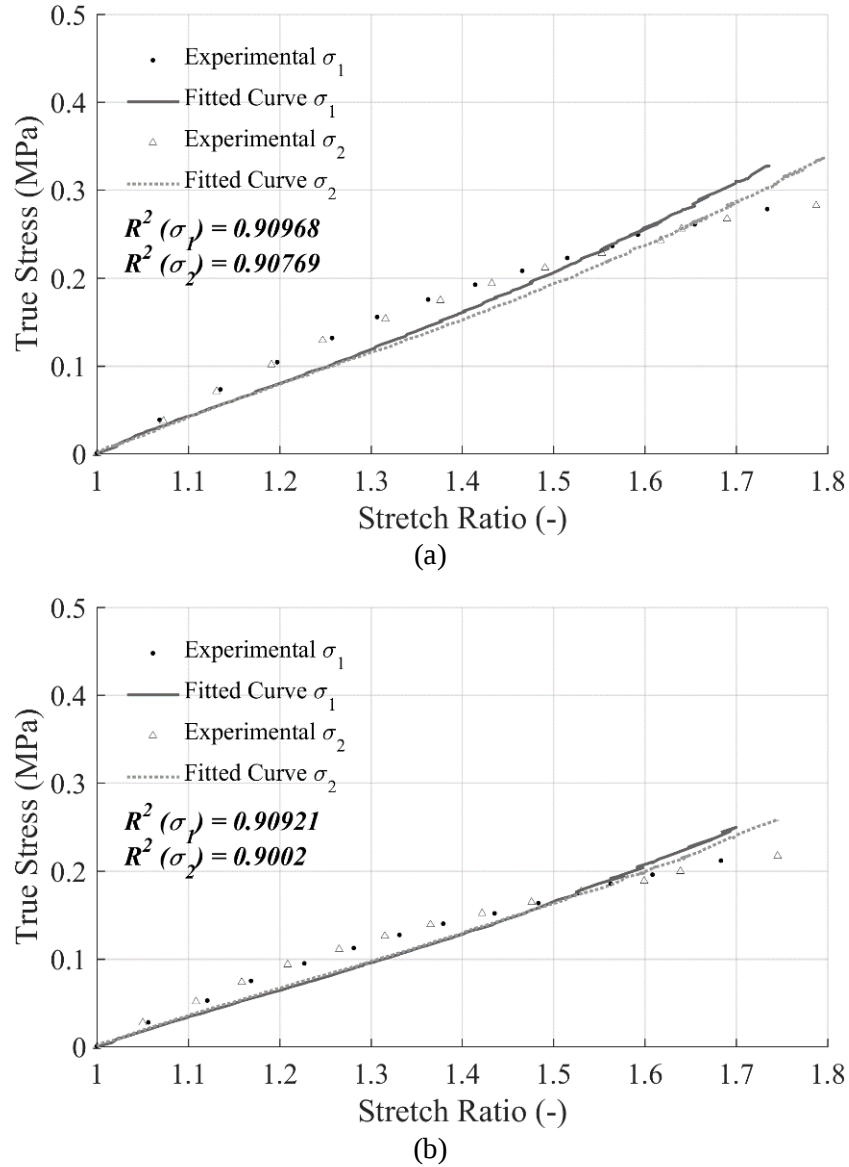


Figure 4.13: Example of curve fitting for individual biaxial experiments at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$ for (a) VHB 4905 tape trial and (b) VHB 4910 tape trial

It can be seen in either case that the curve fitting for both materials yielded values of reasonably high precision. It should be noted that due to the limitations brought on by the experimental instrumentation, the material was unable to be elongated to a biaxial stretch ratio sufficiently large to demonstrate a discernable exponential behaviour. This greatly affected the overall accuracy of the model parameter fitting, as it is of exponential nature.

The experimental data for biaxial tensile tests yielded curves with decaying slopes, as the stretch ratios did not reach large enough values to demonstrate elastomeric strain-hardening. This affected the model's ability to fit the data, since its mathematical structure is purely exponential and does not possess the ability to interpret the initial softening typically observed in elastomers under small deformation. The goodness of fit was calculated through the R^2 coefficient. The averaged values for the results of the first parameter fitting, along with the standard deviations for both the angular frequency and complex modulus, are displayed in Table 4.4 and Table 4.5. The values for all experiments can be found in Appendix B.5.

It can be noted that, in all cases, a clear proportional increase in dynamic modulus was observed with respect to the stretch rate of the experiment. This correlation is reflective of the viscoelastic response of the elastomer, and follows the same logic as the results under uniaxial tension. The values for VHB 4905 tape moduli are also greater in stiffness than those found for the VHB 4910 tape, which agrees with the physical principles discussed previously.

The standard deviation for all angular frequencies are negligible. This level of accuracy illustrates the consistency in experimental results for the stretch ratio and stretch rates achieved. As was previously mentioned, due to sample deformation around the tensile test fixtures, all tests experienced slight variations in maximum stretch ratios achieved. The angular frequency, being directly dependent on this maximum, would therefore also vary between each test under similar loading conditions. Having such small deviations, as well as identical averaged values between both tapes, attests to the consistency in the material's deformation during experimentation. The equivalent values of deviation between x and y axes in most cases also demonstrates the experiments' ability to maintain equiaxial stretch ratio, despite sample deformation.

The values for complex moduli among similar experiments were found to have slightly higher standard deviations, with values ranging between 0.01 and 0.02 MPa. These results are attributed to the greater fluctuations in experimental stresses. Despite these variations, the overall mechanical trends in (averaged) dynamic modulus growth was consistent with the actual mechanical response of the material, and proved very representative during final parameter fitting.

Table 4.4: VHB 4905 tape averaged angular frequencies and optimized dynamic complex moduli for 5 biaxial tensile experiments

Experimental Stretch Ratio $\dot{\lambda}$ (s ⁻¹)	λ_i	Averaged Angular Frequency ω_1 (rad s ⁻¹)	Standard Deviation (rad s ⁻¹)	Averaged Complex Modulus E_{eq}^* (MPa)	Standard Deviation (MPa)	Average R ² Value
0.025	1	0.03927	3.469×10^{-18}	0.08698	0.003556	0.88451
	2	0.03927	4.907×10^{-18}	0.08385	0.006671	0.90473
0.050	1	0.07854	6.939×10^{-18}	0.09558	0.005517	0.8628
	2	0.07854	9.813×10^{-18}	0.09515	0.01017	0.8768
0.075	1	0.1178	6.939×10^{-18}	0.09999	0.008179	0.88605
	2	0.1178	6.939×10^{-18}	0.1001	0.008720	0.89378
0.100	1	0.1571	1.963×10^{-17}	0.1037	0.01275	0.87343
	2	0.1571	1.388×10^{-17}	0.1057	0.01014	0.88373
0.200	1	0.3142	3.925×10^{-17}	0.1179	0.01286	0.8524
	2	0.3142	3.925×10^{-17}	0.1182	0.008920	0.82113
0.300	1	0.4717	6.206×10^{-17}	0.1266	0.01231	0.82418
	2	0.4717	6.206×10^{-17}	0.1258	0.01543	0.84715

Table 4.5: VHB 4910 tape averaged angular frequencies and optimized dynamic complex moduli for 5 biaxial tensile experiments

Experimental Stretch Ratio $\dot{\lambda}$ (s ⁻¹)	λ_i	Averaged Angular Frequency ω_1 (rad s ⁻¹)	Standard Deviation (rad s ⁻¹)	Averaged Complex Modulus E_{eq}^* (MPa)	Standard Deviation (MPa)	Average R ² Value
0.025	1	0.03927	3.469×10^{-18}	0.07429	0.004732	0.88099
	2	0.03927	0	0.07422	0.005738	0.88205
0.050	1	0.07854	6.939×10^{-19}	0.08189	0.005303	0.88237
	2	0.07854	6.939×10^{-19}	0.08237	0.006461	0.90094
0.075	1	0.1178	1.388×10^{-17}	0.08539	0.006672	0.88723
	2	0.1178	6.939×10^{-17}	0.08513	0.007203	0.90049
0.100	1	0.1571	0	0.08981	0.009414	0.86927
	2	0.1571	1.388×10^{-17}	0.09127	0.01007	0.85981
0.200	1	0.3142	3.925×10^{-17}	0.1022	0.0078097	0.85169
	2	0.3142	3.925×10^{-17}	0.1030	0.009313	0.83868
0.300	1	0.4717	7.343×10^{-17}	0.1115	0.009041	0.84343
	2	0.4717	7.343×10^{-17}	0.1098	0.009917	0.84237

Lastly, the goodness of fit for the stress-stretch ratio curves all averaged above 0.82 (or 82% accuracy). This signifies that the polynomial fitting has a good accuracy and reliability. As was earlier discussed, experimental results for biaxial tensile tests were unable to demonstrate large exponential behaviour due to limitation in maximum elongation. This lack of nonlinearity limited the precision of the optimization function, and the current parameters will therefore reflect said limitations.

4.3.2.2 Parameter Fitting

As with the dynamic modulus fitting, the overall parameters for the model were fitted to either axes separately, in order to provide separate values for comparison. A depiction of the optimizations can be seen in Figure 4.14 and Figure 4.15. These figures demonstrate the averaged dynamic moduli including, standard deviations, plotted against their respective angular frequencies. The optimized theoretical curve based on these values can be seen for either axis.

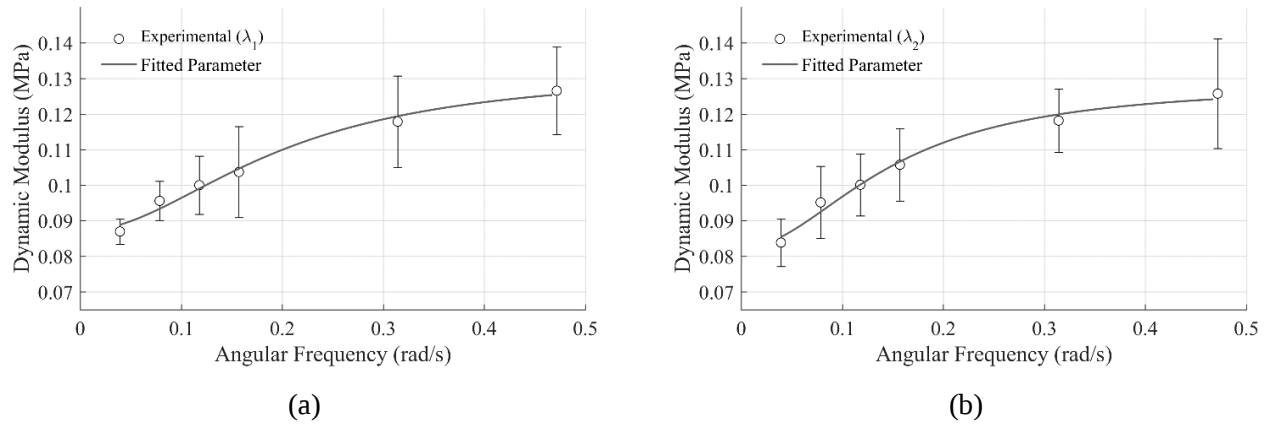


Figure 4.14: Curve fitting for averaged dynamic moduli and angular frequencies under biaxial loading for VBH 4905 tape along (a) λ_1 axis, and (b) λ_2 axis

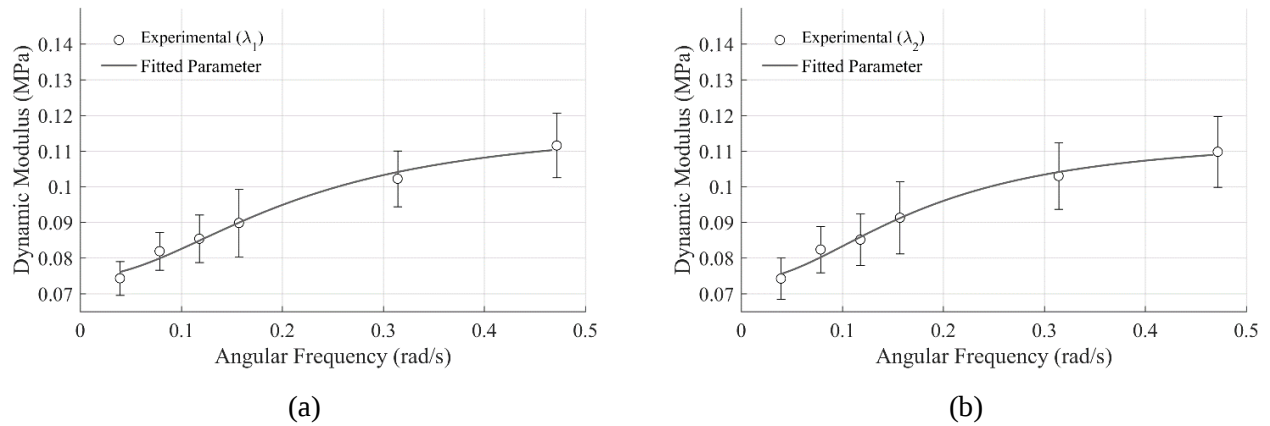


Figure 4.15: Curve fitting for averaged dynamic moduli and angular frequencies under biaxial loading for VBH 4910 tape along (a) λ_1 axis, and (b) λ_2 axis

It can be seen that, in all cases, the `lsqnonlin` function was able to fit the final parameters of the model with high accuracy. The curves of the optimized values fell within very good agreement to the dynamic moduli obtained for each stretch rate. Transverse isotropic properties between axes, however, was not achieved for either tape due to inconsistencies in experimental data. This discrepancy was greater for the VHB 4905 tapes, as the variations between the σ_1 and σ_2 values were much greater (see data from Chapter 3). The values obtained from the final parameter fitting can be found in Table 4.6.

Table 4.6: Final optimized spring and damper moduli for VHB 4905 and VHB 4910 tapes under biaxial tensile consideration

Model Constants	VHB 4905		VHB 4910	
	λ_1	λ_2	λ_1	λ_2
Serial Spring Modulus E_s (MPa)	0.1323	0.1285	0.1177	0.1142
Parallel Spring Modulus E_p (MPa)	0.2550	0.2293	0.2036	0.2070
Parallel Damper Modulus D_p (MPa s ⁻¹)	1.765	2.150	1.350	1.597

Despite the slight differences, it can be noted that the values for VHB 4910 tape demonstrate a closer correlation along axes for λ_1 and λ_2 . The slight fluctuations between the two axes is the result of the sample undergoing imperfectly symmetrical tension. In the case of the VHB 4905 tape, larger discrepancies were present in the data, which resulted in a much greater variation between the parameters of the two axes. As with the uniaxial model, the VHB 4905 tape also demonstrates slightly greater damper modulus (D_p). This is consistent with the different mechanical properties between the two tapes, as the thinner VHB 4905 tape exhibits more sensitive viscoelastic response to external loading. In order to apply these parameters to the model, the average for each parameter was taken, and assigned to both x and y axes equally. This was done to comply with the assumption of isotropy in mechanical behaviour of the VHB elastomer.

4.3.2.3 Model Plotting

In order to evaluate the model's accuracy when simulating visco-hyperelastic response, the final averaged parameters for both VHB tapes were used to plot load-unload curves under various conditions. That is to say that, for VHB 4905 tape $E_s = 0.1304$ MPa, $E_p = 0.2421$ MPa, and $D_p = 1.9575$ MPa. For VHB 4910 tape, $E_s = 0.1163$ MPa, $E_p = 0.2054$ MPa, and $D_p = 1.4708$ MPa. Data for experiments possessing similar stretch rate were averaged for each

axis independently, and then plotted next to a theoretical curve of the same stretch rate. In either case, the stretch rate and maximum stretch ratio were calculated to reflect the experimental deformation, and the stresses for either axis was subsequently plotted using these values. Due to the phase shift applied to create the hysteresis loop, the data calculated from the model parameters were zeroed prior to plotting. Figure 4.16 illustrates a comparison for VHB 4910 tape at $\dot{\lambda}_{1,2} = 0.025 \text{ s}^{-1}$ and 0.200 s^{-1} respectively. All theoretical versus experimental plots for the model adaptation under biaxial consideration can be found in Appendix B.6.

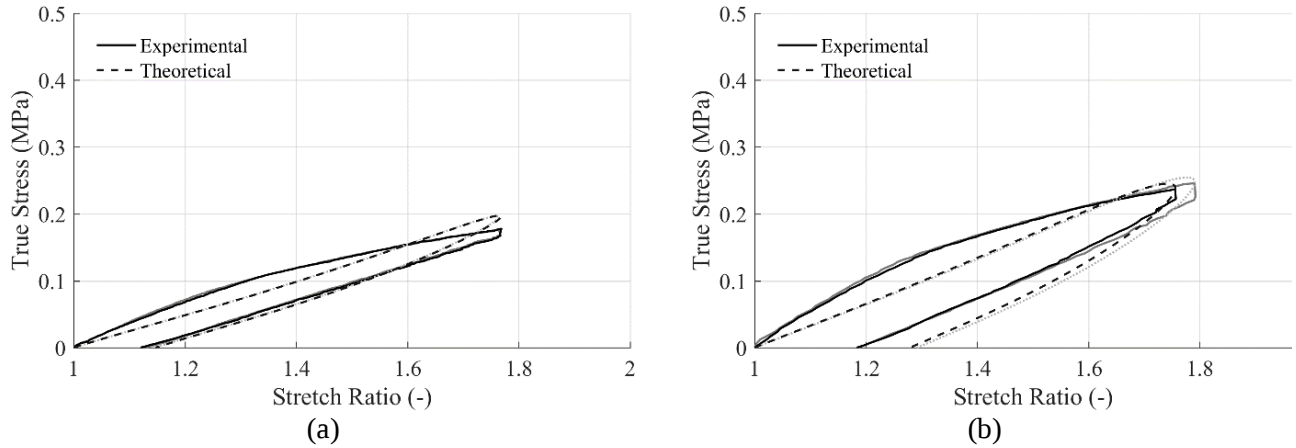


Figure 4.16: Theoretical and experimental plots for biaxial tensile tests of VHB 4910 tape at (a) $\dot{\lambda}_{1,2} = 0.025 \text{ s}^{-1}$ and (b) $\dot{\lambda}_{1,2} = 0.200 \text{ s}^{-1}$, (where black curves represent λ_1 axis, and gray represents λ_2 axes)

It can be seen that, despite the model's loading curve underestimation with respect to experimental data, peak stresses for both axes are still predicted with good accuracy. As mentioned earlier, due to the experiments' lack of demonstrable exponential growth, the model has difficulty replicating exact experimental behaviour. The true mechanical response exhibits a material "softening" while remaining within a certain range of smaller deformations. This results in a slope decay during its loading phase, as can be seen in Figure 4.16. Due to the mathematical simplicity of the current model, behaviours deviating from a purely exponential progression will inevitably be underestimated. It can also be seen that the model exhibits the same variation in energy loss prediction as the uniaxial model. Although slightly less significant, when angular frequency values reach the point of loss-factor maximum, the internal dissipation of the model tends to exceed the values observed. This may partly be due to the previous challenge with fitting the parameters. Had the experimental values displayed greater exponential growth, the hysteresis loop would have

potentially been more in-line with theoretical predictions. This may also, however, be linked to the loss factor's variation with respect to angular frequency.

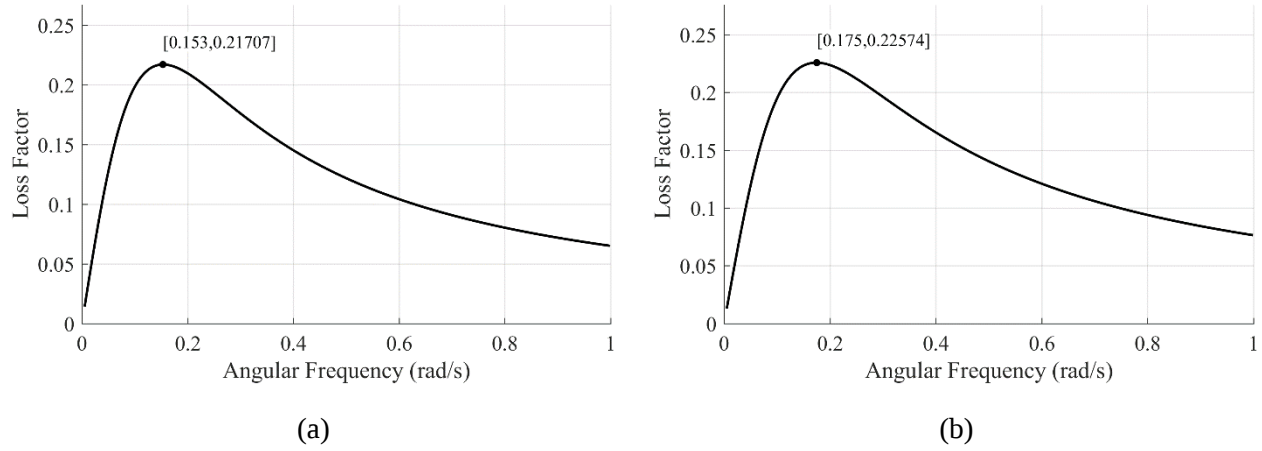


Figure 4.17: Distribution of loss factor variation with respect to angular frequency under biaxial loading for (a) VHB 4905 tape and (b) VHB 4910 tape

The change in loss factor with respect to angular frequency can be seen in Figure 4.17 for both types of VHB tape. The trend reflects that of the previous uniaxial model, since the equation for loss factor remains unchanged. As can be seen, the thresholds of internal dissipation are $\eta = 0.217$ & 0.226 for VHB 4905 and VHB 4910 tapes respectively. In reference to Table 4.5, this predicts a peak internal dissipation value somewhere between $\dot{\lambda}_{1,2} = 0.100 \text{ s}^{-1}$ & 0.200 s^{-1} for VHB 4910 tape, where the angular frequencies are $\omega_{1,2} = 0.15708 \frac{\text{rad}}{\text{s}}$ & $0.31416 \frac{\text{rad}}{\text{s}}$.

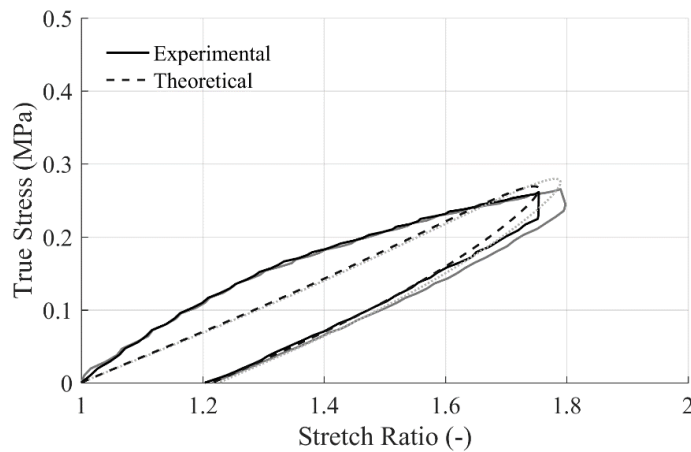


Figure 4.18: Theoretical and experimental plots for biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_{1,2} = 0.300 \text{ s}^{-1}$ where black curves represent λ_1 axis, and gray represents λ_2 axes

This phenomenon is not reflected, however, in the experimental data. As can be seen in Figure 4.18, for a stretch ratio of $\dot{\lambda}_{1,2} = 0.300 \text{ s}^{-1}$ the experimental internal dissipation continues to increase with respect to the model's maximum loss factor (seen in Figure 4.16 (b)). There is thus reason to believe that the limited experimentally achieved maximum elongations may have affected the model's ability to properly fit the parameters to reflect the loss factor variation.

Despite this discrepancy in the value for maximum loss factor, the model was plotted while modifying one of two kinematic experimental variables in order to demonstrate the changes in internal dissipation and visco-hyperelastic response. Figure 4.19 provides an example of both tape models elongated to $\lambda_{1,2(max)} = 1.3, 1.5, \& 1.7$, at a constant stretch rate of $\dot{\lambda} = 0.025 \text{ s}^{-1}$. These stretch ratios were selected arbitrarily, within an acceptable range of the achieved experimental stretch ratios.

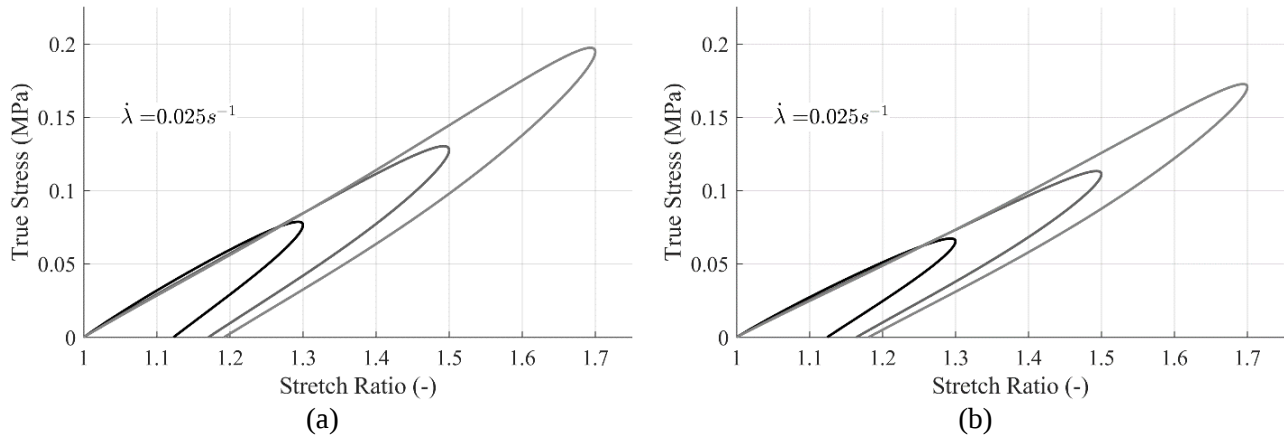


Figure 4.19: Theoretical plot of biaxial tensile test at various maximum stretch ratios ($\dot{\lambda}_{1,2} = 0.025 \text{ s}^{-1}$) for (a) VHB 4905 tape and (b) VHB 4910 tape

It can be seen that the model manages to portray the effects of percent-elongation on the behaviour of the material. For both tapes, a beginning of exponential mechanical behaviour starts to show as the stretch ratio increases. The VHB 4905 tape also reaches higher peak stresses due to its stiffer overall behaviour. The change in internal dissipation is also reflected in the plots, despite not showing precise loss factors with respect to the experimental behaviour.

An additional simulation for VHB 4910 tape was plotted at stretch ratios well above the achieved experimental results. Figure 4.20 represents the model's ability to still demonstrate proportionally increasing nonlinear response with respect to maximum elongation. This illustrates its potential

at providing an accurate portrayal of the elastomer's mechanical response, with parameters optimized to a greater value of experimental stretch ratios. Evidently, due to the testing limitations, changes to testing mechanisms would need to be implemented to allow the material to be elongated biaxially at stretch ratios greater than the ones achieved in this body of work.

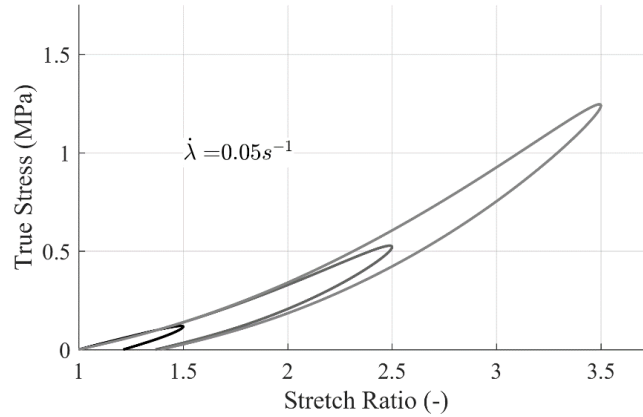


Figure 4.20: Theoretical plot of biaxial tensile test at various large maximum stretch ratios for VHB 4910 tape ($\dot{\lambda}_{1,2} = 0.050 \text{ s}^{-1}$)

The next set of plots, depicted in Figure 4.21 represent the model under varying stretch rates of $\dot{\lambda}_{1,2} = 0.030 \text{ s}^{-1}, 0.060 \text{ s}^{-1}, \& 0.090 \text{ s}^{-1}$. All three rates were set to elongate at a maximum stretch ratio of $\lambda_{max} = 1.7$, in order to keep within the limits of the experimental data used for parameter fitting.

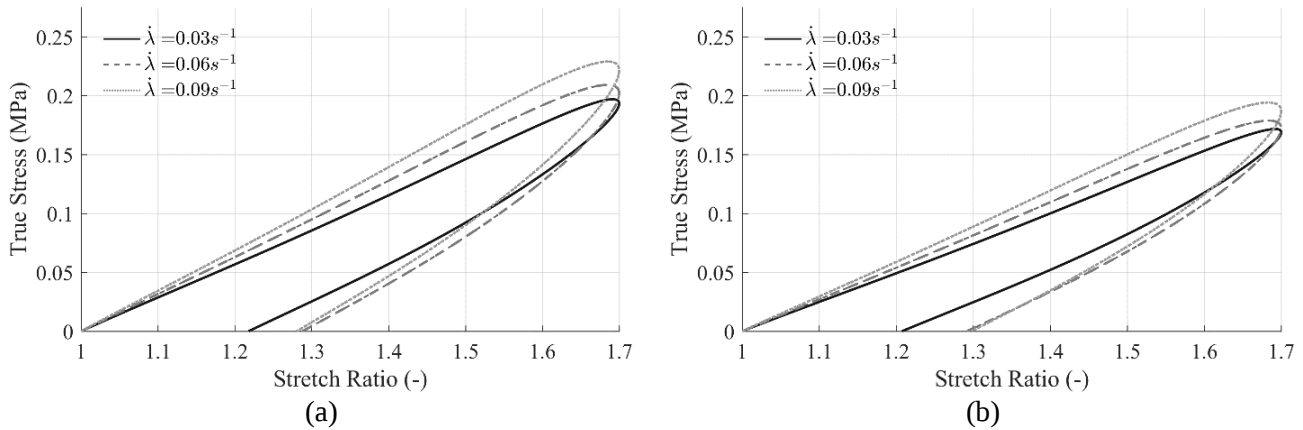


Figure 4.21: Theoretical plot of biaxial tensile test for various stretch rates at $\lambda_{max} = 1.7$ for (a) VHB 4905 tape and (b) VHB 4910 tape

For both tapes, a clear correlation between the stretch rate and peak stresses is displayed. This demonstrates the model's ability to predict the elastomer's viscoelastic response to an increase in

rate of elongation. It can be seen that the variation in loss factor is also demonstrated with respect to the change in angular frequency. In both plots, the stretch rates and maximum stretch ratio equate to a ω value nearing the maximum loss factor value represented in Figure 4.17. It can therefore be seen that, due to approaching energy-dissipation maxima, the increase in total energy loss is progressively less noticeable. Past this point, internal dissipation will start to decrease with respect to the increasing stretch rates.

A last series of tests was performed in order to evaluate the model under non-equiaxial tension. That is to say that λ_1 and λ_2 are not elongating to the same maximum stretch ratio. The model was then applied to this experimental data to evaluate its abilities of simulating kinematic parameters that may be more representative of true DE based actuator configuration (since not all designs will stretch the elastomer to equiaxial stretch ratios). The tests were arranged for two stretch ratios for λ_1 . Specifically, $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ and 0.300 s^{-1} . Three cases for each stretch rate were applied; the maximum stretch ratios for either axes were set to $\lambda_{1(max)} \times \lambda_{2(max)} = 2 \times 1.25, 2 \times 1.50$, and 2×1.75 . The stretch rate $\dot{\lambda}_2$ was calculated to ensure a paralleled motion between the two axes. In other words, even though their maximum achieved stretch ratios were not equal, the loading cycles for λ_1 and λ_2 reached their peak at the same time. A figure of two examples can be found in Figure 4.22. All examples of these experiments can be found in Appendix B.6.

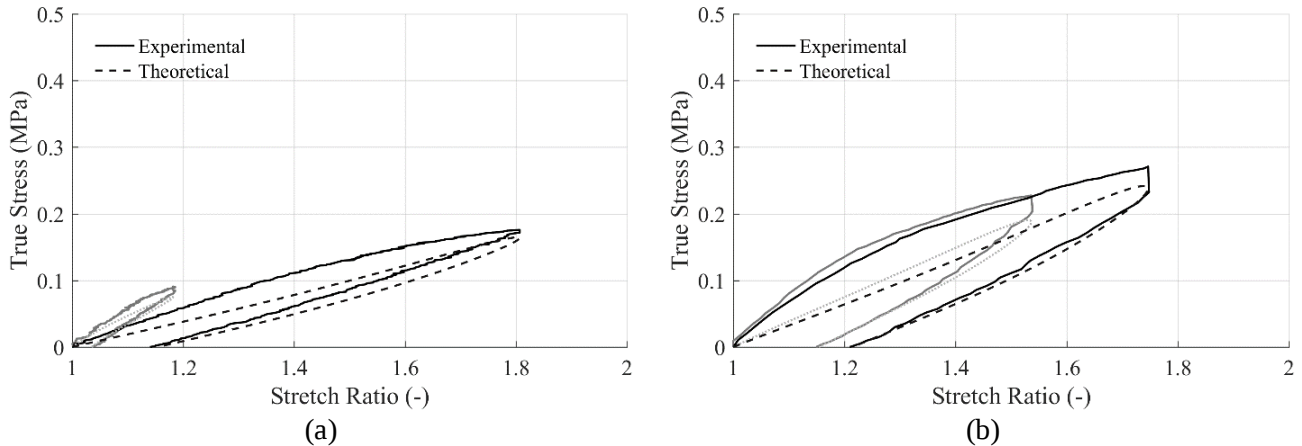


Figure 4.22: Theoretical plot of biaxial tensile test for various non-equiaxial stretch rates for VHB 4910 tape at (a) $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.25$, and (b) $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.75$

The model demonstrates the ability to adjust the axes stresses according to the change in parameters for both stretch rates. It can be noted that, unlike the equiaxial conditions, the

theoretical stresses undershoot the peak experimental stress values, particularly for the higher stretch rate. The prediction of energy dissipation is also much less accurate. The decaying slope behaviour of the elastomer is not reflected in these examples, due the same reasons previously discussed. Further investigation will be required to confirm its abilities to model non-equiaxial stretching at greater elongations. This ability to predict such behaviour is, however, greatly valuable for design purposes. In many cases, dielectric elastomers will not be stretched to equiaxial configurations for applications in actuators. It is therefore important to understand their behaviour under uneven tensile loading. The novel proposed biaxial visco-hyperelastic mechanical model could therefore provide a useful tool for these types of elastomer configuration during design considerations.

This newly developed biaxial visco-hyperelastic model, based on the enhanced Kelvin-Voigt rheological model, has thus demonstrated a simple and straightforward approach to analytically describe the mechanical behaviour an acrylic based dielectric elastomer. Through the use of a simple mathematical structure based on the generalized Hooke's law (for isotropic materials) under biaxial tensile loading, it has proven effective in anticipating the material's mechanical response variations relative to changes in stretch rate and maximum elongation. Errors in its behaviour stem from the same assumption of harmonic motion as the uniaxial consideration. In addition, the model was only fitted to a small spectrum of stretch ratios. Although this provided the model with an adequate range of angular frequencies for fitting purposes, the experimental data did not illustrate the elastomer's intrinsic nonlinear exponential response. This generally affected the parameters, and ultimately decreased the model's ability to give accurate stress curve trends for various loading conditions. Despite this aspect, the model still maintained expected peak stress values for the variations of kinematic parameters. It has also proven effective at providing general mechanical response for unequal biaxial tension. This, along with the aforementioned predictive abilities, will prove very useful for design considerations. The model also provides the foundation for a biaxial electro-mechanical model, which would enable the forecasting of dielectric elastomer behaviour under electro-mechanical coupling. This would deliver an additional design tool for actuator modelling under activation.

CHAPTER 5

Linear Actuator Prototype

Following the experimental and analytical characterization of the selected VHB tape, this chapter presents the design and development of a proof of concept for a DE-based linear actuator. Through preliminary experimental testing, the actuator prototype has successfully demonstrated adequate concept validation, and offers the foundation for future design development and optimization. This chapter further describes the development and pilot testing of the prototype, based on the operational principles of the originally proposed actuator design. It will first illustrate the structure and assembly of the prototype, followed by preliminary testing to achieve reciprocal linear motion.

5.1 Prototype Design

In Chapter 1, the development of a novel DE-based linear actuator was proposed. As was shown in Figure 1.1, the actuator consists of a multi-layer dielectric elastomer flat core, which is held in a stretched configuration by a series of flat springs. The working principle of this concept is simple: as the voltage is applied to the electrodes, the induced electric field applies a compressive force across the dielectric elastomer and results in an expansion of the core material. When the voltage is removed, the elastomeric core is in an inactive mode and will thus return to its initial position, creating the reciprocal motion of the actuator.

Given the scope of the thesis, a simplified prototype was developed to validate the fundamental principles of operation of the proposed linear actuator. The goal of the prototype was to qualitatively illustrate an achievable reciprocal linear motion by using a DE film and external springs. The main design criterion for the prototype was to achieve maximum linear actuation using a simple design mechanism. This would also allow straightforward fabrication and permit the testing parameters of the device to be easily modified.

To accomplish this, the prototype's structure was therefore established to be a single-film DE core with a pair of mirrored external springs acting against the film's x-y plane (i.e. " $\lambda_1 \times \lambda_2$ " planar surface). As in previous chapters, x-axis (" λ_1 ") is the axis of desired linear motion, and y-axis (" λ_2 ") is its orthogonal (or lateral) counterpart. For the remainder of the chapter, this plane will be referred to as the membrane plane. Since the structure will only be supported by the two springs, additional lateral (y-axis) support was necessary to ensure proper linear motion. The prototype was therefore fitted with a linear guiding track. The track was added to simulate the lateral stability, which would otherwise be enforced by the circumferential multi-spring structure of the proposed design concept. This ensured that the major deformation of the membrane would be focused along the axial direction (i.e. x-axis), and that no lateral or transverse (i.e. y- or z-axis) sway would interfere with the motion. A fully assembled rendering of the final prototype structure, excluding the dielectric film, is shown in Figure 5.1. It is composed of four main components: the DE film and compliant electrodes, the slider-supports, the external springs, and the linear guiding track. The DE film and electrodes component was comprised of a single layer of 3M VHB 4905/4910 film coupled with carbon conductive grease, as was used in Chapter 3.

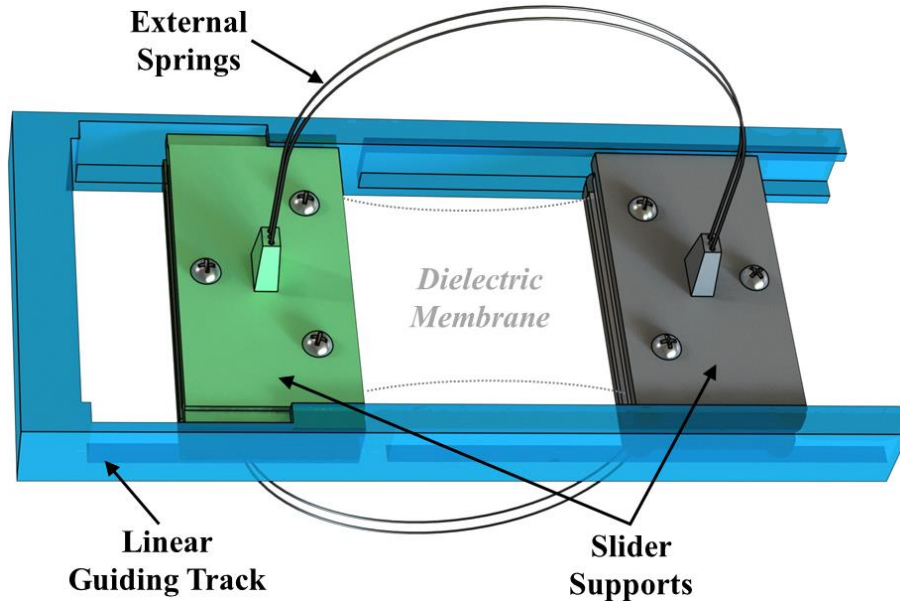


Figure 5.1: Full prototype assembly rendering (excluding DE film)

To fix the membrane to the rigid structure and springs, a pair of slider-supports were devised for either end of the membrane. Renderings of these slider-supports can be found in Figure 5.2. The supports' subassembly was comprised of an acrylic-plate core (which served as the adhesion site for the DE film), and a polylactide (PLA) outer frame (which provided the sliding interfaces and spring connections). Four plates of 2.54 mm-thick (0.1 in) poly(methyl methacrylate) (PMMA) were laser-cut to size with necessary screw-holes, using an Epilog Mini 24 Laser Cutter. PMMA was selected for these plates to provide a smooth uniform surface for VHB tape adhesion. The tape has also been described as particularly effective for bonds between acrylic surfaces, by the manufacturer, which reinforced the selection of acrylic as an appropriate bonding surface. Having the application plates as separate entities also proved to be better for the assembly process, since the spring-connection columns on the slider-supports would otherwise create a challenging geometry to stabilize while applying the DE.

The plates were then combined with an outer-frame. These provided a connection site for the springs, as well as shoulder-type supports that are compatible with the linear guiding track. The outer-frames were first drawn using SolidWorks 3D CAD Software and then printed using an Ultimaker 2+ 3D Printer and associated Cura software. Ultimaker PLA filament was used to produce the parts. The printer settings were set to high resolution and dense infill in order to achieve accurate dimensions, with a smooth surface finish and rigid structure.

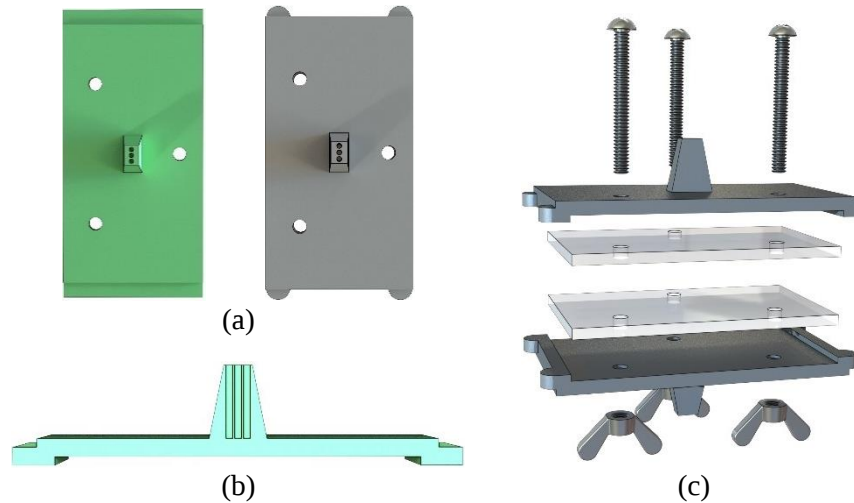


Figure 5.2: Sliding-support structure and assembly
 (a) Stationary (left) and mobile (right) slider-support geometry top view,
 (b) Slider-support cross-section view to demonstrate spring connection cavities, and
 (c) Exploded view of slider-support assembly (without DE film)

The parts were then finished by filing down any uneven or rough surfaces, and by boring the screw and spring holes using a drill-press and appropriate drill bit sizes. The outer-frames' geometry was comprised of a housing for the acrylic plates, side appendages which serve as the supports for the sliding track, and the spring connection column. As can be seen in Figure 5.2 (a), two separate structures were developed for the sliding supports. This is due to the fact that one pair of supports will be slotted into the guiding track to remain stationary, whilst the other pair will be mobile within the track. The stationary supports were therefore outfitted with a full-length side-shoulder to allow complete contact within the slot. This was done to ensure it remains locked in place during the linear actuation process. Alternatively, the mobile supports were cut down to have four small semi-circular shoulder geometries and reduce the surface of contact (thus minimizing the friction along the slider-track interface). The outer-frames have a spring connection column placed at the centre of their geometry (Figure 5.2 (b)). This column contains 12.7 mm-deep (0.5 in) cylindrical cavities, which allow the springs to easily be slotted into the prototype during assembly, without the need of additional fixation. The walls of the cavities resist the spring forces and transmit them to the DE film. Three cavities were chosen for the design to allow multiple spring combinations to be used during experimentation. The overall sliding support subassemblies were secured using machine screws and nuts. An exploded view of the mobile slider support (excluding DE film) can be seen in Figure 5.2 (c).

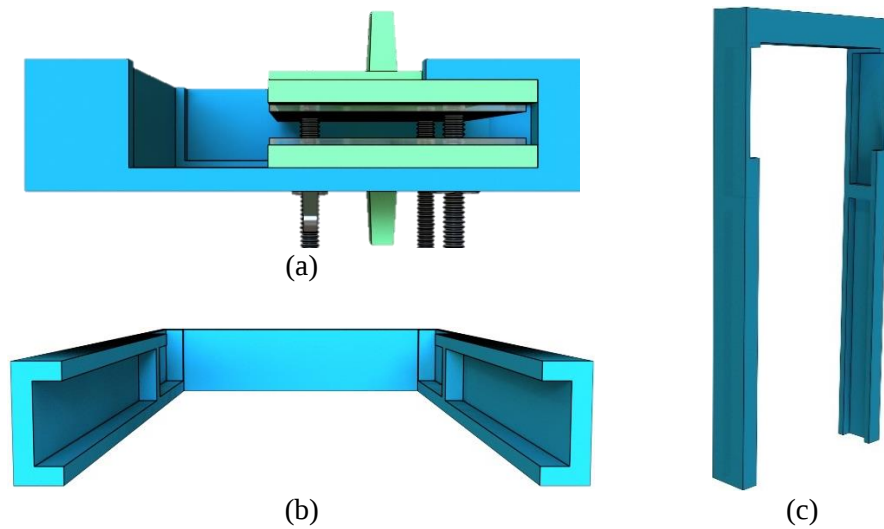


Figure 5.3: Linear guiding track

- (a) Cross-section showing stationary slider-support in its resting slot,
- (b) Front view showing sliding tracks with open end, and
- (c) Side view with slight transparency to demonstrate parallel geometry of tracks

As shown in Figure 5.3, the linear guiding track is comprised of two distinct parts: the resting slot for the stationary support, and the track for the mobile support. One extremity of the linear guide consists of a cut-out insertion point that is connected to the “resting” slot, which serves as the fixation point for the stationary slider-support (Figure 5.3 (a)). Below this slot, a second independent track follows the remainder of the guide’s length to an open end (Figure 5.3 (b)). This portion acted as the linear director for the mobile slider-support. The linear guide was first drawn using SolidWorks and printed using an Ultimaker 2+ 3D Printer with Ultimaker PLA filament, similar to the slider-supports. The printer settings were set to high resolution and dense infill, in order to achieve accurate dimensions, with a smooth surface finish and rigid structure. It should be noted that the linear guide was not printed in one piece. It was separated at the top connecting-bridge, into the two sides and an top piece, and then assembled post-printing. This allowed the inner-surfaces of the tracks to be printed facing upwards, which eliminated the need for structural supports during the printing process (by removing any overhanging portions of the structure). Supports typically leave residual pieces on the parts’ surfaces, which greatly affect its smoothness and uniformity. By removing the need of supports, the inner surfaces of the track were therefore printed with high surface finish, to minimize friction during the sliding motion. The three-piece assembly was glued together using IPS Weld-On 16 Plastic Cement, to create the final structure. A rendering of the full structure is depicted in (Figure 5.3 (c)).

To replicate the external forces created by the flat springs in the proposed actuator design, the simplified prototype made use of music wires. The wires, from K&S Precision Metals, were selected with different diameters to provide a variety of stiffness options for experimental iteration. They are composed of spring-tempered, phosphate coated, carbon steel (ASTM A228) [99]. As previously described, the springs are installed in the prototype by simply slotting them into the cavities within the slider-supports' column. A cross-section depicting this can be seen in Figure 5.4. Full engineering drawings of all components of the prototype can be found in Appendix C.

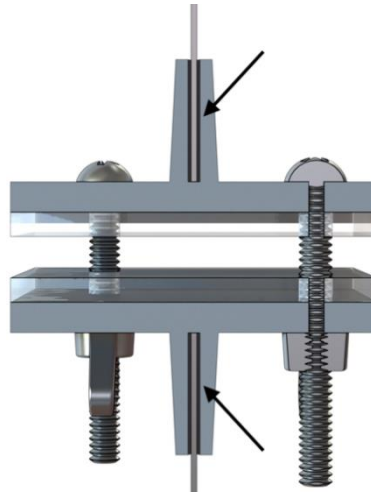


Figure 5.4: Side cross-section of spring and slider-support assembly (excluding DE film)

The working principle of the prototype is based on the equilibrium of forces between the DE film and the external spring forces, as seen in Figure 5.5. The following provides an illustrative explanation of these principles. At initial resting state (a), the membrane tension force and spring forces are in equilibrium. When the voltage is applied to the electrodes on either side of the DE, the Maxwell stresses (created by the attraction between the electrodes) will force the tape to expand due to its incompressible nature. This deformation results from the decrease in membrane tension, similar to that discussed for the experimental case in Figure 3.15.

At the first instance when the film expands (i.e. prior to any movement made by the mobile-end of the actuator) the membrane will “relax”, causing an imbalance between the membrane tension and the external forces of the springs. A depiction of this theoretical mid-phase can be seen in Figure 5.5 (b). To reach a new state of equilibrium, the mobile slider-support will extend under the greater external axial forces of the springs, and tighten the relaxed film. The tension within

the activated membrane will increase during this elongation until it reaches a new force equilibrium, resulting in a linear expansion Δl . This final equilibrium state is represented in Figure 5.5 (c). It should be noted that, in actual terms, the film's relaxation and expansion happen simultaneously rather than independently.

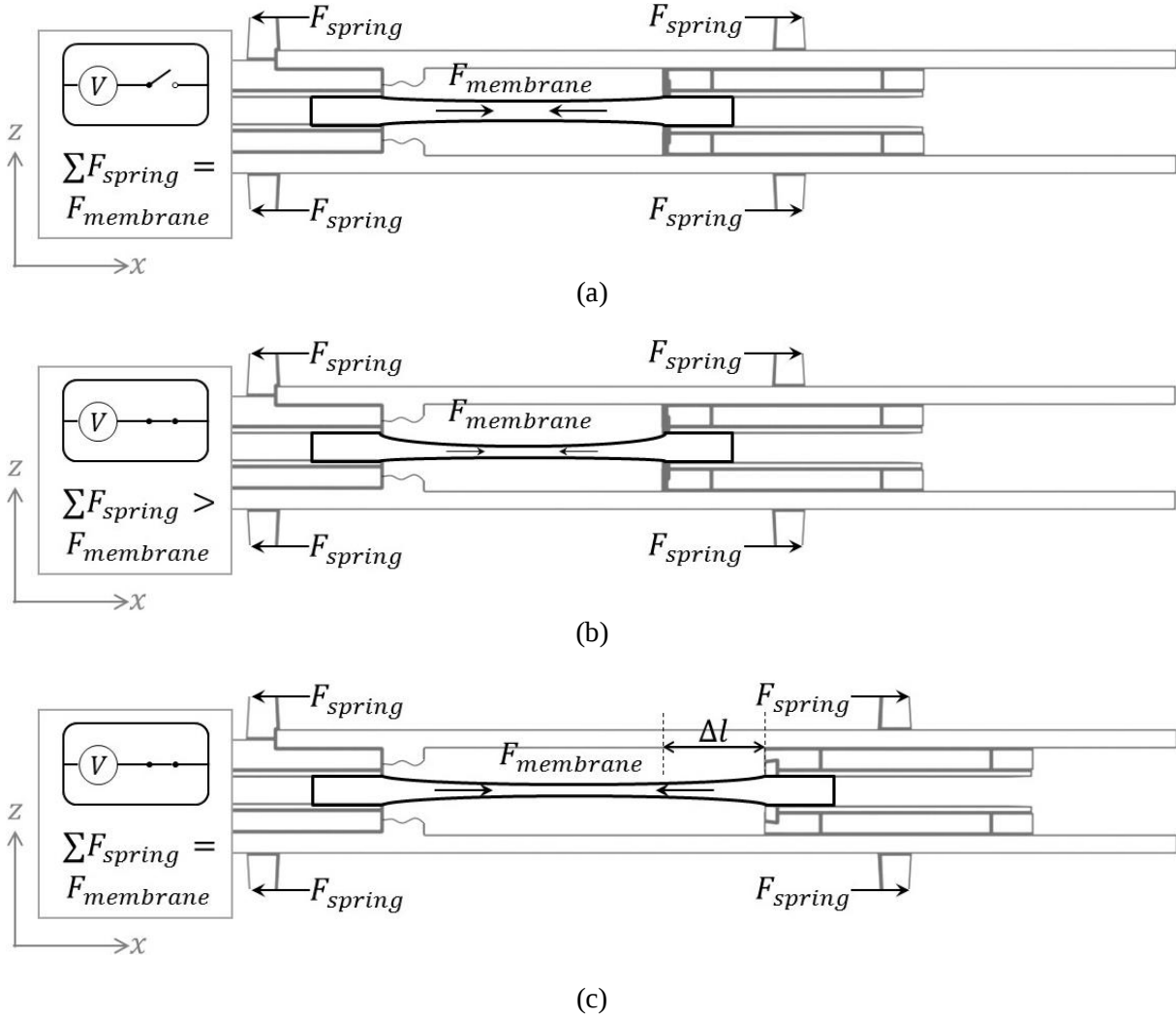


Figure 5.5: Working principles of prototype actuation

- (a) Film is at rest and no voltage is applied,
- (b) Theoretical moment immediately after voltage application when film has relaxed, and
- (c) Final state of equilibrium after voltage has been applied

The process of recovery can be explained with the exact same logic, in reverse order. In other words, once the voltage is removed, the Maxwell stresses that kept the membrane in an expanded state are now removed. This causes the DE film to recoil back to its original size, which in turn

increases the membrane tension. The increased tension will thereby cause an imbalance between the external and internal axial forces of the system. The mobile slider-support will thus be retracted back to its original position (by translating a length of Δl in the negative-axial direction) in order to re-establish a force equilibrium between the elastomer's internal forces and those applied by the external springs.

The working principles presented are theorized under several assumptions. The system displayed in Figure 5.5 neglects any friction along the slider-track interfaces. It is evident that there will in fact be frictional forces acting along the mobile slider-support's contact points. This will inevitably affect the system's mobile efficiency, since part of its energy will be expended on overcoming this friction. With the combination of the parts' relatively low weight and high surface smoothness, the friction forces have been assumed negligible for the aforementioned explanations, but will be considered during experimentation.

Another assumption is that the spring forces acting on the top and bottom portions of the slider-supports are identical in magnitude and direction, and remain planar along x-z plane (i.e. " $\lambda_1 \times \lambda_3$ " planar direction). For the remainder of the chapter, this plane will be referred to as the thickness plane. Each spring connection point can be seen as a fixed-type support, which infers the presence of resulting reaction forces along both axial and transverse axes, as well as a bending moment (Figure 5.6 (a)). By assuming perfect symmetry between the opposing spring connections (of the same slider-support), the transverse forces and bending moments created by these connections will cancel each other out, through the sum of forces in static analysis. As can be seen in Figure 5.6 (b), the resulting force diagram for equilibrium at any membrane elongation will therefore only be a factor of the membrane tension and the horizontal component of the spring forces on either side of the supports.

Achieving the level of spring-force symmetry and pure planar orientation assumed is physically improbable, which not only implies that transverse forces and bending moments will be present within the thickness plane, but that certain lateral forces and bending moments within the membrane plane will be present as well. The occurrence of off-axis forces and moments within the thickness plane would cause uneven force distribution along the eight contact points of the mobile slider-support. This will result in increased and concentrated frictional forces at the points which have greater normal forces with respect to the linear track.

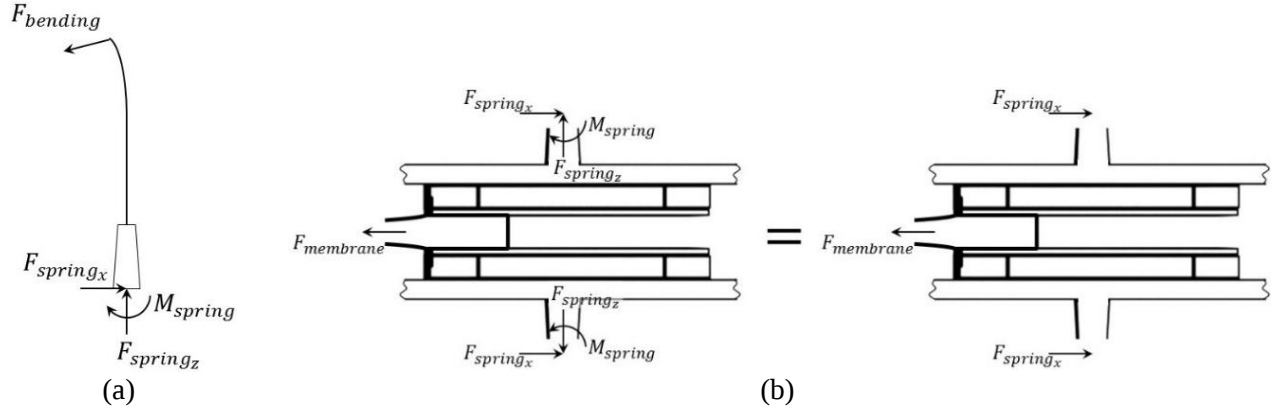


Figure 5.6: Spring reaction forces on slider-supports

- (a) Bending spring force and resulting reaction forces at base of connection point, and
(b) Equivalent force diagram after cancelling all opposing forces from mirrored spring reactions

Furthermore, the presence of lateral forces and moments within the membrane plane would result in unfavourable lateral translation and rotation of the DE film, which would reduce the efficiency of linear actuation. In the current prototype configuration, transverse z-forces and bending moments (due to unsymmetrical spring reactions) have been supposed negligible since their magnitudes will be small relative to the axial actuation forces. The lateral y-forces and bending moments along the membrane plane, due to spring misalignment, have also been deemed negligible since the greatest deflection of the wire will still remain along the thickness plane. The linear track will ensure that the slider-supports (and therefore springs) are aligned along the thickness plane within reasonable limits, and that any off-plane deflection would be minimal. This thereby implies that the resulting forces and moments are also negligible.

The final assumption made for the current illustration of working principles considers the membrane as being purely elastic, thus allowing it to fully recover during deactivation. This assumption is inaccurate, as was demonstrated in Chapter 3, where both VHB tapes demonstrated discernible viscoelastic behaviour. It is therefore expected that the prototype will not fully recover to its original position, due to the material's inherent mechanical properties. The recovery of the prototype will be observed during experimental proof of concept, in order to confirm whether viscoelasticity of the polymer will have noticeable effects on its efficacy.

5.2 Prototype Assembly

To ensure consistency, a series of assembly steps were carefully developed and implemented for the production of various prototype configurations. This process included three phases, namely: the membrane application phase, the structure assembly phase, and the electrode application phase. These steps are summarized below. A detailed description of the assembly process is provided in Appendix C.2. It should be noted that, given the thickness of the VHB 4905 tape and its challenges during preliminary experimentation (e.g. membrane tearing during application, frequent dielectric breakdown, etc.), only VHB 4910 tape was tested as a membrane for the prototype proof of concept.

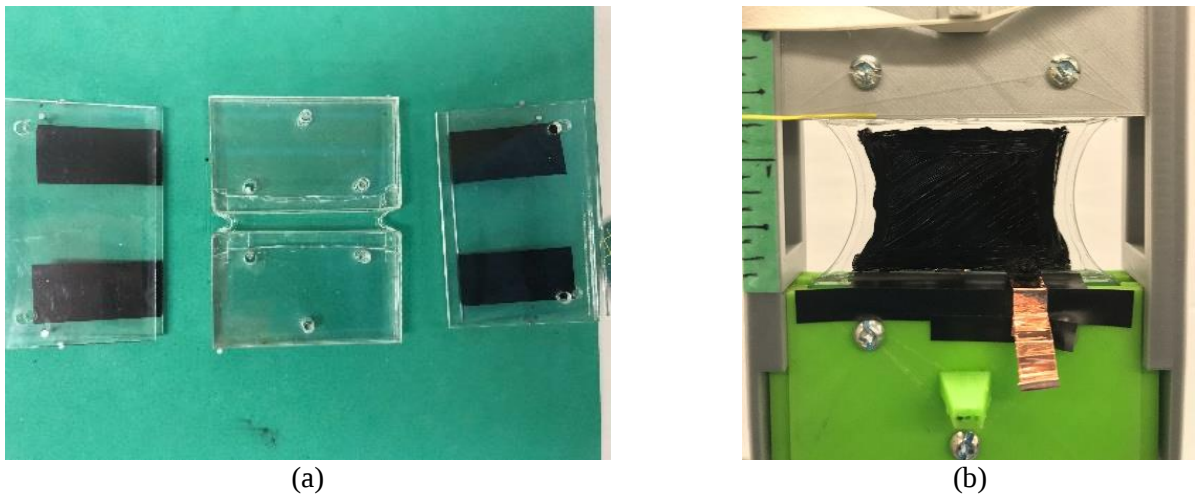


Figure 5.7: Prototype assembly process

- (a) Final membrane once top plates have been applied and sides have been separated from application plates, and (b) Slider-supports in linear track with painted membrane (compliant carbon grease electrodes)

The first step in the process consisted of stretching the dielectric membrane and applying it to the acrylic slider-support internal plates. Similar to the electro-mechanical specimens of Chapter 3, the internal surfaces of all acrylic plates were lined with a piece of VHB 4905 tape. This was done to ensure proper adhesion of the membrane while also minimizing the risk of film tearing (due to contact with the edged of the acrylic, or by over-compressing it between the plates). The acrylic plates were held down using a template, which used a series of guiding-rods and nails that slotted in and around the plates. The VHB 4910 tape was cut to size and stretched to the width of the supports. It was then carefully pressed down onto one pair of plates, and sandwiched between the second pair. It should be noted that the membrane's free-hanging y-axes edges were reinforced using a narrow layer of VHB 4905 tape on either of its sides. This was done to both

reduce the effects of edge defects caused by the cutting process, and also to reduce the inwards bowing of the membrane's edges. The result of the first phase of assembly is shown in Figure 5.7 (a).

Following the application of the dielectric film, the prototype plates were removed from the application pad and fitted with slider-support outer frames. These supports were attached using a series of machine screws and nuts. The supports were then installed within the linear guiding track by first inserting the mobile (grey) slider-support into the linear track and sliding it up to the inner most portion of the track. The stationary (green) slider-support was then stretched upward and slotted into the resting slot of the linear guiding track. Once the structure assembly phase was complete, the prototype was then held in a bench vice for the final electrode application phase.

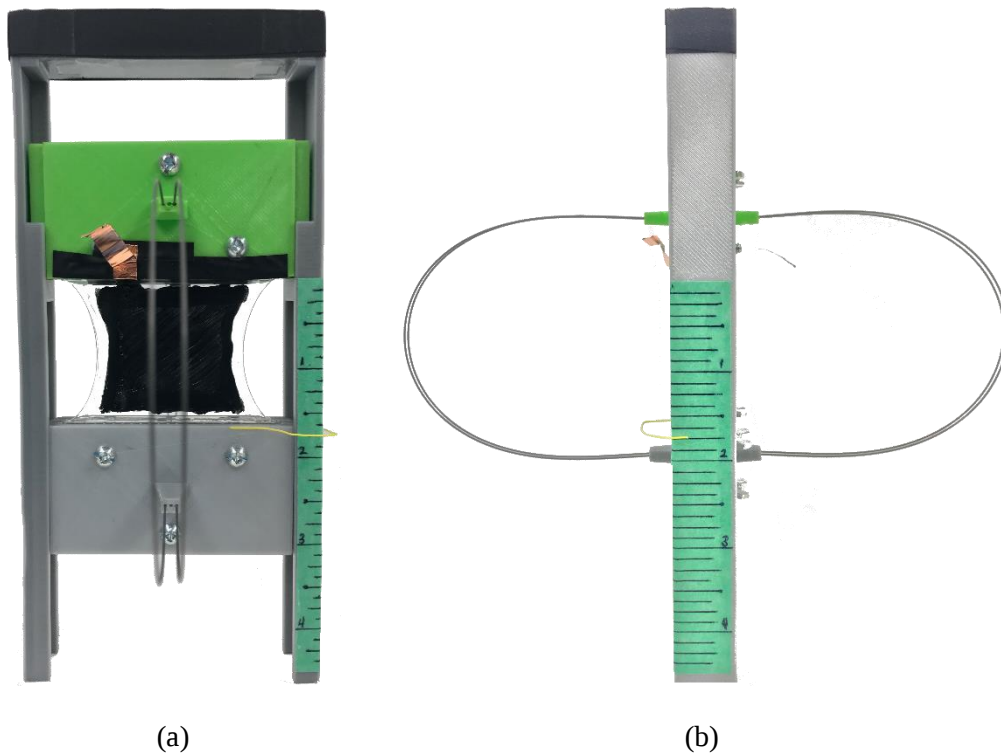


Figure 5.8: Full prototype assembly
(a) Front view, and (b) Side view

The inner faces of the slider-supports were first lined with electrical tape. A copper-tape electrode was then applied on either side of the stationary (green) slider-support, to be used as the connection point for the circuit. The dielectric film was painted using the same 3:1 solution of carbon conductive grease and motor oil used for experimentation (Chapter 3). A 10-mm unpainted edge

was maintained for all prototypes, to avoid the risk of failure due to dielectric breakdown. An illustration of this final stage can be seen in Figure 5.7 (b). Following the application of the electrodes, the music-wire external springs were inserted into their respective slots to complete the prototype assembly. The wires were selected in 0.051 mm (0.020”), and 0.064 mm (0.025”) diameters for the experimental setup, as they both offered appropriate stiffness to resist the force of the DE film. Once all springs were installed into the assembly, the prototype was left to rest for 30 minutes, to allow the polymer to achieve its full stress-relaxed state. An example of a fully assembled prototype can be seen in Figure 5.8.

5.3 Testing and Proof of Concept

To confirm proof of concept, the prototype was tested under various parameters to illustrate the design proposal’s achievable reciprocal linear motion and potential customizability. The prototype was tested in two positions with respect to the direction of actuation: horizontal relative to the ground, and downward-vertical relative to the ground. A single value for width stretch ratios (λ_2) was selected, based on the optimal parameters discussed in Chapter 3. This stretch ratio was then combined with three different spring-stiffness configurations that would elongate the film to an approximate axial stretch ratio (λ_1) that (in combination with its fixed width stretch ratio) fall within or above the optimal ranges of activation.

Initially, a width stretch ratio of $\lambda_2 = 3$ was selected, based on the higher total force drop observed (Chapter 3). After several attempts with varying spring combinations, no discerning reciprocal motion was achieved. A prototype width stretch ratio of $\lambda_2 = 4$ was therefore selected for the proof of concept. As previously mentioned during experimentation, the $\lambda_1 \times \lambda_2 = 4 \times 4$ equiaxial stretch ratio combination also seems to be the popular choice in literature, which reinforces this decision.

A summary of the stretch ratio combinations for the three music wire spring combinations are listed in Table 5.1, for the prototype held in both horizontal and downward-vertical positions. This table provides the number of total wires (springs) installed in the prototype, and the approximate axial stretch ratio achieved after allowing the prototype to rest in stretch-state for 30 minutes. It should be noted that the wires listed in the table were distributed symmetrically on both sides of the prototype. This is to say that if, for example, 4 springs of the same dimensions are listed, this

means 2 springs were installed per side. It should also be noted that dimensions are listed in SI units for consistency, however, were provided by the manufacturer and measured in US Standard (e.g. 228.6 mm = 9 in). The differences in horizontal and vertical initial stretch ratios are the result of additional applied weight of the mobile slider-support onto the membrane (due to gravity in a vertical orientation).

Table 5.1: Music wire spring combination and achieved initial stretch ratio

Config.	Music Wire Spring Combination (no. of springs) $\times$ [wire diameter $\times$ wire length]	Approximate Initial λ_1 (mm/mm)	
		<i>Horizontal</i>	<i>Vertical</i>
(1)	$2 \times [0.064 \text{ mm} \times 228.6 \text{ mm}]$	4	6
(2)	$4 \times [0.064 \text{ mm} \times 228.6 \text{ mm}]$	6.5	8
(3)	$\begin{cases} 2 \times [0.051 \text{ mm} \times 228.6 \text{ mm}] \\ 4 \times [0.064 \text{ mm} \times 228.6 \text{ mm}] \end{cases}$	7.5	8.5

The full experimental setup, with prototype in horizontal configuration, can be seen in Figure 5.9. The prototype was held in position by a bench vice, and the copper contact electrodes were connected to the circuit using alligator clips. A rubber band was placed behind the stationary slider-support to prevent any potential kick-back while activated. During experimentation, a thin piece of wood, cut to the linear track's exact width, was placed at the farthest edge of the track (which can be seen in Figure 5.10). This was done to prevent the plastic track's width from potentially narrowing along its length, due to the structure's flexibility. In order to provide the electrodes with the appropriate voltage, the same circuit and DC-to-HVDC converter from Chapter 3 were used.

To test the prototype's electro-mechanical behaviour, three cycles of 0V to 5 kV were performed. The power source was turned up to the 12V maximum input voltage accepted by the EMCO G50R HVDC converter, and the prototype was left to rest for 10 seconds prior to recording its final elongation. This was done to ensure sufficient film-expansion response time was provided. The same series of tests were performed with the prototype in downward-vertical configuration. In this case, the experimental setup was identical, however the prototype was held by the bench vice with the track-opening facing the ground (i.e. downwards linear motion of the actuator).

Appropriate safety measures were taken throughout experimentation. All exposed connections and adjacent surfaces to the HVDC converter were covered with rubber sheets and electrical tape prior to testing. Throughout experimentation, safety goggles and safety gloves (rated up to 12 kV) were worn, and all experiments were performed standing over an insulative switchboard mat (rated up to 17 kV). In all cases, experiments were conducted at standard ambient temperature and pressure.

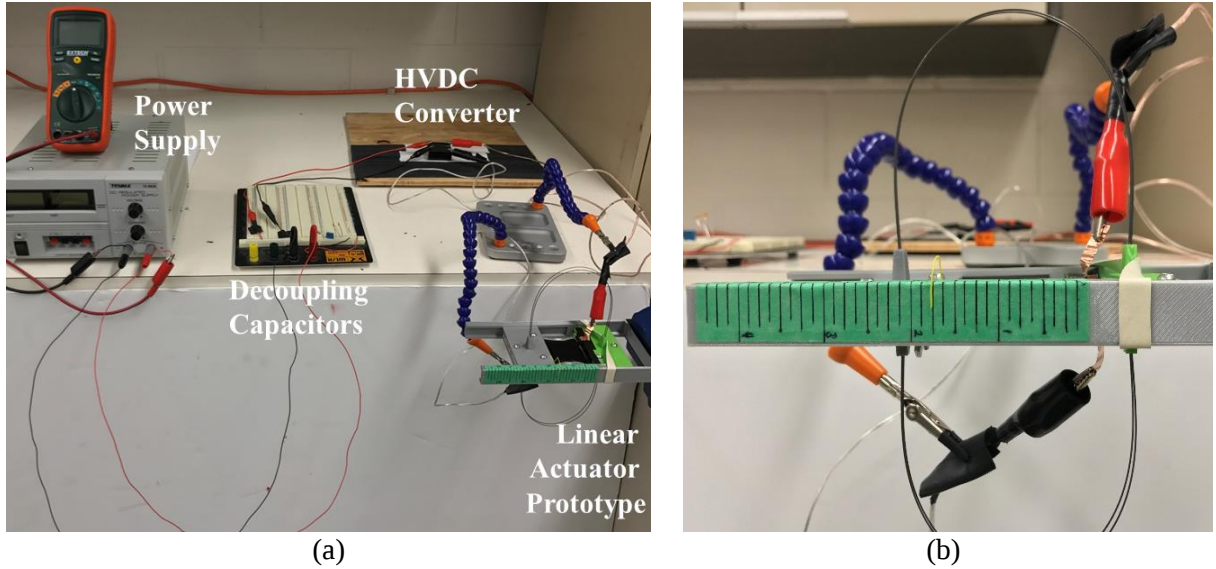


Figure 5.9: Experimental setup for prototype testing in horizontal configuration
 (a) Full experimental configuration, and
 (b) Close-up of actuator with circuit connections to copper foil electrodes

The following section will report and comment on the results of the experimental proof of concept. The actuation of the prototype will be described in terms of elongation (Δl) and recovery loss (ρ). The elongation Δl_i will be calculated as the displacement from the previous recorded position after retraction to the position reached after elongation. The recovery loss ρ_i will be calculated as the difference between the current position at rest with respect to initial origin (which was taken as the position of the actuator prior to any voltage application).

The experimental data recorded for the horizontal configuration can be found in Table 5.2. This table provides the position of the mobile slider-support for initial position, as well as both applications of voltage to the membrane electrodes. It should be noted that the measurements were taken in US Standard, since all specifications for parts purchased/designed were provided in this unit system. The scale drawn on the prototype was therefore also in US Standard, in order to facilitate the calculation of initial stretch ratio based on the membrane dimensions. The values

were then converted to SI units in order to maintain consistency with the remainder of the report. The values in SI units have been rounded to their nearest significant digit. It can be seen that, in all cases, an evident change in length of actuator was observed. It can also be noted that the total expansion increases proportionally with respect to the initial axial stretch ratio (λ_1).

Table 5.2: Approximate elongation measurements for prototype in horizontal configuration

Config.	Initial Length (mm [in])	1 st Elongation (mm [in])	1 st Retraction (mm [in])	2 nd Elongation (mm [in])	2 nd Retraction (mm [in])
(1)	25 [1]	27 [$1\frac{1}{16}$]	27 [$1\frac{1}{16}$]	30 [$1\frac{3}{16}$]	30 [$1\frac{3}{16}$]
(2)	41 [$1\frac{5}{8}$]	44 [$1\frac{3}{4}$]	43 [$1\frac{11}{16}$]	48 [$1\frac{7}{8}$]	44 [$1\frac{3}{4}$]
(3)	46 [$1\frac{13}{16}$]	52 [$2\frac{1}{16}$]	49 [$1\frac{15}{16}$]	54 [$2\frac{1}{8}$]	48 [$1\frac{7}{8}$]

In the case of configuration (1), it can be seen that reciprocal motion was not achieved. The slider expanded initially by approximately $\Delta l_1 = 2$ mm upon first activation, but did not recover. After second application of maximum voltage to the membrane, an expansion of approximately $\Delta l_2 = 3$ mm was reached, with a second unachieved recovery. It is possible that, at this configuration, the resulting membrane tension was insufficient to overcome the static frictional forces applied to the contact points of the mobile slider-support. This suggests that it is therefore essential for the spring-membrane force equilibrium to be reached at a force that is above the static frictional forces of the slider-track interface. Alternatively, the prototype would need to be modified in order to eliminate frictional forces altogether. It should be noted, however, that this obstacle only concerns the prototype, since the proposed final actuator design structure is meant to be trackless.

Both the (2) and (3) configurations were able to achieve reciprocal motion when applying a voltage to the electrodes repeatedly. In case (2), the initial deformation achieved was of $\Delta l_1 = 3$ mm, followed by a recovery with a loss of $\rho_1 = 2$ mm with respect to the origin. The second activation brought on an elongation of $\Delta l_2 = 5$ mm, and recovered to a final length with a loss of $\rho_2 = 3$ mm (which means an additional 1 mm was lost from the previous recovery stage). The loss in recovery lengths can perhaps again be attributed to the effects of friction on the support contact surfaces. In both cases, despite overcoming the static friction, the membrane may not have built up sufficient potential energy through elongation to overcome the effects of kinetic friction along the linear

track. This would have caused the recovery loss to increase incrementally until the film has reached a threshold large enough to start exhibiting repeatable cyclical motion.

Viscoelastic effects may have also played a part in the recovery loss during actuation. As was demonstrated in previous material experimentation, the VHB tape exhibits clear viscoelastic and time-dependant responses to tensile forces, more specifically through the effects of energy dissipation and stress-relaxations. This brings on two possible causes for the inability to return to the origin. It is firstly probable that, due to the energy dissipation (within the material) in tension the final state of the film will not recover to its original position. This behaviour has been characterized for both the mechanical and electro-mechanical responses of the material in Sections 3.1.3 and 3.2.3. A second factor affecting the polymer's ability to recover pertains to its stress-relaxed state. Upon first activation, which can be considered a type of "priming stage", further stress-relaxation may have occurred within the elastomer's microstructure due to the effects of external Maxwell stresses. This would be in addition to the stress-relaxed state enforced in the assembly process, prior to experimentation. To distinguish between effects of viscoelastic hysteresis, or polymer "pre-conditioning", further investigation would be necessary during prototype optimization.

A similar phenomenon was observed in case (3). The initial deformation achieved was of $\Delta l_1 = 6 \text{ mm}$ (the largest achieved axial extension in horizontal configuration), followed by a recovery with loss of $\rho_1 = 3 \text{ mm}$. The second extension reached approximately $\Delta l_2 = 5 \text{ mm}$, and recovered to a position with $\rho_2 = 2 \text{ mm}$. In this case, the second recovery was therefore more successful than the first, as it returned to a closer position relative to the origin. The success of this configuration can be attributed to the membrane's stiffer mechanical response. Referring back to Chapter 3, it is evident that, as the DE film's elongation is increased, its axial tension (and thus stiffness) will also increase. This will enable the film to counteract the static and kinetic frictional forces, therefore allowing the actuator to recover to nearly the same initial position. The greater success of the second activation's recovery can also be attributed to this same logic. It can be noted that, although the displacement of 1st elongation was greater, the second phase reached a further overall extension with respect to the origin. By using the analogy of a "sling-shot", it can be rationalized that this greater extension of the membrane increased the potential energy of the mobile slider-support. When deactivating the circuit, the larger stiffness built up within the film

allowed it to “shoot back” further, overcoming more of the kinetic frictional forces than in the first phase. This ultimately led to the actuator’s more successful recovery.

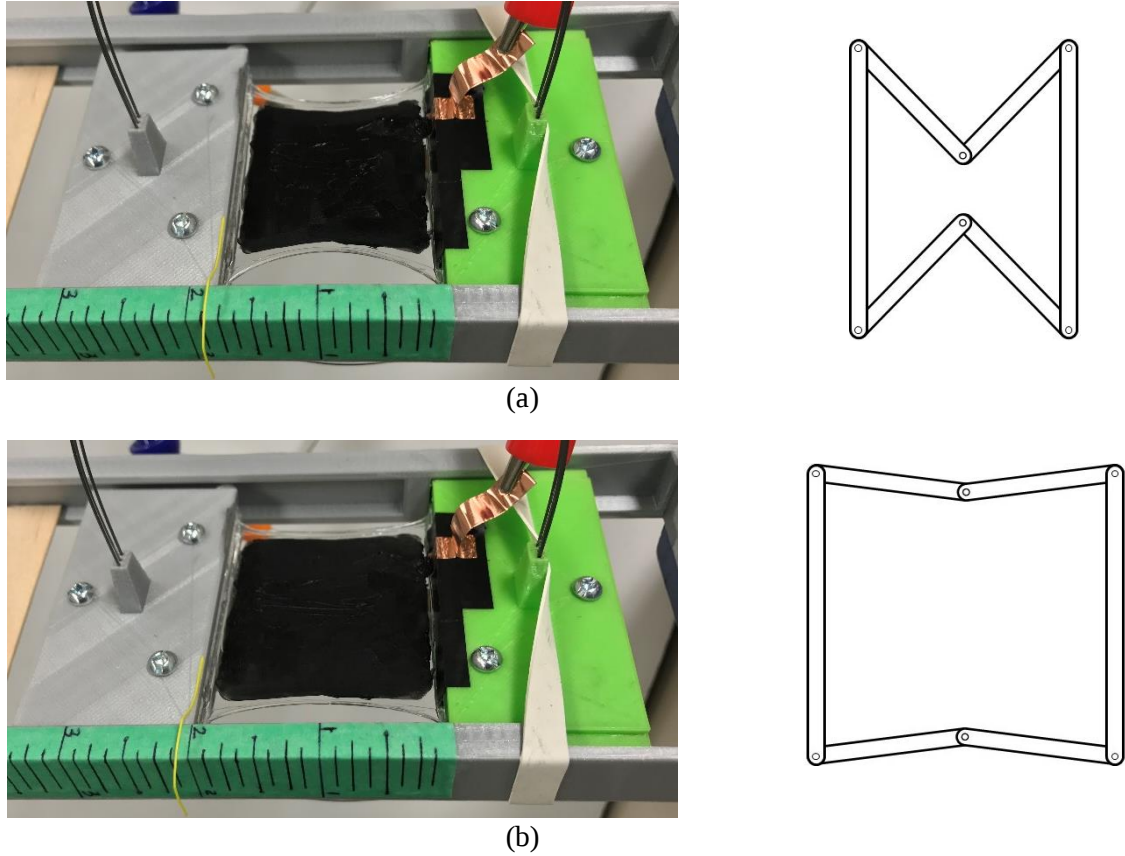


Figure 5.10: Prototype activation in horizontal position for spring configuration (3) where (a) is at rest and (b) is activated

Scenario (3) was also deemed the most successful in terms of overall achieved actuation, with an average elongation of $\Delta l_{avg} = 5.5 \text{ mm}$. A top view of this configuration is illustrated in Figure 5.10. The membrane relaxation can clearly be distinguished when the voltage is applied in Figure 5.10 (b). The film’s bowed geometry relaxes into a more rectangular profile, while the actuator extends forward. This change in the lateral geometry, which can be compared to a pseudo-scissoring mechanism, could potentially be optimized to increase performance. By changing the membrane’s width-to-length ratio, there would be an increase in lateral expansion. This would be analogous to increasing the length of the linkage lengths within the scissoring system displayed in Figure 5.10, thereby resulting in an overall greater lengthening of the actuator. It would also be of particular interest to try and couple the biaxial deformation with a rigid frame. This would be similar to the bow-tie geometry discussed in literature. Although it would lead to a more complex

assembly, this solution may prove more effective in transmitting linear motion. It would also provide a suitable frame to allow a stacked geometry to be developed in later iterations of the design. Further investigation of the lateral deformation and its effects of actuation efficacy is required, in order to quantify its potential exploitation.

Overall, it is evident that, although achievable, the reciprocal motion of the actuator is affected by the current prototype design. The friction between the surfaces of the slider-guide interfaces creates an obstacle for the mobile slider-support. This ultimately affects its efficacy and consistency. The structure will thus require design improvements in future actuator optimization.

The experimental data recorded for the vertical configuration can be found in Table 5.3. This series of tests was performed to examine the effects of the different spring stiffness conditions while attempting to eliminate the influence of friction on the edges of the mobile slider. This configuration, however, brought on the added factor of gravity as a parameter along the axis of actuation. The additional weight of the mobile slider was applied to the membrane, which in turn caused a greater initial stretch ratio (as seen earlier in Table 5.2). Contrary to the horizontal configuration, the results for all cases demonstrated a clear reciprocal motion. Similar to the previous setup, however, a proportional increase in achieved elongation, relative to the initial axial stretch ratio (λ_1), was also observed.

Table 5.3: Approximate elongation measurements for prototype in vertical configuration

Config.	Initial Length (mm [in])	1 st Elongation (mm [in])	1 st Retraction (mm [in])	2 nd Elongation (mm [in])	2 nd Retraction (mm [in])
(1)	37 [1 $\frac{7}{16}$]	41 [1 $\frac{5}{8}$]	40 [1 $\frac{9}{16}$]	41 [1 $\frac{5}{8}$]	40 [1 $\frac{9}{16}$]
(2)	49 [1 $\frac{15}{16}$]	54 [2 $\frac{1}{8}$]	51 [2]	56 [2 $\frac{3}{16}$]	51 [2]
(3)	54 [2 $\frac{1}{8}$]	60 [2 $\frac{3}{8}$]	56 [2 $\frac{3}{16}$]	60 [2 $\frac{3}{8}$]	56 [2 $\frac{3}{16}$]

In all three cases, an initial elongation (Δl_1) of approximately (1) 4 mm, (2) 5 mm, and (3) 6 mm were observed. For configuration (1), the recovery exhibited a loss of $\rho_1 = 3$ mm, whereas in the cases of (2) and (3), the recovery only exhibited a loss of approximately $\rho_1 = 2$ mm. This phenomenon, also observed in the previous horizontal configuration, is most likely attributed to the viscoelastic properties of the VHB tape. In this case, the configuration has virtually removed all effects of friction, which reinforces the influence of intrinsic material properties on actuation.

As previously discussed, the cause of this loss can either be attributed to internal energy losses of the elastomer, or by a potential additional stress-relaxation within its microstructure.

All cases in vertical configuration also demonstrated an almost unanimous repeated behaviour during the second activation phase. For cases (1) and (3), the second activation led to an actuation that reached a maximum elongation identical to the first phase. This signifies that, in both (1) and (3), the second elongation was less effective than the first, due to the recovery loss after first activation. In case (2), however, the film elongated beyond the first elongation measurement ($\Delta l_2 = 5 \text{ mm}$). This configuration therefore demonstrated a consistent elongation of $\Delta l = 5 \text{ mm}$ in both elongation steps, even after the recovery loss. It is possible that the first phase of actuation may have been affected by external forces acting on the mobile slider-support.

Despite attempts to fully reduce effects of friction, the slider was still in contact with the surface of the track. The mobile slider-support also exhibited uneven extension (i.e. rotation of slider about the transverse z-axis was observed). This may have been caused by ununiform weight distribution along the bottom of the membrane. It may also have been caused by unequal spring forces between the music wires, or because of the inconsistent stretch ratio of the film across the membrane plane. Despite these factors, the actuator managed to recover without additional loss, which demonstrates consistency in the deactivation phases. Figure 5.11 shows all five steps of configuration (3) in the vertical position. This demonstrates the clear reciprocal and repeated motion of the prototype. Following the origin line etched on the diagram, the losses in recovery can be noticed in the 1st and 2nd relaxation steps of (c) and (e).

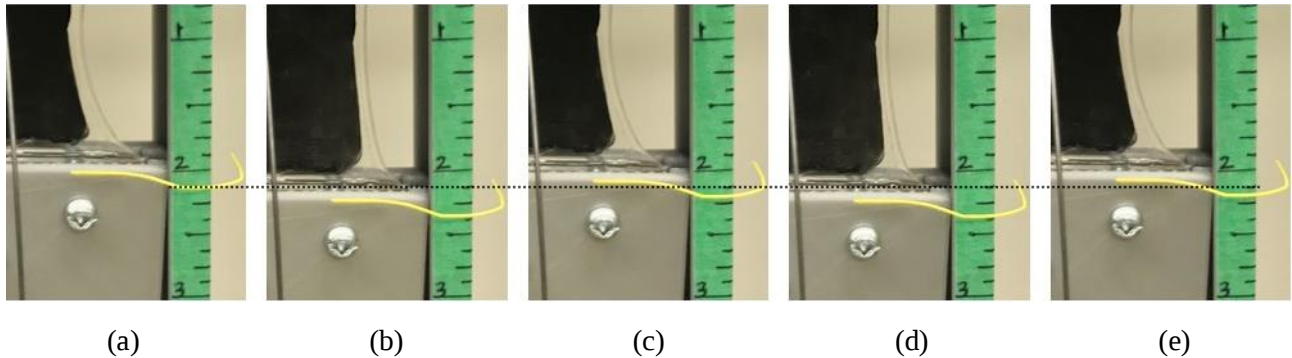


Figure 5.11: Prototype activation in vertical position for spring configuration (3) where (a) initial position, (b) 1st elongation, (c) 1st retraction, (d) 2nd elongation, and (e) 2nd retraction

Contrasting both experimental configurations, the consistency in the results of the vertical position firstly suggests that the frictional forces of the prototype's structure play a much larger role in its efficiency, and cannot be neglected. Of course, the two experimental configurations cannot be compared in parallel, since the initial axial stretch ratios for the same spring configurations was different. However, successful repeatability in the downward-vertical experiments attest to the correlation between friction and the actuator's elongation efficiency (compared to the horizontal configuration). It should also be noted that in the vertical case, the forces acting on the membrane are more constant than those during horizontal experimentation. This is due to the changing stiffness of the springs. As the actuator elongates, the curvature of the music wire decreases, which diminishes its "spring" force as the mobile slider-support translates further. Having the weight of the slider in addition to this spring force creates a more constantly applied load during elongation, which will result in a larger overall deformation of the membrane. The variable spring stiffness is a factor that needs to be improved in future developments of prototype optimization.

Overall, the vertical configuration proved more successful in demonstrating reciprocal linear motion, with better consistency and repeatability. Factors such as diminished friction and more constant external forces favoured the setup, and should be considered when optimizing the prototype. Greater initial axial stretch ratios may have also played a role in the success of the experiments. The correlation between initial axial stretch ratio and achieved actuation was noticed for the vertical setup, and should also be further investigated in contrast to the experimental results of Chapter 3. The prototype's testing has demonstrated achievable reciprocal linear motion, and can be deemed successful in proving the concept for the working principles. In both horizontal and vertical positions, a clear elongation-retraction motion was observed for all but one case. The actuator also demonstrated the potential of customizability, based on variable spring stiffness, which is a beneficial feature for its potential in multiple applications.

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The objective of this thesis was to provide the ground work for the development of a novel linear actuator design using a DE, followed by the development and testing of a working prototype. A literature review was first conducted to understand the working principles of these smart materials, and to examine the current advancements for their application and implementation. This survey led to the identification of certain gaps in current research. More specifically, 3M™ VHB 4910 series tapes lack mechanical characterization under biaxial tensile loading conditions, as well as a universally representative electro-mechanical characterization of the material. Furthermore, this investigation demonstrated absence of straightforward mechanical models able to assist in design and analysis of actuators exhibiting biaxial reciprocal linear motion. This led to the development of biaxial tensile experimental analysis of the elastomer's mechanical and electro-mechanical properties.

These analyses provided a comprehensive experimental evaluation of the VHB tapes biaxial tensile load-unload and stress-relaxation behaviour for various testing parameters. Through these experiments, the elastomer's viscoelastic and time-dependant behaviours were demonstrated, while illustrating its transversely isotropic characteristic. The material's electro-mechanical behaviour was also evaluated for biaxially strained configurations under uniaxial tension. Through static and dynamic experiments, the variation in electro-mechanical response was evaluated for different stretch ratio combinations. It was observed that the DE's relaxation, while activated, was directly affected by the changed in its thickness. No distinctive optimal stretch ratios were specifically concluded. Alternatively, the presence of a potential performance plateau region was noted, which complied with previous theoretical findings in the literature.

Subsequent to the experimental evaluation, a visco-hyperelastic analytical model was evaluated and modified for its application under biaxial tensile loading. This model proved effective at predicting the elastomer's viscoelastic response to varying stretch rates with a straightforward mathematical structure. The model demonstrated the ability to represent the changes of material behaviour based on variations of both maximum stretch ratios and stretch rates being applied to the elastomer. It also demonstrated its potential use for actuator design and modelling purposes by expanding its capabilities to the prediction of stress response for unequal biaxial stretching of the VHB tapes.

Finally, a simple prototype was developed using the working principles of the proposed actuator design. It achieved reciprocal actuation for various configurations, which has validated the feasibility of the design's structure. By the same token, it has demonstrated the design's ability to be customized for desired actuation outputs based on application. The actuator's assembly was also a simple process, which is of great importance to the design's success. Providing an easy assembly promotes the design's appeal for future applications.

6.2 Recommendations

In this work, the scope mainly revolved around the material characterization and preliminary prototyping of a DE based linear actuator. The first prototype iteration was therefore built based on findings from experimental results and the basic working principles of the proposed actuator design. In future advancements, the optimization of the prototype would be imperative to evaluating the feasibility of the design. Further investigation of structural and parameter modifications would broaden the knowledge on the efficacy of the actuator.

The experimental results proved valuable in the material characterization of the VHB tapes for both its mechanical and dielectric properties. Results were restricted, however, by the available instrumentation and its limitations. Firstly, it would be suggested to investigate the same sets of experiments using alternate fixation methods. Hexagonal samples with biaxial clamps would potentially provide a more secure fixation, with lesser deformation. It would also allow the samples to be deformed to much greater biaxial stretch ratios, without the risk of tearing samples. This method would additionally allow true biaxial evaluation of electro-mechanical properties, by

enabling the elastomers to be deformed on both planar axes while applying voltage to the electrodes.

These changes to the experimental setup would also enable further investigation of the validity of the proposed biaxial visco-hyperelastic model. Allowing experiments to be biaxially stretched to ratios above $\lambda = 2$ would provide a more realistic analysis for future applications in design and modelling of actuators. It would also enable the model to be trained on a wider spectrum of parameters, to provide more accurate parameters. Following this improvement to the current parameters, the model also has the potential to be further developed for electro-mechanically coupled consideration. This would allow the prediction of biaxial elastomer deformation optimization based the applied external Maxwell stresses.

The prototype testing led to the validation of achievable reciprocal motion. This preliminary testing demonstrated the actuator design's potential customisability for various applications. Future investigation of its output force, achievable elongation, and response time would be required to further quantify its efficacy. Creating a new prototype structure without the need of a linear support track would also greatly advance the actuator development, by removing the influence of friction from affecting its movement. Furthermore, integrating multiple layers of the elastomer film would be imperative to evaluate the feasibility of its functioning and manufacturing.

Current developments in elastomer processing and compliant electrode alternatives have proven promising for the advancement of dielectric elastomer based actuators. Particularly, the use of Interpenetrating Polymer Networks (IPNs) have removed the need of rigid frames for maintaining the VHB tapes at a pre-stretched configuration. This type of processing would enable the proposed actuator design to have a more uniform core, and simplify the manufacturing process. Application of more sophisticated electrodes, such as carbon nanotube (CNT) electrodes would also improve the design by providing more uniform and reliable electrodes within the multilayered core. Finally, the development of a control system for the electrical circuit should be considered for actuator implementation. The control of voltage application for synchronized actuation is imperative to the success of the actuator as part of specific applications.

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Appendix A

Appendix A.1 – Biaxial Tensile Test Sample Preparation

The following section will illustrate the process for biaxial sample preparation and installation. Before mounting on the rakes, the tape samples were cut down to size and prepped. All specimens were sized to a 10mm x 10mm square. This specific size was selected both based on the rakes' dimensions, and the material's tendency to tear easily at the puncture sites while testing. Based on previous experimental observation, Eilaghi et al. [100] have suggested that an apron width of approximately 0.6-1.0 times the tine spacing is appropriate for many materials. After testing various sample sizes in tension at the BioTester's maximum speed of 10 mm/s, a 2-mm apron was added to the 6mm x 6mm testing perimeter, to provide enough support at the connection sites.

3M™ VHB tape is packaged as a roll with a red polyethylene film liner on its outer surface, and therefore needs to be cut to size and detached from the film for each experiment. The tape was first unrolled enough to allow the sheet to lay flat. A ruled cutting mat was used as a reference for the following sample cutting processes. Using a black thin-tip marker and a ruler, a small reference dot was drawn at the top and bottom edges of the tape, at a 10-mm distance from its outer edge. The bottom edge of the unrolled sheet of tape was then carefully placed parallel to one of the horizontal lines on the mat. Its vertical edge was offset by 10 mm from one of the vertical lines, using the reference dots as a guide. The line on the mat can be seen through the tape, as it is vibrant yellow, and the tape's red film is translucent. The distance between the mat's vertical line and the tape's edge was measured a second time (at the top and bottom) to ensure a 10-mm offset was achieved.

A ruler covered in painter's tape was then carefully pressed onto the tape, ensuring to line up its edge with the edge of the line on the mat (Figure A.1 (a)). The painter's tape was applied to the ruler in order to reduced adhesion when removing it from the unrolled portion of the tape sheet. Once the ruler has been placed, a roller cutter was used to cut the 10-mm strip, by following the edge of the ruler. It should be noted that the roller cutter was found to be the best method for cutting VHB tape. Using a conventional precision blade seemed to leave jagged and uneven edges on the samples. After having cut the initial 10 mm width strip, it was then cut down to square samples of 10 mm x 10 mm, using the same method described above (Figure A.1 (b)). Each

sample was measured with a Vernier caliper, to ensure a consistent sample size within ± 0.2 mm was met.

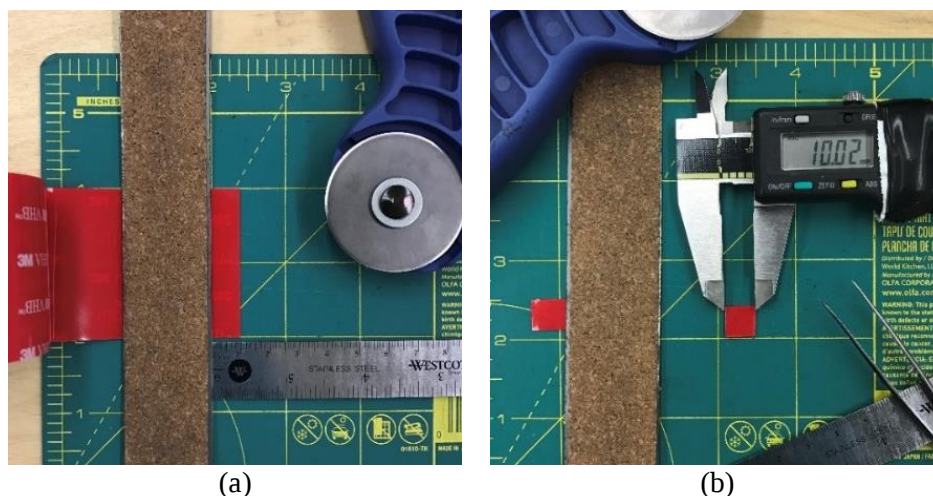


Figure A.1: VHB sample cutting using cutting mat and roller cutter

The specimen's surfaces were then prepped for mounting and image tracking. It should be noted that the following specimen preparation steps were performed using nitrile powder-free gloves. This was done to ensure no finger grease was transmitted to any of the specimens during their preparation. For all pre-mounting specimen processing, sheets of ethylene-vinyl acetate foam (craft foam) were used. This material allows the VHB tape to easily bond temporarily and be removed from its surface without greatly affecting its adhesive properties. The first step of specimen preparation is to reduce the adhesiveness of the surface that will be in contact with the BioTester's mounting bridge (the mounting process will be described in detail further in this section). To achieve this, a piece of foam was lightly dusted with a fine layer of corn starch powder (Figure A.2 (a)). The specimen was then turned onto its adhesive side and pressed down, along the red liner, to allow as much corn starch to bind to its surface.

The protective film was then carefully removed with the help of precision blade and forceps (Figure A.2 (b)). The edge of the film was pried upwards and folded over using the sharp edge of the blade. While holding the edge of the VHB tape down on the foam with the blade's surface, the unadhered corner was gripped by the forceps, and the film was pulled off with a single swift motion. The film needs to be removed as quickly as possible, otherwise the VHB tape has a tendency to stretch and warp during the process. After this step was completed, the specimen then needed to be prepped for the image tracking.

CellScale's LabJoy software follows the relative motion of contrasting points on the surface of the specimen, and evaluates their experimental displacement. To enable this type of tracking, specimens were sparsely coated with a charcoal powder. A cotton swab was used to apply the powder. It was first dipped into the charcoal and then tapped to remove any excess particles. The swab was then rolled along the surface of the freshly-exposed surface of the VHB specimen until enough powder has adhered to its surface, to allow proper tracking.

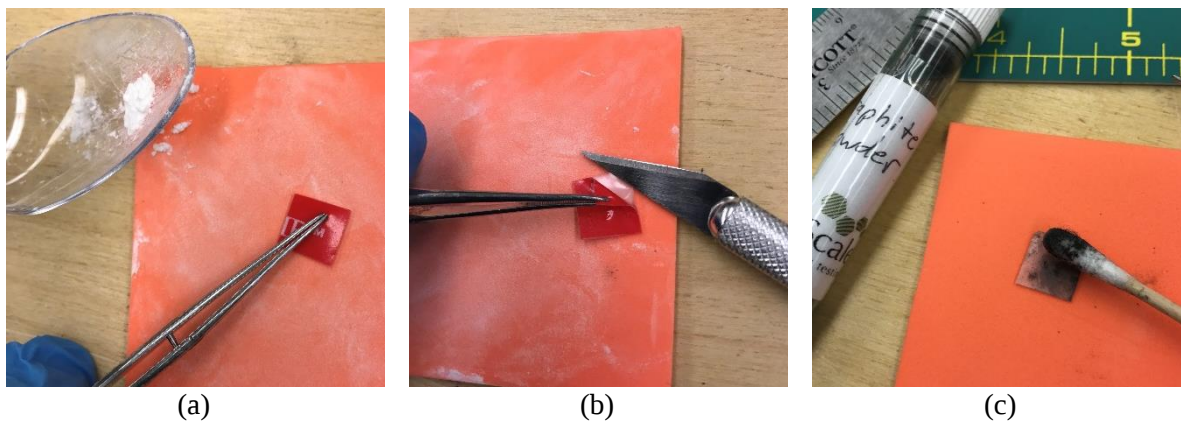


Figure A.2: VHB specimen pre-mounting preparation

The specimen was then mounted to the rakes using the provided mounting bridge, which has been covered with a piece of craft foam, to decrease adhesion between the specimen to the mounting platform during the process (Figure A.3 (a)). The mounting bridge was placed on the machine's raiseable fluid chamber, located below the rakes. Once the specimen could be seen on the software's live camera feed, it was carefully moved around until the specimen was centred about all four rakes. If need be, the rakes were shifted slightly to best fit the sample's geometry. The centred specimen was then raised until contact was made with the tines of the rakes. Each of the 20 tines were individually pushed into the specimen using a small piece of acrylic, ensuring complete penetration through the specimen. The platform was then lowered and removed. In the case where the foam backing would stick to the specimen after mounting, a pair of forceps were used to grasp opposing corners of the foam and carefully remove it from the specimen and tines. Extra care was taken to ensure the specimen was not unhooked from any of the tines.

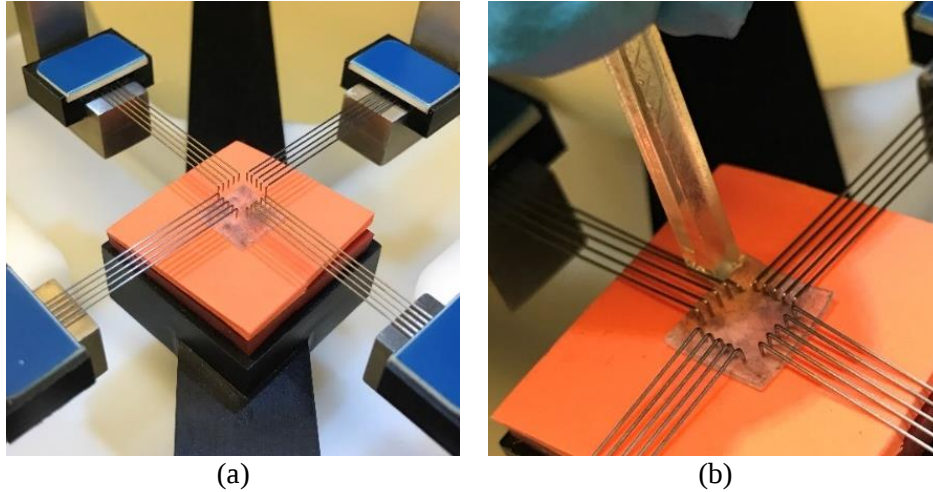


Figure A.3: VHB sample mounting and tine puncturing

Before initiating an experiment, the forces on load cells were zeroed by using the Force Control Setting. This setting automatically adjusts the distance between rakes, along both axes, until the desired load is achieved. A preload of 0 mN was input for the specified load. It should be noted that a static value of 0 was unachievable using this device, due to the load cell's high sensitivity to noise. A fluctuation within a range of -10 mN to 10 mN was accepted as a zero-load initial condition. In the event where the Force Control Setting was unable to achieve the zero-load initial condition, the rake positions were manually adjusted using the Actuator Control jog arrows.

Appendix A.2 – Iso-Parametric Mapping Equation Derivations

Figure 3.3 represents the mapping between a quadrilateral element and its parent geometry. This parent (“ideal”) geometry is expressed in natural coordinates (r, s) in two-dimensions, and possesses a shape function (expressed using Lagrange interpolation):

$$N_i = \frac{1}{4}(1 + rr_i)(1 + ss_i) \quad \text{for } -1 \leq r \leq 1 \text{ and } -1 \leq s \leq 1$$

Its nodes are located at $N_1(-1, -1)$, $N_2(1, -1)$, $N_3(1, 1)$, and $N_4(-1, 1)$, which leads to an $[N]$ matrix that can be expressed as:

$$[N(r, s)] = [N_1 \quad N_2 \quad N_3 \quad N_4]$$

$$[N(r, s)] = \left[\frac{1}{4}(1-r)(1-s) \quad \frac{1}{4}(1+r)(1-s) \quad \frac{1}{4}(1+r)(1+s) \quad \frac{1}{4}(1-r)(1+s) \right]$$

For a quadrilateral element having nodes in 2D expressed in terms of x_i and y_i , we can interpolate nodal values of the parent coordinate system:

$$\varphi(r, s) = [N] \begin{Bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{Bmatrix} = [N] \{\varphi^e\}$$

This relationship is applied so either the nodal coordinate locations (i.e. x or y), or their displacements (i.e. u or v) can be found. It is clear that $u = x - X$, where X is the initial position of the nodes (and same for v). The following relationship can therefore be derived:

$$u(r, s) = [N(r, s)] \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{Bmatrix} = [N] \{u^e\} \qquad v(r, s) = [N(r, s)] \begin{Bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{Bmatrix} = [N] \{v^e\}$$

By definition, the displacement-strain relationship dictates that normal strain is $\varepsilon = \frac{\Delta l}{l_0}$, therefore $\varepsilon_{xx} = \frac{\partial u}{\partial X}$ and $\varepsilon_{yy} = \frac{\partial v}{\partial Y}$ (where X and Y are the positions of the quadrilateral element in unloaded configuration). For any displacement $w(X(r, s), Y(r, s))$, where $w = u$ or v , abiding by the chain rule yields the following:

$$\frac{\partial w}{\partial r} = \frac{\partial w}{\partial X} \cdot \frac{\partial X}{\partial r} + \frac{\partial w}{\partial Y} \cdot \frac{\partial Y}{\partial r} \qquad \frac{\partial w}{\partial s} = \frac{\partial w}{\partial X} \cdot \frac{\partial X}{\partial s} + \frac{\partial w}{\partial Y} \cdot \frac{\partial Y}{\partial s}$$

Which can be represented in matrix form as:

$$\begin{pmatrix} \frac{\partial w}{\partial r} \\ \frac{\partial w}{\partial s} \end{pmatrix} = \begin{bmatrix} \frac{\partial X}{\partial r} & \frac{\partial Y}{\partial r} \\ \frac{\partial X}{\partial s} & \frac{\partial Y}{\partial s} \end{bmatrix} \begin{pmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{pmatrix} = [\mathbf{J}] \begin{pmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{pmatrix}$$

These partial derivatives can also be expressed as:

$$\frac{\partial w(r,s)}{\partial r} = \left[\frac{\partial N(r,s)}{\partial r} \right] \{w^e\} \qquad \frac{\partial w(r,s)}{\partial s} = \left[\frac{\partial N(r,s)}{\partial s} \right] \{w^e\}$$

where

$$\frac{\partial N(r,s)}{\partial r} = \frac{1}{4} [-1 + s \quad 1 - s \quad 1 + s \quad -1 - s]$$

$$\frac{\partial N(r,s)}{\partial s} = \frac{1}{4} [-1 + r \quad 1 - r \quad 1 + r \quad -1 - r]$$

Inverting the equation, in order to solve for displacements of interest $\frac{\partial w}{\partial X}$ and $\frac{\partial w}{\partial Y}$, the following final equation is derived:

$$\begin{pmatrix} \frac{\partial w}{\partial X} \\ \frac{\partial w}{\partial Y} \end{pmatrix} = \frac{1}{|\mathbf{J}|} \begin{bmatrix} \frac{\partial Y}{\partial s} & -\frac{\partial Y}{\partial r} \\ -\frac{\partial X}{\partial s} & \frac{\partial X}{\partial r} \end{bmatrix} \begin{pmatrix} \frac{\partial w}{\partial r} \\ \frac{\partial w}{\partial s} \end{pmatrix}$$

where $|\mathbf{J}| = \det[\mathbf{J}]$. Expanding this transformation matrix leads to:

$$[\mathbf{J}] = \begin{bmatrix} \frac{\partial X}{\partial r} & \frac{\partial Y}{\partial r} \\ \frac{\partial X}{\partial s} & \frac{\partial Y}{\partial s} \end{bmatrix} = \begin{bmatrix} \left[\frac{\partial N(r,s)}{\partial r} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial r} \right] \{Y^e\} \\ \left[\frac{\partial N(r,s)}{\partial s} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial s} \right] \{Y^e\} \end{bmatrix}$$

In order to find $\det[\mathbf{J}]$, the matrix convention $\det = \frac{1}{ad - cb}$ is applied:

$$|\mathbf{J}| = \frac{1}{ad - cb} = \frac{1}{\left[\frac{\partial N(r,s)}{\partial r} \right] \{X^e\} \cdot \left[\frac{\partial N(r,s)}{\partial s} \right] \{Y^e\} - \left[\frac{\partial N(r,s)}{\partial r} \right] \{Y^e\} \cdot \left[\frac{\partial N(r,s)}{\partial s} \right] \{X^e\}}$$

The final system to solve can therefore be expressed as:

$$\begin{Bmatrix} \frac{\partial u}{\partial X} \\ \frac{\partial u}{\partial Y} \\ \frac{\partial v}{\partial X} \\ \frac{\partial v}{\partial Y} \end{Bmatrix} = \frac{1}{|\mathbf{J}|} \begin{bmatrix} \left[\frac{\partial N(r,s)}{\partial r} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial r} \right] \{Y^e\} & 0 & 0 \\ \left[\frac{\partial N(r,s)}{\partial s} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial s} \right] \{Y^e\} & 0 & 0 \\ 0 & 0 & \left[\frac{\partial N(r,s)}{\partial r} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial r} \right] \{Y^e\} \\ 0 & 0 & \left[\frac{\partial N(r,s)}{\partial s} \right] \{X^e\} & \left[\frac{\partial N(r,s)}{\partial s} \right] \{Y^e\} \end{bmatrix} \begin{Bmatrix} \frac{\partial u}{\partial r} \\ \frac{\partial u}{\partial s} \\ \frac{\partial v}{\partial r} \\ \frac{\partial v}{\partial s} \end{Bmatrix}$$

The corresponding stretch ratio would then be found, by definition of the deformation gradient tensor $\bar{\bar{F}} = \frac{\partial \mathbf{u}}{\partial \mathbf{X}} + \bar{\bar{I}}$. This therefore results in the following equality:

$$\begin{bmatrix} \lambda_1 & F_{12} \\ F_{21} & \lambda_2 \end{bmatrix} = \begin{bmatrix} \frac{\partial u}{\partial X_1} + 1 & \frac{\partial u}{\partial X_2} \\ \frac{\partial v}{\partial X_1} & \frac{\partial v}{\partial X_2} + 1 \end{bmatrix}$$

The true stress along either axis can then be calculated. The current thickness of the specimen h can be expressed with known quantities as $h = \frac{H}{J_{2D}}$, where H is the original thickness. The determinant of the deformation gradient tensor must be equal to 1:

$$[\bar{\bar{F}}] = \begin{bmatrix} \lambda_1 & F_{12} & 0 \\ F_{21} & \lambda_2 & 0 \\ 0 & 0 & \frac{1}{J_{2D}} \end{bmatrix}$$

which therefore results in $J_{2D} = \lambda_1 \lambda_2 = F_{12} F_{21}$. This relationship is justified by the incompressibility condition, in which $\lambda_1 \lambda_2 \lambda_3 = 1$. The change in thickness can therefore be expressed as $h = \lambda_3 H = \frac{H}{\lambda_1 \lambda_2}$, which reiterates the previous relationship.

The true stress acting on both axes of the specimen can then be calculated by introducing the Cauchy Stress tensor. This will apply the forces f_1 and f_2 along the current cross-sectional areas of the specimen. Cauchy Stress tensor can be expressed as:

$$[\bar{\bar{t}}] = \frac{1}{H} \begin{bmatrix} \frac{\lambda_1 f_1}{L_2} & \frac{F_{12} f_2}{L_2} & 0 \\ \frac{F_{21} f_1}{L_2} & \frac{\lambda_2 f_2}{L_1} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where L is the original length of the sample. This yields final equations of $\sigma_1 = \frac{\lambda_1 f_1}{H L_2}$ and

$$\sigma_2 = \frac{\lambda_2 f_2}{H L_1}.$$

Appendix A.3 – Experimental Analysis MATLAB Code

```
%-----  
% This is the main function to process biaxial tensile mechanical  
% experiments. It must be run in a folder alongside subfolders containing  
% the excel files with the data for the experiments to be analyzed.  
%-----  
function main_function()  
  
clear all  
clc  
  
% Find subfolders for data and functions  
addpath(genpath('C:\Thesis Data Processing\Mechanical'))  
  
p = 0;  
  
% Analysis loop  
while p == 0  
  
clear all  
clc  
  
% Prompt user to input file name  
prompt = 'File name : '  
file_name = input(prompt,'s');  
file_name = char(file_name);  
  
% Identify tape and test type from file name  
[tape_thick,test_type] = file_identity(file_name);  
  
%% ----- EXCEL FILE DATA EXTRATION AND PROCESSING -----  
  
if test_type == 1    %% LOAD-UNLOAD  
  
% Isoparametric mapping of the coordinates for the image tracking  
[str_ratio_x,str_ratio_y] = iso_mapping(file_name);  
  
% Change file name to corresponding data file with forces  
file_name = [file_name(1:end-11),'Data.xlsx'];  
fprintf('Data File name : '  
fprintf(file_name)  
  
% True stress calculation based on stretch ratios  
[stress_x,stress_y] = cauchy_stress(file_name,tape_thick,str_ratio_x,...  
    str_ratio_y);  
  
% Data Smoothing  
[stress_x_smooth,stress_y_smooth] = stress_smooth(...  
    file_name,stress_x,stress_y,test_type);
```

```

elseif test_type == 2 || test_type == 3 %% STRESS RELAXATION

% Calculate stretch ratios using actuator displacement data (no image
% tracking)
[str_ratio_x,str_ratio_y,time] = single_multi_str_ratio(file_name,...
    tape_thick);

% True stress calculation based on stretch ratios
[stress_x,stress_y] = cauchy_stress(file_name,tape_thick,str_ratio_x,...
    str_ratio_y);
[stress_x_smooth,stress_y_smooth,max_ind_x,max_ind_y] = stress_smooth(...
    file_name,stress_x,stress_y,test_type);

% Stretch ratio steps for plotting
time_x_peaks = time(max_ind_x);
str_ratio_x_peaks = str_ratio_x(max_ind_x);
time_y_peaks = time(max_ind_y);
str_ratio_y_peaks = str_ratio_y(max_ind_y);
end

%% ----- PLOT GRAPHS -----

file_path = which(file_name);

if test_type == 1 %% LOAD-UNLOAD
file_name_save = [file_path(1:end-9) 'Fig.png'];
fig = figure('Name',file_name(1:end-9),'NumberTitle','off');

set(gcf,'DefaultTextFontSize',11, ...
'DefaultTextFontname','Times New Roman', ...
'DefaultTextFontWeight','bold', ...
'DefaultAxesFontSize',13, ...
'DefaultAxesFontname','Times New Roman');
set(gcf,'visible','off')

hold on
h2 = plot(str_ratio_y,stress_y_smooth,'-.',...
    'Color',[150/255 150/255 150/255],'LineWidth',1.5);
h1 = plot(str_ratio_x,stress_x_smooth,':',...
    'Color',[0/255 0/255 0/255],'LineWidth',1.5);

hold off
aspect_x = 5;
aspect_y = 3;
pbaspect([aspect_x aspect_y 1])
grid on
axis([1 2 0 0.5])
grid on
l = legend([h1 h2],{'\sigma_1','\sigma_2'},'Location','NW');
l.Orientation = 'horizontal';
xlabel('Stretch Ratio (-)')
ylabel('Stress (MPa)')
print(file_name_save,'-dpng','-r350');

```

```

elseif test_type == 2 || test_type == 3      % STRESS RELAXATION

file_name_save = [file_path(1:end-9) 'Fig.png'];
fig = figure('Name',file_name(1:end-9),'NumberTitle','off');

set(gcf,'DefaultTextFontSize',13, ...
'DefaultTextFontname','Times New Roman', ...
'DefaultTextFontWeight','bold', ...
'DefaultAxesFontSize',15, ...
'DefaultTextColor','black',...
'DefaultAxesFontname','Times New Roman');
set(gcf,'visible','off')
set(fig,'defaultAxesColorOrder',[0 0 0; 0 0 0]);

hold on
yyaxis left
xlabel('Time (s)')
ylabel('True Stress (MPa)')
h2 = plot(time,stress_y_smooth,'-','...',...
'Color',[150/255 150/255 150/255],'LineWidth',1.5);
h1 = plot(time,stress_x_smooth,':','...',...
'Color',[0/255 0/255 0/255],'LineWidth',1.5);
axis([-100 inf 0 (max(max(stress_x_smooth),max(stress_y_smooth))*1.10)])

yyaxis right
h3 = plot(time,str_ratio_x,'-','...',...
'Color',[75/255 75/255 75/255],'LineWidth',0.5);
h4 = plot(time_x_peaks,str_ratio_x_peaks,'o','...',...
'Color',[128/255 0/255 0/255],'MarkerSize',3);
axis([-100 inf 1 ((max(str_ratio_x_peaks)-1)*2+1)])
ylabel('Stretch Ratio (-)')
hold off

aspect_x = 5;
aspect_y = 3;
pbaspect([aspect_x aspect_y 1])
grid on
if test_type == 2; corner = 'NE';
elseif test_type == 3; corner = 'NW'; end;
l = legend([h1 h2 h3],{'\sigma_1','\sigma_2','\lambda'},'Location',corner);
l.Orientation = 'horizontal';
print(file_name_save,'-dpng','-r350');
end

fprintf('\n'); prompt = 'Again? [y/n] : '; again = input(prompt,'s');

if again == 'y'; p = 0;
else p = 1; end;
close all
end
end

```

```

%-----
% This function identifies the experiment type and tape type for further
% processing.
%-----
function [tape_thick,test_type,tape_type,test_name] = ...
    file_identity(file_name)

% Split up name to find tape type and test type
file_name_split = strsplit(file_name, '_');

% Find type of tape for this file
tape_comp = strmatch('VHB4910',file_name_split);

if isempty(tape_comp)
    tape_comp = strmatch('VHB4905',file_name_split);
if isempty(tape_comp)
    disp('Tape name in file wrong (''VHB4905''/' 'VHB4910'')')
    return
else tape_type = ('VHB4905'); tape_thick = 500; % in um
end
else tape_type = ('VHB4910'); tape_thick = 1000; % in um
end

% Find type of test for this file
test_comp = strmatch('Multi-step',file_name_split);
if isempty(test_comp); test_comp = strmatch('SingleStep',file_name_split);
if isempty(test_comp); test_comp = strmatch('LoadUnload',file_name_split);
if isempty(test_comp); disp('Test type name in file wrong ',...
    (''Multi-step''/' 'SingleStep''/' 'LoadUnload''))
return
else test_name = ('LoadUnload'); test_type = 1; end;
else test_name = ('SingleStep'); test_type = 2; end;
else test_name = ('Multi-step'); test_type = 3; end;
end

%-----
% This function will take '[...]Coords.xlsx file from image tracking and
% apply iso-parametric mapping in order to calculate strains of the sample.
% The file will contain the X-Y positions of the four nodes selected from
% the software and apply the transformations.
%-----
function [str_ratio_x,str_ratio_y,F12,F21] = iso_mapping(file_name)

format long % data output format
file_path = which(file_name);
data = xlsread(file_name,1);

% Index time and 4 node coordinate columns
time = data(:,1); % in s
x{1} = data(:,2); y{1} = data(:,3); % in um
x{2} = data(:,6); y{2} = data(:,7); % in um
x{3} = data(:,8); y{3} = data(:,9); % in um
x{4} = data(:,4); y{4} = data(:,5); % in um

```

```

% Calculate and index displacements in u and v
for k=1:4
    u{k}      = x{k}-x{k}(1); % in um
    v{k}      = y{k}-y{k}(1); % in um
end

% Index positions and displacements into cell of arrays
X = [x{1}(1); x{2}(1); x{3}(1); x{4}(1)];
Y = [y{1}(1); y{2}(1); y{3}(1); y{4}(1)];
u = [u{1}'; u{2}'; u{3}'; u{4}'];
v = [v{1}'; v{2}'; v{3}'; v{4}'];

% Interested in finding values for centre of element therefore r = s = 0
r = 0;
s = 0;

% Find values of partial derivatives for all values of dX, dY, du, and dv
[dX_dr,dX_ds] = partial_deriv(X,r,s);
[dY_dr,dY_ds] = partial_deriv(Y,r,s);

[du_dr,du_ds] = partial_deriv(u,r,s);
[dv_dr,dv_ds] = partial_deriv(v,r,s);

determ_val = (dX_dr*dY_ds-dX_ds*dY_dr);

% Calculated strains du/dX, du/dY, dv/dX and dv/dY
du_dX = (1/determ_val).*[dY_ds -dY_dr]*[du_dr;du_ds];
du_dY = (1/determ_val).*[-dX_ds dX_dr]*[du_dr;du_ds];
dv_dX = (1/determ_val).*[dY_ds -dY_dr]*[dv_dr;dv_ds];
dv_dY = (1/determ_val).*[-dX_ds dX_dr]*[dv_dr;dv_ds];

% Find final stretch ratios and F12 F21
str_ratio_x = (du_dX + 1)'; % in um/um
str_ratio_y = (dv_dY + 1)'; % in um/um
F12 = (du_dY)'; % in um/um
F21 = (dv_dX)'; % in um/um

% Write data to Excel File
xlswrite(file_path,{'Time (s)'},2,'A1');
xlswrite(file_path,time,2,'A2');
xlswrite(file_path,{'Str Ratio X (um/um)'},2,'B1');
xlswrite(file_path,str_ratio_x,2,'B2');
xlswrite(file_path,{'Str Ratio Y (um/um)'},2,'C1');
xlswrite(file_path,str_ratio_y,2,'C2');
xlswrite(file_path,{'F12 (um/um)'},2,'D1');
xlswrite(file_path,F12,2,'D2');
xlswrite(file_path,{'F21 (um/um)'},2,'E1');
xlswrite(file_path,F21,2,'E2');

end

```

```

%% ----- SHAPE FUNCTION -----
function [dN_dr,dN_ds] = lagrange_int(r,s)

% Coordinates of the four corners in the parent geometry, as can be seen in
% Figure 3.4. These values are represented as ri = [r1 r2 r3 r4] and si =
% [s1 s2 s3 s4]
ri = [-1 1 1 -1]; si = [-1 -1 1 1];

% Partial derivatives of shape function w.r.t. r and s, as can be seen in
% Equation (3.3)
for j=1:4
    dN_dr(1,j)=(1/4)*ri(j)*(1+s*si(j));
    dN_ds(1,j)=(1/4)*si(j)*(1+r*ri(j));
end
end

%% ----- PARTIAL DERIVATIVES -----
function [dPhi_dr,dPhi_ds] = partial_deriv(phi,r,s)

% Call function to express partial derivatives of shape function w.r.t. r
% and s
[dN_dr,dN_ds] = lagrange_int(r,s);

% Find resulting partial derivative of phi. dN_dr = [1 x 4] mtx, and phi =
% [4 x 1] mtx, where phi is the value of interest (such as x, y, u, or v)
dPhi_dr = dN_dr*phi; dPhi_ds = dN_ds*phi;
end

%-----
% This function will calculate the stretch ratios of the stress relaxation
% tests without using image tracking. It will use the position of the
% machine's actuators in order to calculate the stretch ratio with respect
% to the initial position of the sample.
%-----
function [str_ratio_x,str_ratio_y,time] = single_multi_str_ratio...
    (file_name,tape_thick)

% Import data from excel file based on name given
numData = xlsread(file_name,1);

% Index time and displacement
time          = numData(:,1); % in s
L_x           = numData(:,3); % in um
L_y           = numData(:,4); % in um
L_initial_x   = numData(1,3); % in um
L_initial_y   = numData(1,4); % in um
H_initial     = tape_thick;    % in um

% Calculate stretch ratios
str_ratio_x = L_x./L_initial_x; % in um/um
str_ratio_y = L_y./L_initial_y; % in um/um

end

```

```

%-----
% This function extracts the force data, along with calculated stretch
% ratios, to calculate true stresses of the membrane under biax tension.
%-----
function [stress_x, stress_y] = cauchy_stress(file_name, tape_thick, ...
    str_ratio_x, str_ratio_y)

file_path = which(file_name);
format long % data output format

% Index forces and other initial conditions of sample
numData = xlsread(file_name, 1);
time      = numData(:, 1); % in s
L_initial_x = numData(1, 3); % in um
L_initial_y = numData(1, 4); % in um
force_x     = numData(:, 7); % in mN
force_y     = numData(:, 8); % in mN
H_initial   = tape_thick;    % in um

% Zero Forces
force_x = force_x - force_x(1);
force_y = force_y - force_y(1);

% In some cases, software adds an additional time entry with no force data.
% This will trim off the last time entry if this is the case.
if length(force_x) ~= length(str_ratio_x)
    cut = min(length(force_x), length(str_ratio_x));
    force_x = force_x(1:cut);
    str_ratio_x = str_ratio_x(1:cut);
    force_y = force_y(1:cut);
    str_ratio_y = str_ratio_y(1:cut);
end

% Calculate true stresses based on Equation (3.8)
stress_x = ((str_ratio_x.*force_x)/...
    (L_initial_y*H_initial))*1000; % in MPa
stress_y = ((str_ratio_y.*force_y)/...
    (L_initial_x*H_initial))*1000; % in MPa

% Write Data to Excel File
xlswrite(file_path, {'Time (s)'}, 2, 'A1');
xlswrite(file_path, time, 2, 'A2');
xlswrite(file_path, {'Str Ratio X (um/um)'}, 2, 'B1');
xlswrite(file_path, str_ratio_x, 2, 'B2');
xlswrite(file_path, {'Str Ratio Y (um/um)'}, 2, 'C1');
xlswrite(file_path, str_ratio_y, 2, 'C2');
xlswrite(file_path, {'Stress X (MPa)'}, 2, 'D1');
xlswrite(file_path, stress_x, 2, 'D2');
xlswrite(file_path, {'Stress Y (MPa)'}, 2, 'E1');
xlswrite(file_path, stress_y, 2, 'E2');

end

```

```

%-----
% This function is responsible for smoothing the biaxial tensile test data.
% It smooths the function in separate parts, in order to ensure that none
% of the peak values are cut off during the cycles. Smoothing is applied
% differently for Load-Unload and Stress Relaxation tests, due to the
% curves' different geometries.
%-----
function [stress_x_smooth, stress_y_smooth, max_ind_x, max_ind_y] = ...
    stress_smooth(file_name, stress_x, stress_y, test_type)

file_path = which(file_name);
format long % data output format

%% ----- Load Unload -----
if test_type == 1
% Find peak of load cycle
cycle_peak_x = ceil(length(stress_x)/2);
cycle_peak_y = ceil(length(stress_y)/2);

% Smooth up cycle and down cycle separately
stress_x_smooth_up = smooth(stress_x(1:cycle_peak_x), 0.90, 'rloess');
stress_x_smooth_down = smooth(stress_x((cycle_peak_x):...
    length(stress_x)), 0.90, 'rloess');
stress_x_smooth_down = stress_x_smooth_down(2:end);

stress_y_smooth_up = smooth(stress_y(1:cycle_peak_y), 0.90, 'rloess');
stress_y_smooth_down = smooth(stress_y((cycle_peak_y):...
    length(stress_y)), 0.90, 'rloess');
stress_y_smooth_down = stress_y_smooth_down(2:end);

% Assemble new smoothed vector
stress_x_smooth = [(stress_x_smooth_up); (stress_x_smooth_down)];
stress_x_smooth = stress_x_smooth - stress_x_smooth(1);
stress_y_smooth = [(stress_y_smooth_up); (stress_y_smooth_down)];
stress_y_smooth = stress_y_smooth - stress_y_smooth(1);

max_ind_x = 0;
max_ind_y = 0;

%% ----- Stress Relaxation -----
elseif test_type == 2 || test_type == 3

% Number of steps in the experiment (single or multi)
if test_type == 2; steps = 1;
elseif test_type == 3; steps = 10; end;

% Number of data points per step
n = length(stress_x)/steps;

% Smooth each step independently from the other
for k = 1:steps

% Create sub-vector with data points for step
stress_x_step{k} = stress_x((1+n*(k-1)):(n*k));
stress_y_step{k} = stress_y((1+n*(k-1)):(n*k));

```

```

% Find peak stress of the step
[max_x,max_ind_x_step(k)] = max(stress_x_step{k});
[max_y,max_ind_y_step(k)] = max(stress_y_step{k});

% Save index of the peak stress values with respect to the entire
% experiment for later plotting purposes
max_ind_x(k) = max_ind_x_step(k)+(k-1)*n;
max_ind_y(k) = max_ind_y_step(k)+(k-1)*n;

% Smooth loading and relaxation separately
stress_x_smooth_up{k} =
smooth(stress_x_step{k}(1:max_ind_x_step(k)),0.10,'loess');
stress_x_smooth_down{k} = smooth(stress_x_step{k}((max_ind_x_step(k)):...
length(stress_x_step{k})),0.10,'loess');
stress_x_smooth_down{k} = stress_x_smooth_down{k}(2:end);

stress_y_smooth_up{k} =
smooth(stress_y_step{k}(1:max_ind_y_step(k)),0.10,'loess');
stress_y_smooth_down{k} = smooth(stress_y_step{k}((max_ind_y_step(k)):...
length(stress_y_step{k})),0.10,'loess');
stress_y_smooth_down{k} = stress_y_smooth_down{k}(2:end);

% Assemble new smoothed vector
stress_x_smooth{k,1} = [stress_x_smooth_up{k};stress_x_smooth_down{k}];
stress_y_smooth{k,1} = [stress_y_smooth_up{k};stress_y_smooth_down{k}];

end

% Convert cell of array into one matrix
stress_x_smooth = cell2mat(stress_x_smooth);
stress_x_smooth = stress_x_smooth - stress_x_smooth(1);
stress_y_smooth = cell2mat(stress_y_smooth);
stress_y_smooth = stress_y_smooth - stress_y_smooth(1);

% Write Data to Excel File
xlswrite(file_path,{'Stress X Smooth (MPa)'},2,'F1');
xlswrite(file_path,stress_x_smooth,2,'F2');
xlswrite(file_path,{'Stress Y Smooth (MPa)'},2,'G1');
xlswrite(file_path,stress_y_smooth,2,'G2');

end

```

Appendix A.4 – Results of Biaxial Tensile Tests

A.4.1 Biaxial Load Unload Experiments

VHB 4905 tape

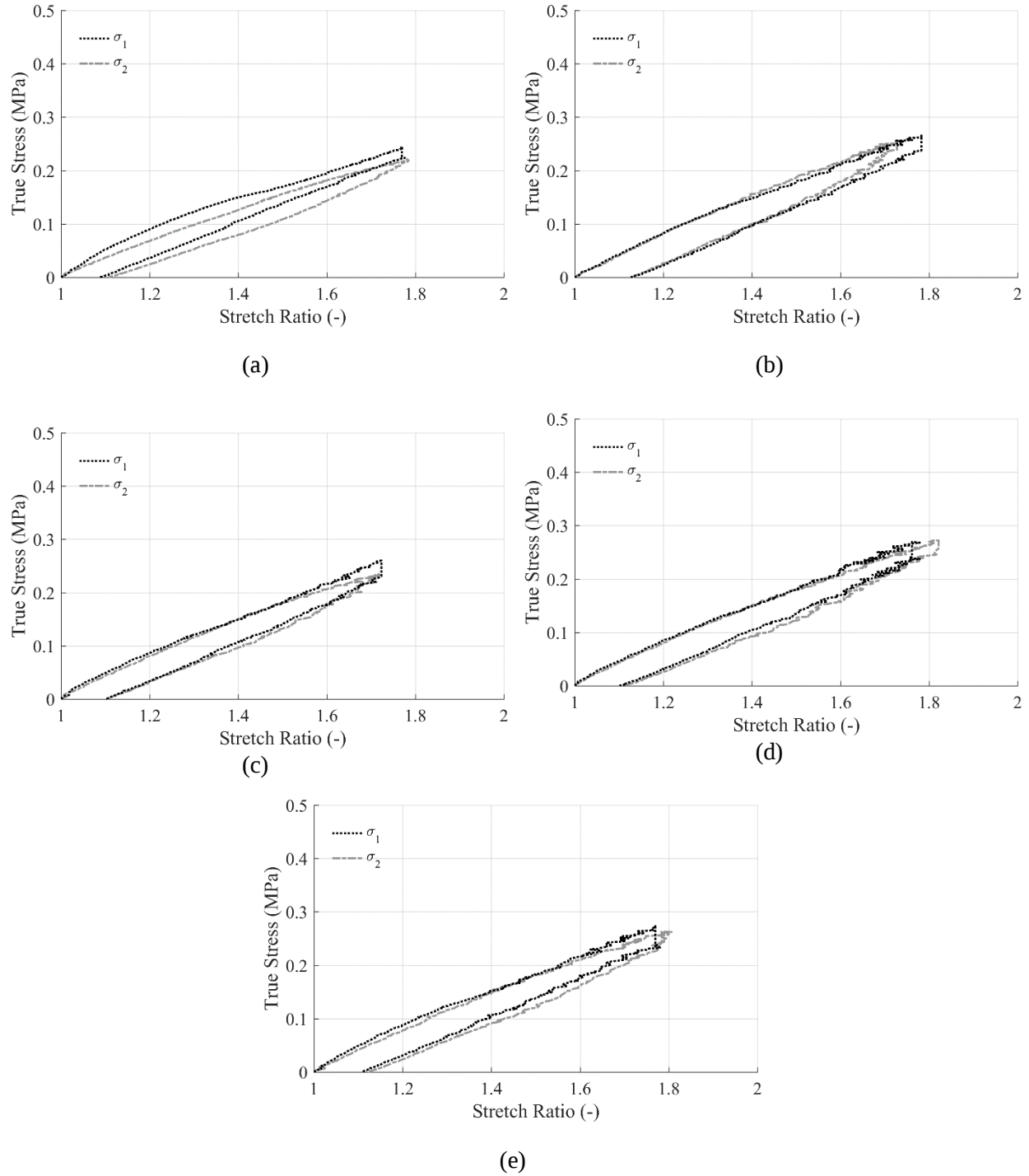


Figure A.4: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.025 \text{ s}^{-1}$

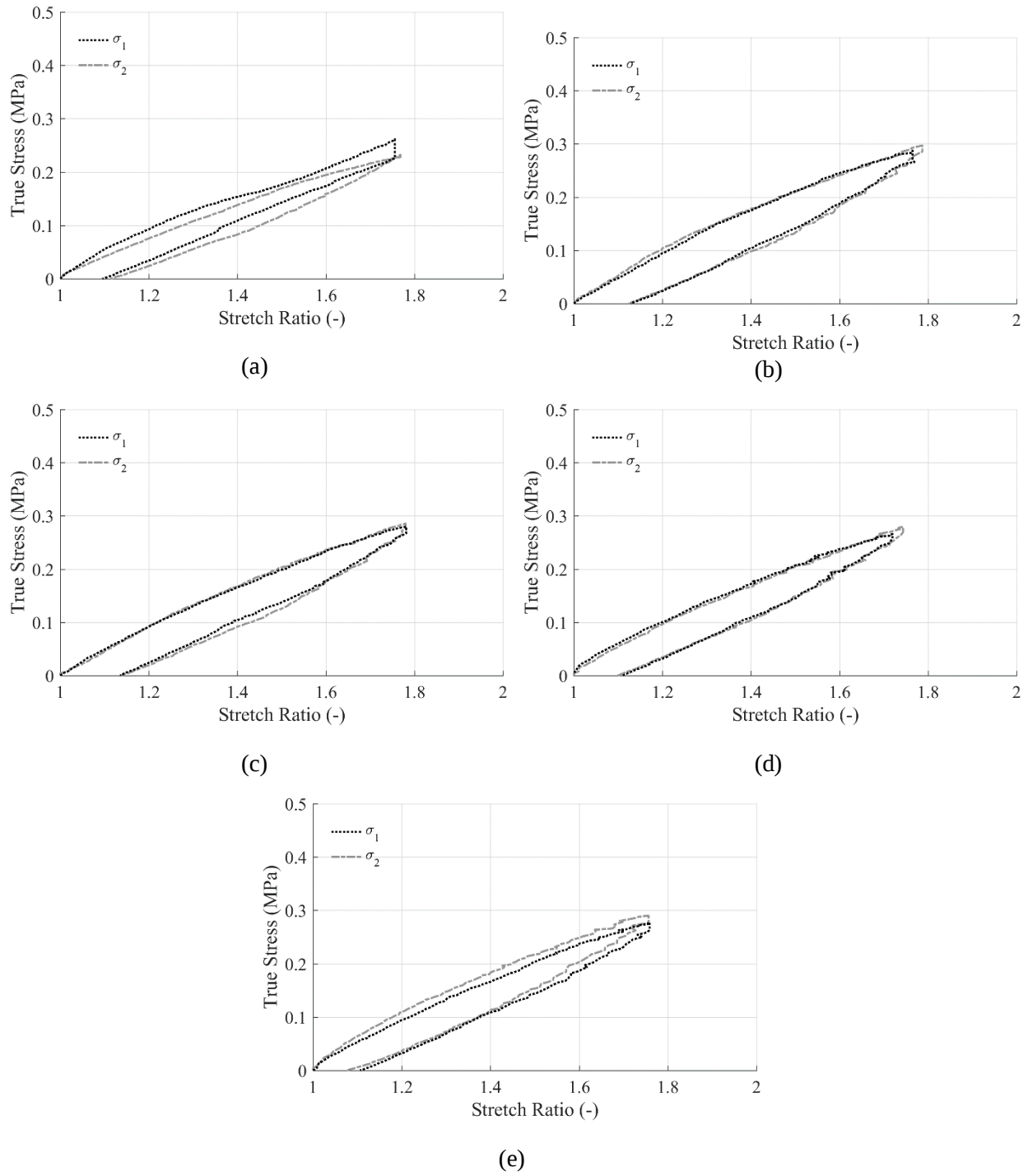


Figure A.5: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.050 \text{ s}^{-1}$

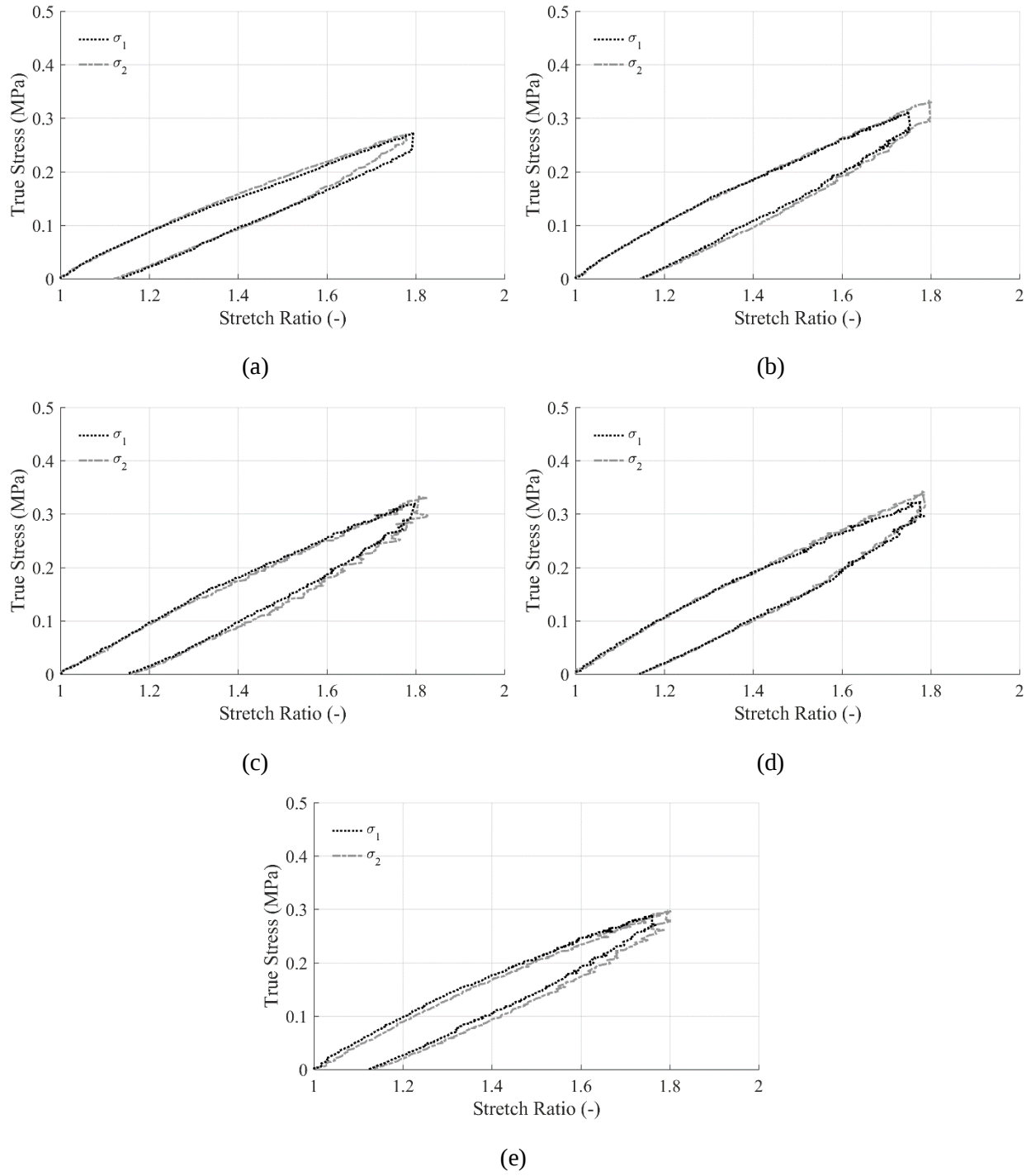


Figure A.6: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.075 \text{ s}^{-1}$

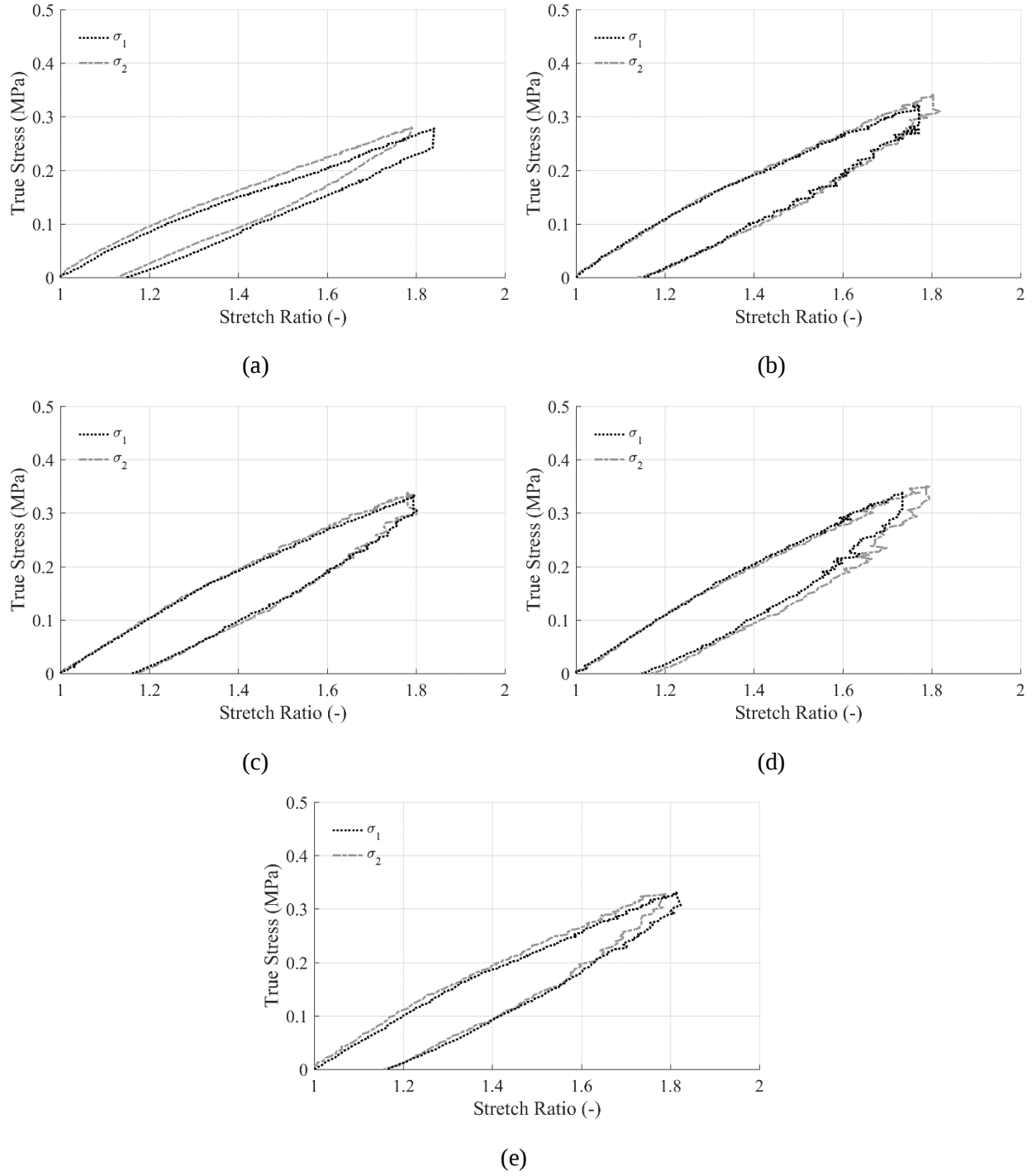


Figure A.7: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.100 \text{ s}^{-1}$

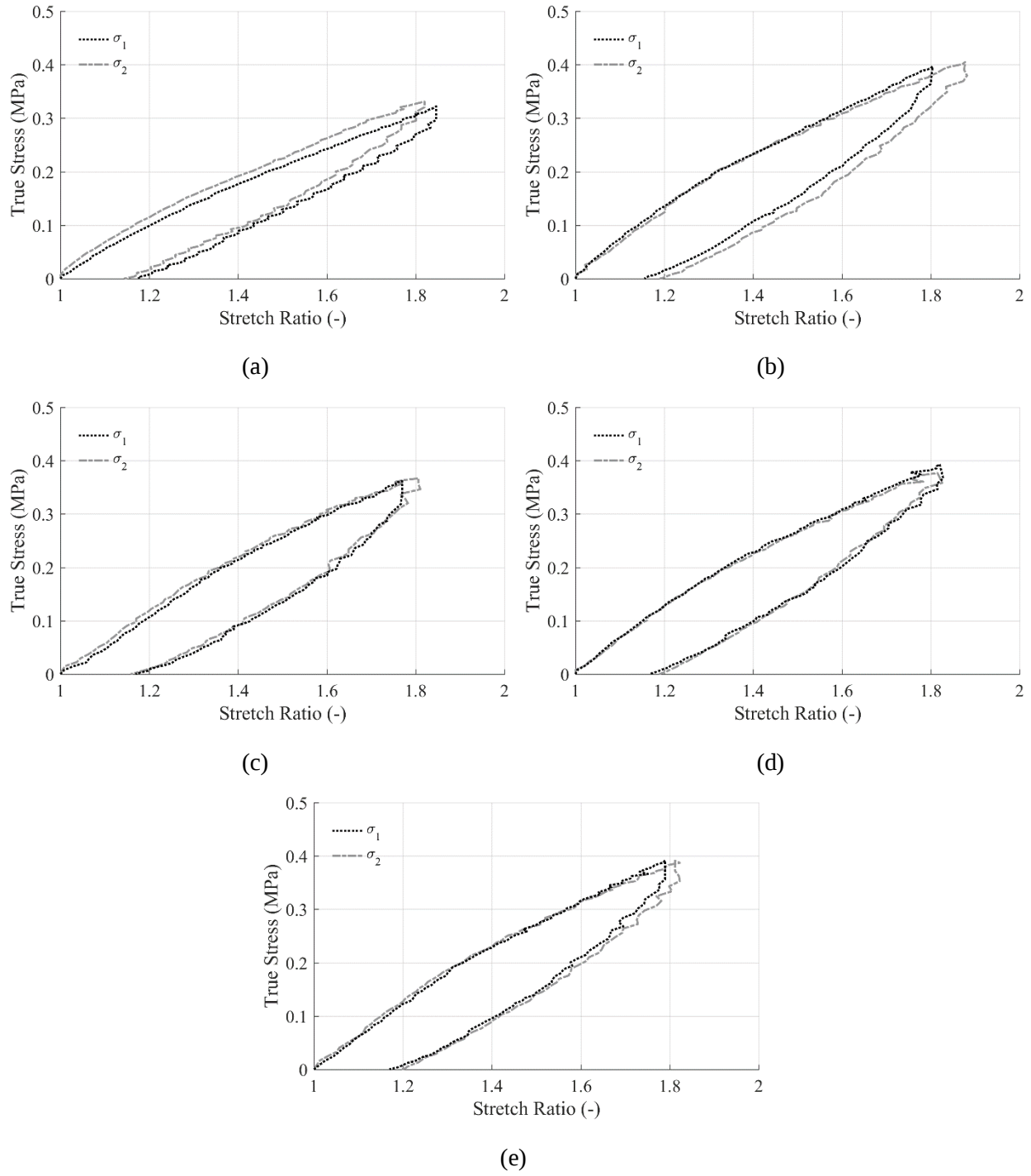


Figure A.8: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.200 \text{ s}^{-1}$

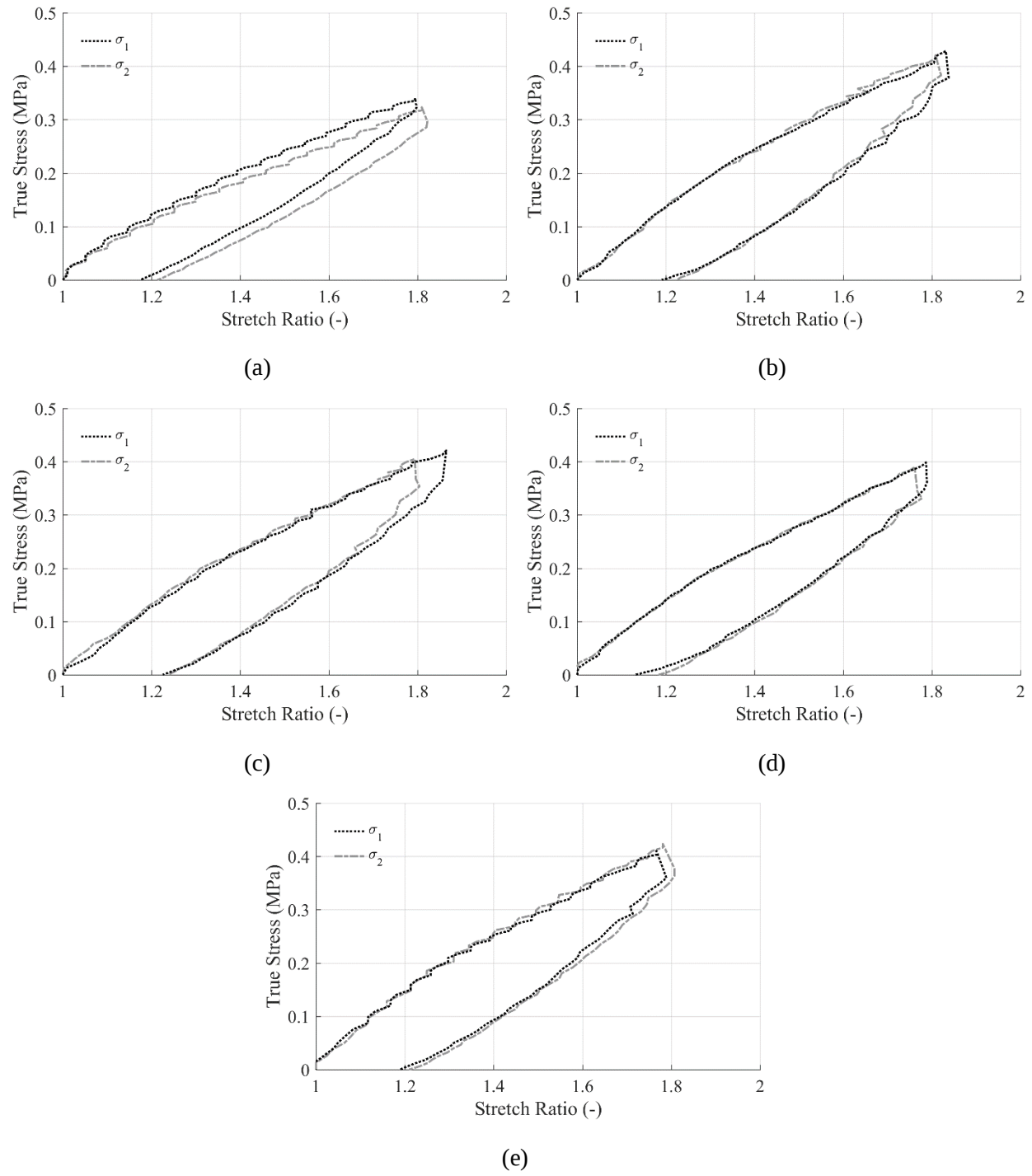


Figure A.9: Biaxial tensile load-unload curves for VHB 4905 tape at $\dot{\lambda} = 0.300 \text{ s}^{-1}$

VHB 4910 tape

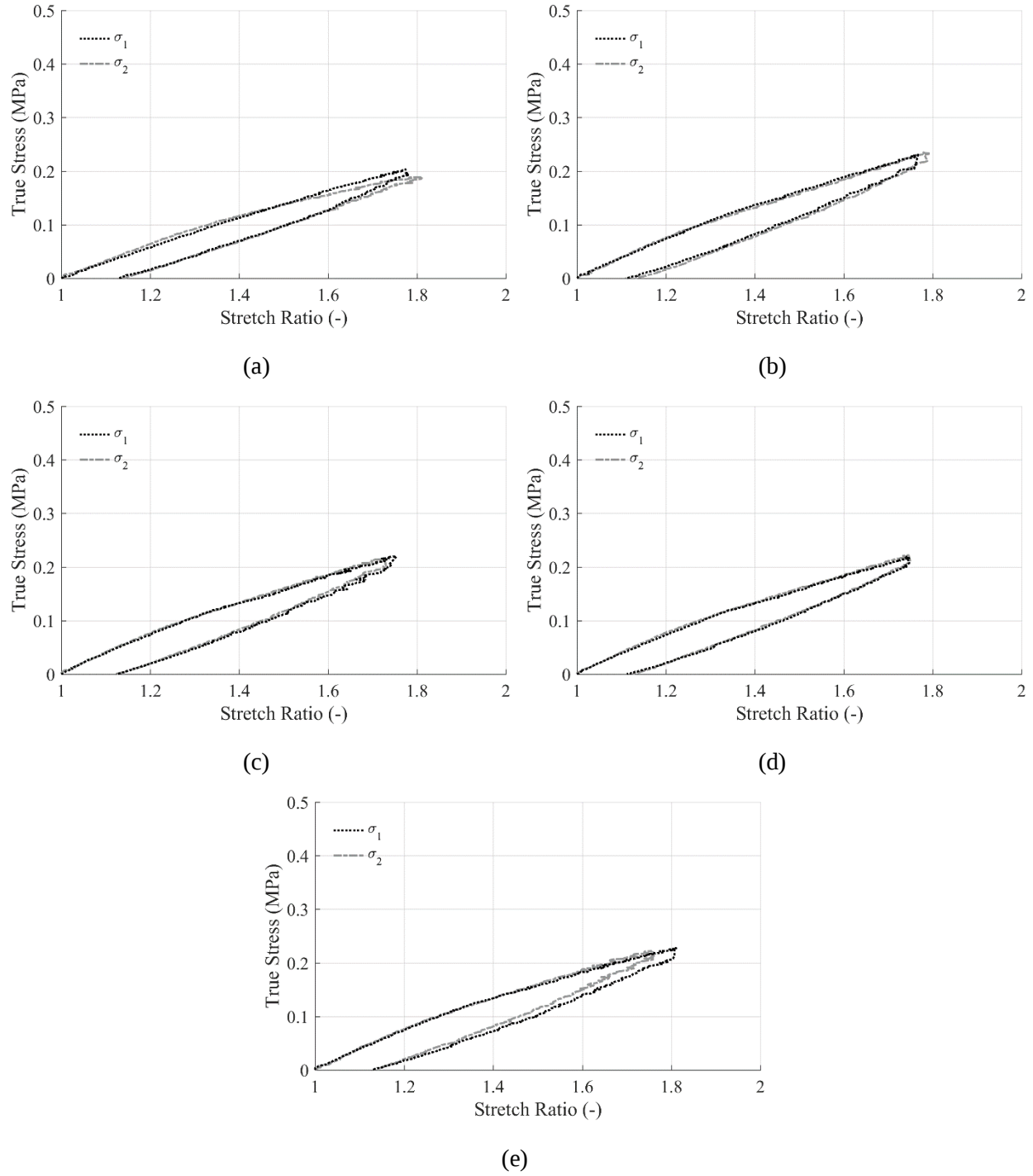


Figure A.10: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.025 \text{ s}^{-1}$

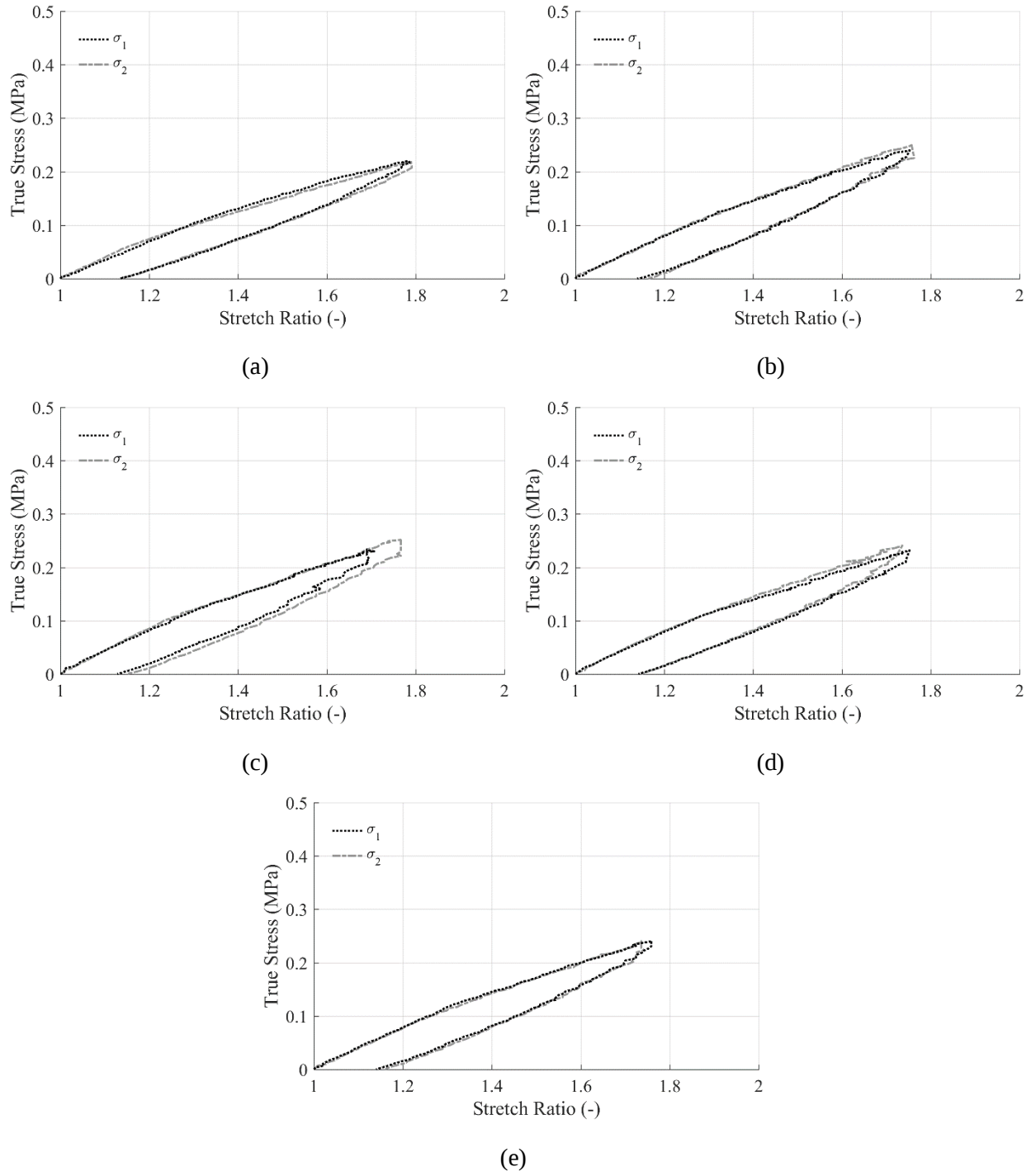


Figure A.11: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.050 \text{ s}^{-1}$

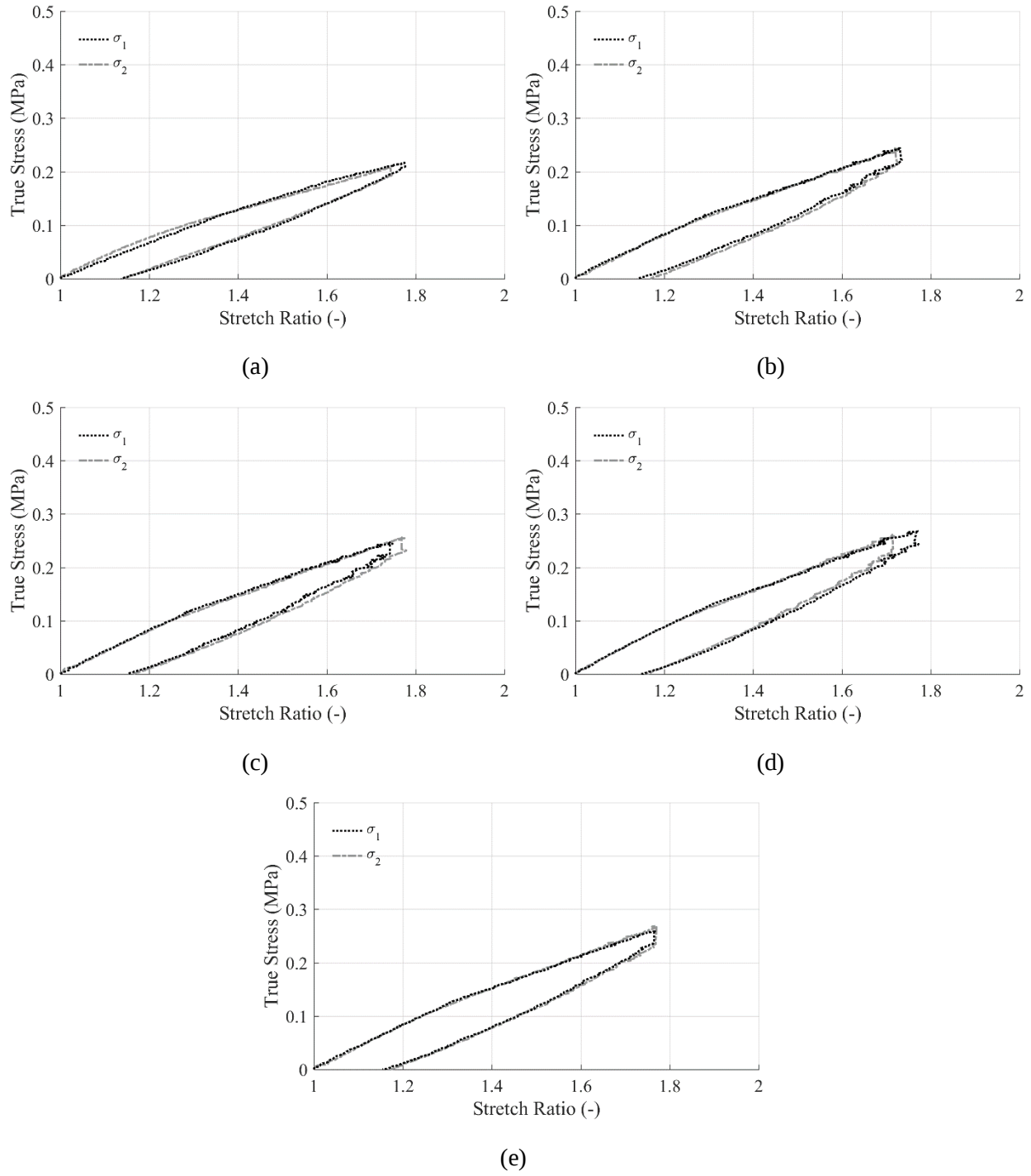


Figure A.12: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.075 \text{ s}^{-1}$

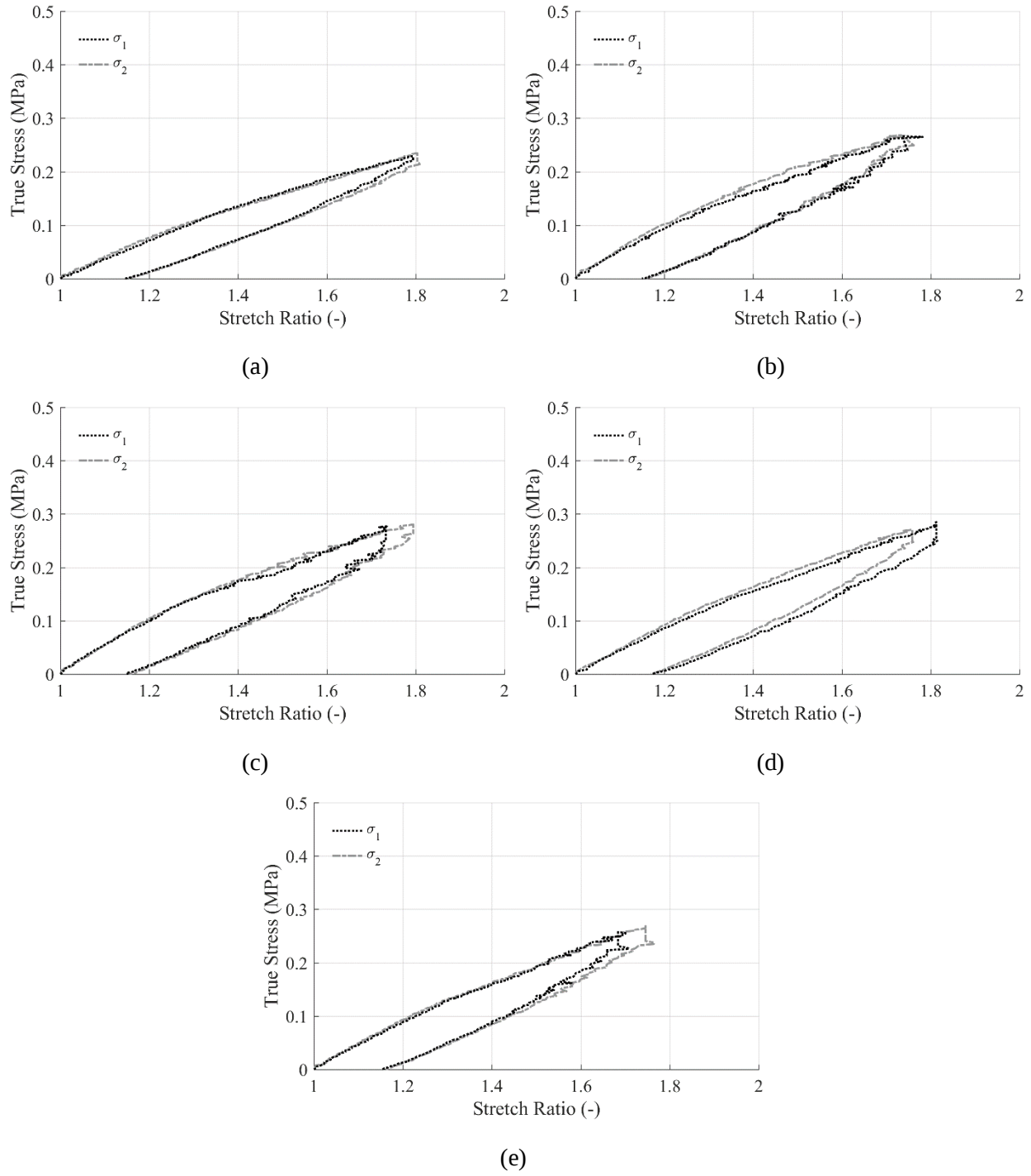


Figure A.13: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.100 \text{ s}^{-1}$

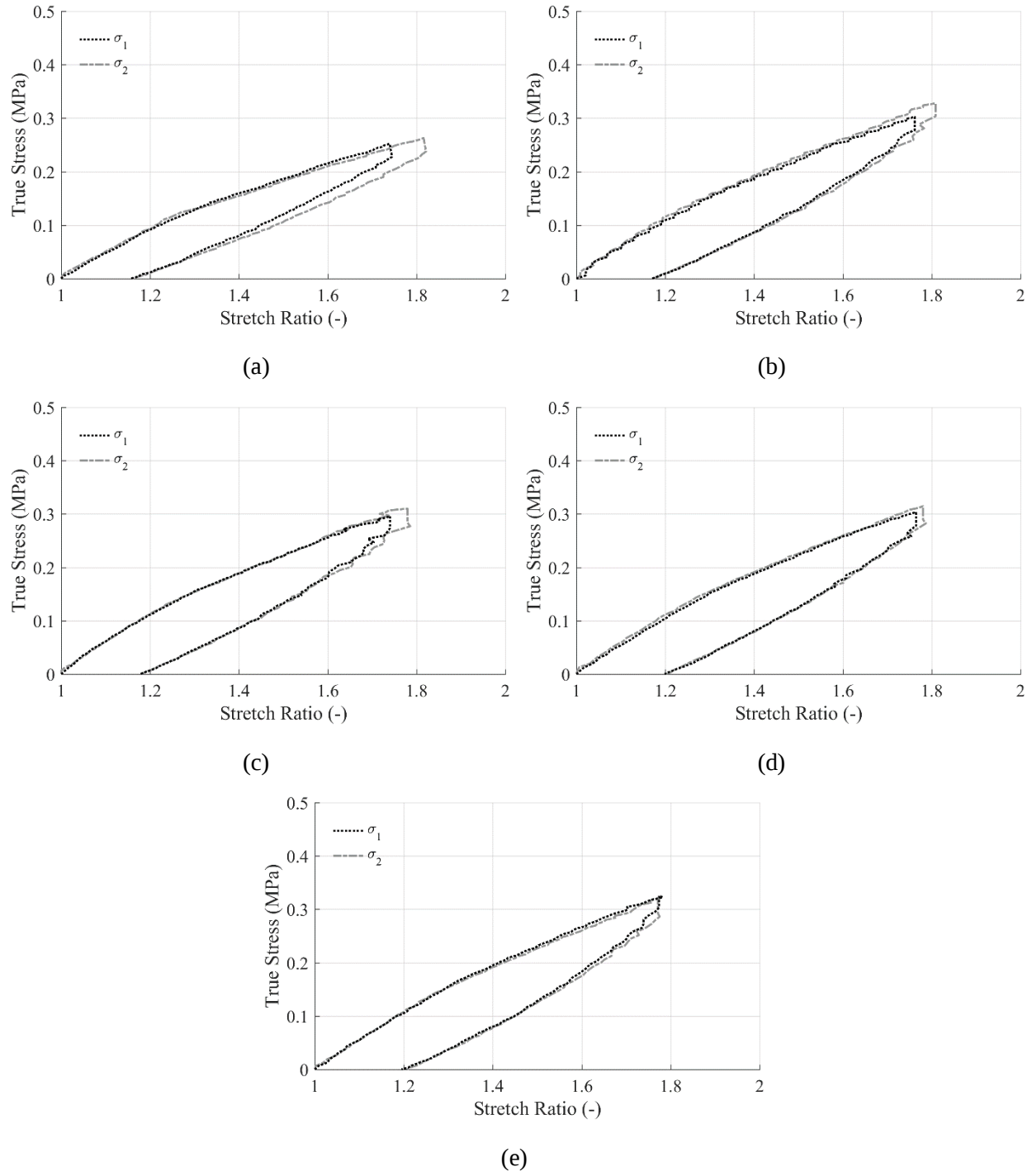


Figure A.14: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.200 \text{ s}^{-1}$

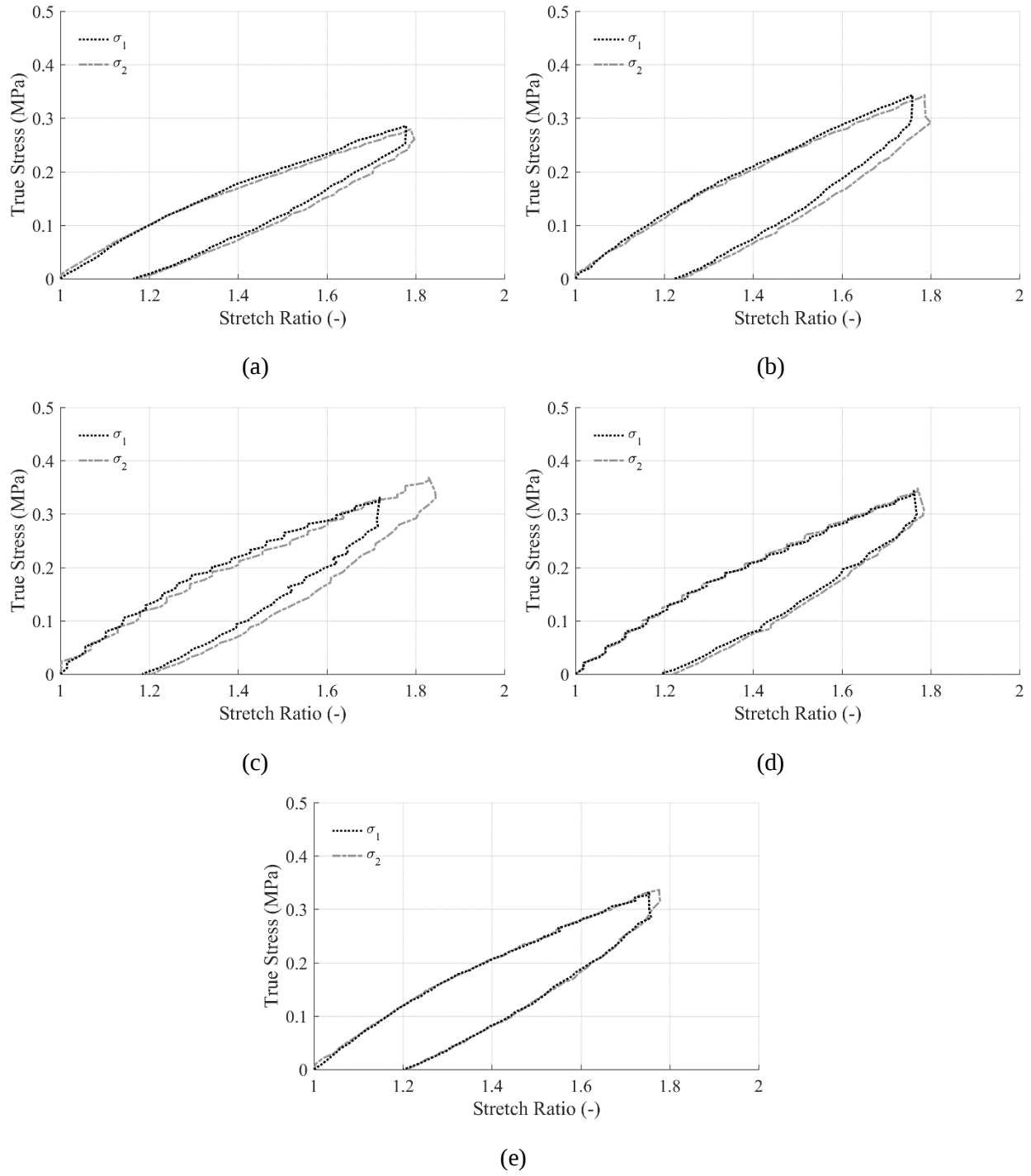


Figure A.15: Biaxial tensile load-unload curves for VHB 4910 tape at $\dot{\lambda} = 0.300 \text{ s}^{-1}$

A.4.2 Biaxial Single Step Stress Relaxation Experiments

VHB 4905 tape

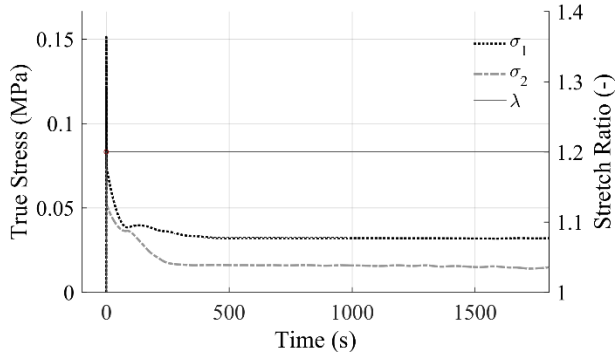


Figure A.16: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 1.2$

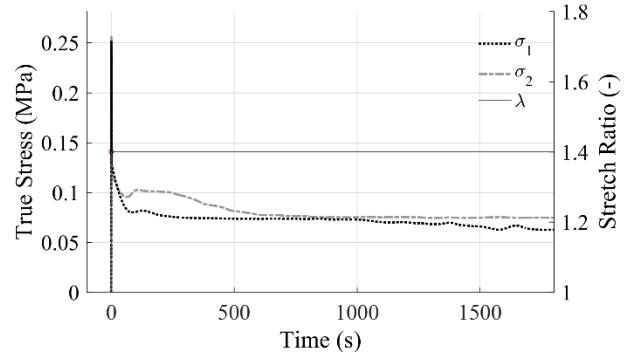


Figure A.17: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 1.4$

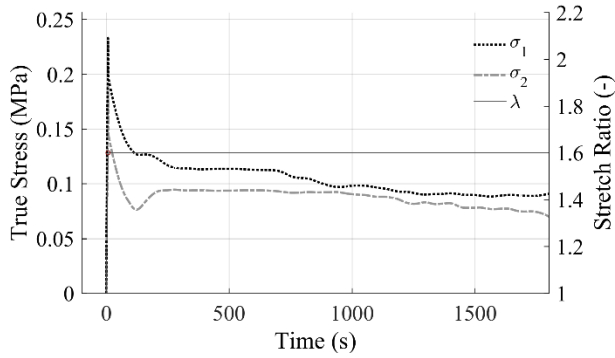


Figure A.18: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 1.6$

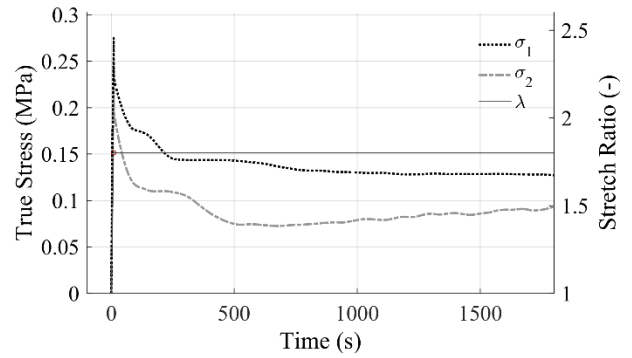


Figure A.19: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 1.8$

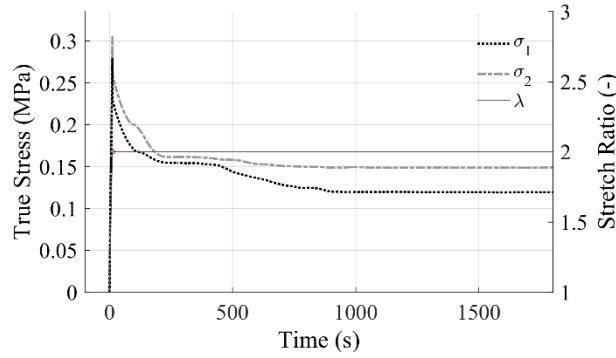


Figure A.20: Biaxial tensile single-step stress relaxation curve for VHB 4905 tape at $\lambda_{max} = 2.0$

VHB 4910 tape

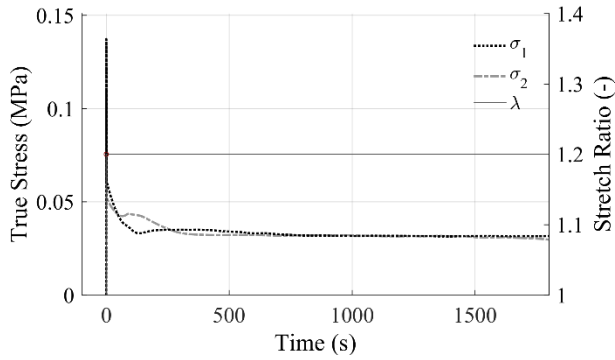


Figure A.21: Biaxial tensile single-step stress relaxation curve for VHB 4910 tape at $\lambda_{max} = 1.2$

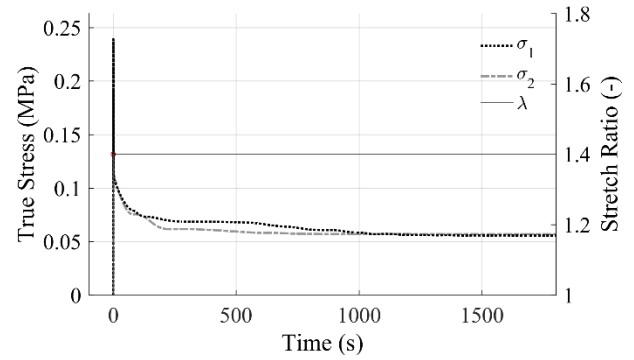


Figure A.22: Biaxial tensile single-step stress relaxation curve for VHB 4910 tape at $\lambda_{max} = 1.4$

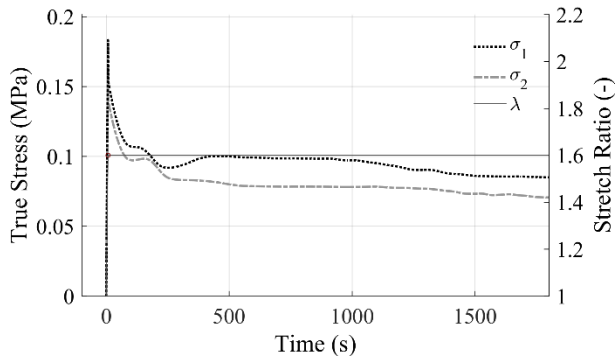


Figure A.23: Biaxial tensile single-step stress relaxation curve for VHB 4910 tape at $\lambda_{max} = 1.6$

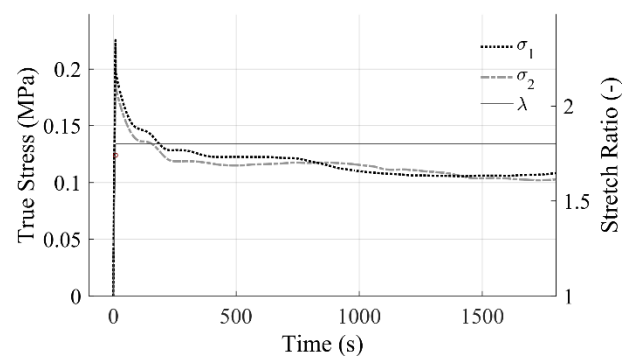


Figure A.24: Biaxial tensile single-step stress relaxation curve for VHB 4910 tape at $\lambda_{max} = 1.8$

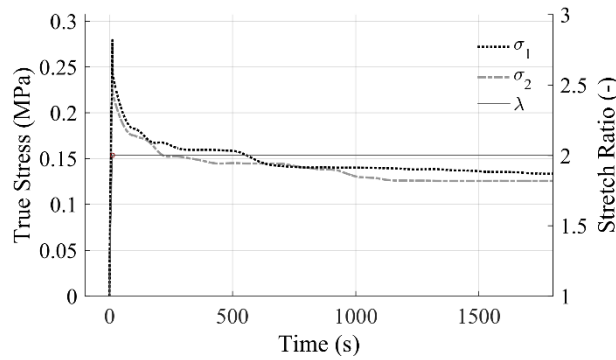


Figure A.25: Biaxial tensile single-step stress relaxation curve for VHB 4910 tape at $\lambda_{max} = 2.0$

A.4.3 Biaxial Multi Step Stress Relaxation Experiments

VHB 4905 tape

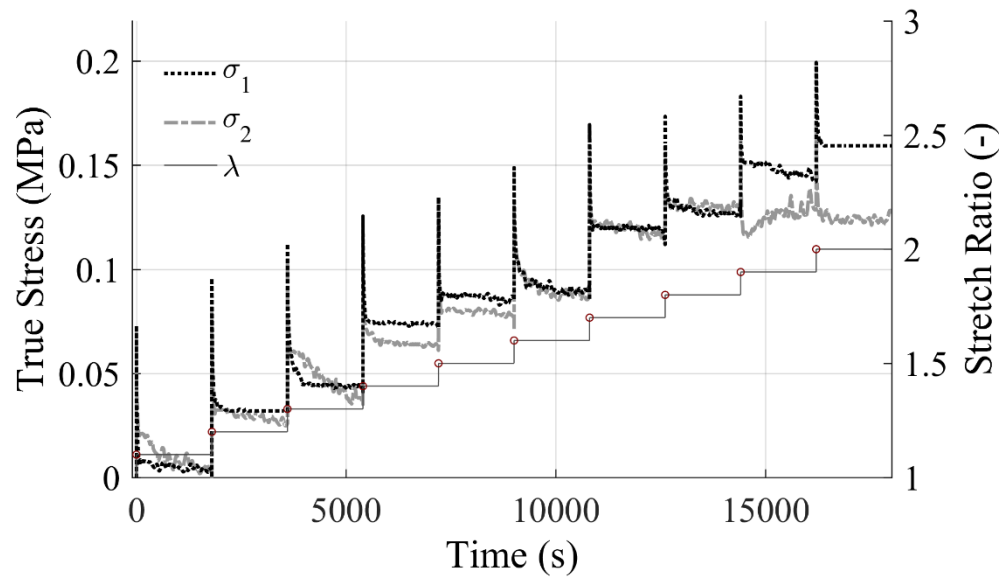


Figure A.26: Biaxial tensile multi-step stress relaxation curve for VHB 4905 tape

VHB 4910 tape

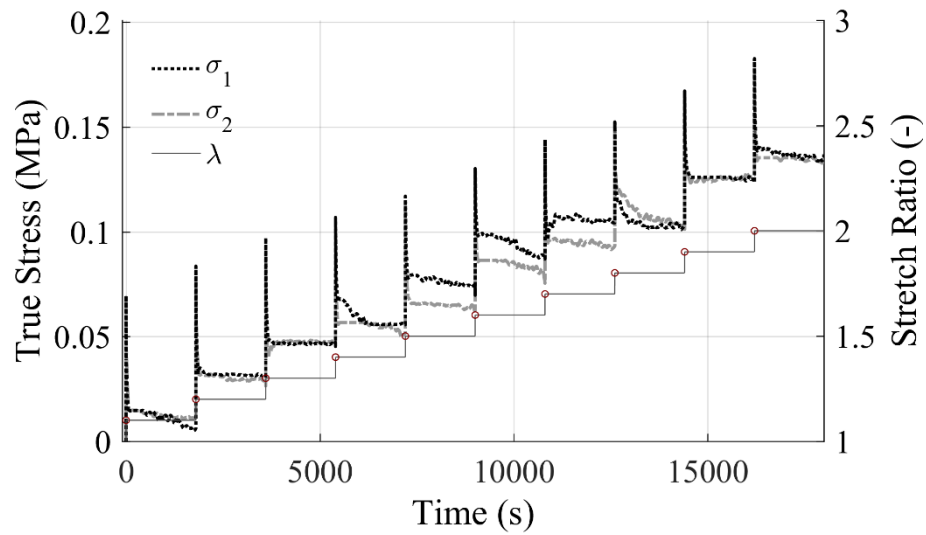
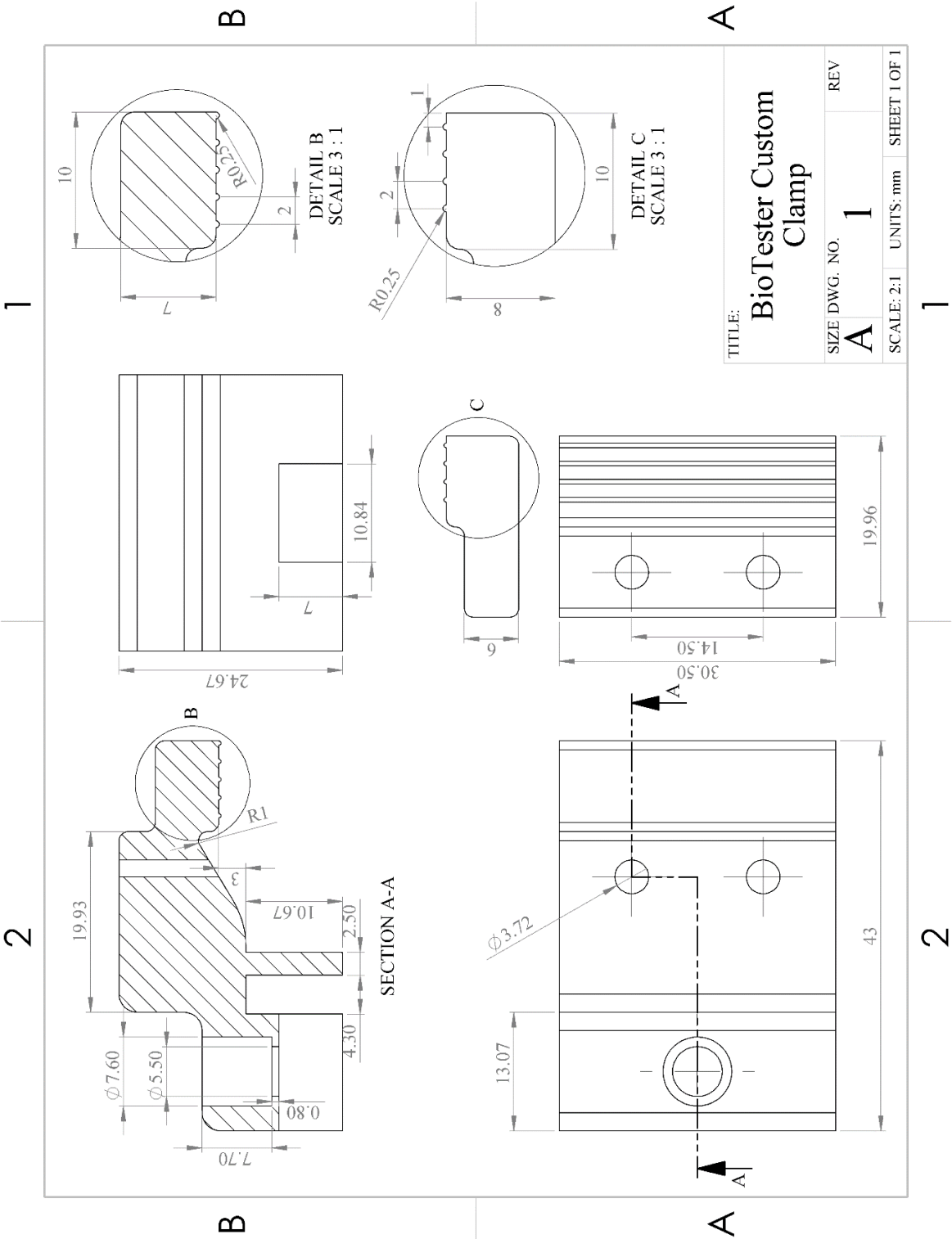


Figure A.27: Biaxial tensile multi-step stress relaxation curve for VHB 4910 tape

Appendix A.5 – Custom Clamp Engineering Drawing



Appendix A.6 – Electro-Mechanical Specimen Preparation

The following section will illustrate the process for electro-mechanical sample preparation and installation. Prior to the application of the tape to the clamps, a series of preparation steps were required for the experimental setup. It should be noted that the following was performed using nitrile powder-free gloves. This was done to ensure no finger grease was transmitted to any adhesion surfaces during the preparation process, which would affect the proper binding of the samples. The side surfaces of the top and bottom jaws of the clamps were wrapped with electrical tape prior to VHB tape application. This was done in order to prevent any contact between the clamps and the copper foil tape, as well as to protect the clamps from any staining during the grease-painting process. A piece of copper tape was then run across the front edge of one top clamp, and the opposing bottom clamp, and its edge was then folded over to create an overhanging tab (that will be used as the clipping site for the alligator clips, once mounted on the machine) (Figure A.28 (a)).

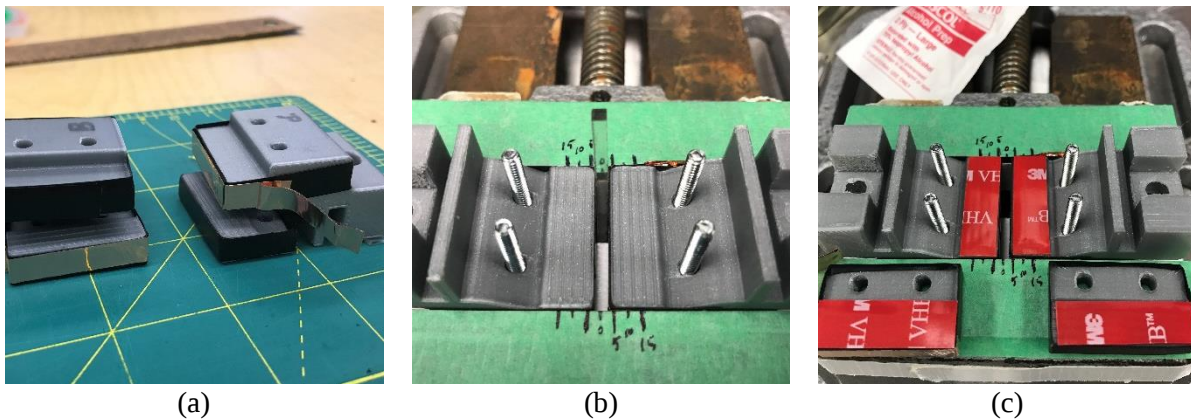


Figure A.28: Uniaxial test clamp preparation steps

Once the clamps were properly taped, the top portions of either clamp (with machine screws inserted into their respective holes) were then placed, upside down, in a bench vise and tightly fixed. The clamp edges were positioned to be 5 mm apart, which is the initial experimental specimen length. Since the tape only has a fixed boundary along the y-axis, its free edges will have a tendency to bow inwards during its elongation. In order to minimize this unwanted cinching, the initial sample length along λ_1 was taken as small as possible, while still allowing its handling and remaining within allowable dimension range of the BioTester's displacement capabilities. A 5-mm distance was found to be the smallest distance between the clamps that

allowed following these conditions, while still permitting the machine to achieve stretch ratios of up to $\lambda_1 = 8$. This distance was measured using a ruler scale that was etched on the edge of the vise jaws, as well as by using a square piece of acrylic with a 5-mm width as a guide (as seen in Figure A.28 (b)). Once fixed within the vise, the clamps were then ready for the application of the specimen.

The clamping surfaces were prepped following 3M™'s instructions on VHB Tape's Application [101]. All parts of the clamps that are intended to be in contact with the tape were first wiped down with solvent wipes (70% isopropyl alcohol solution) to ensure proper bonding of the tape. Due to the innate texturized nature of 3D printed parts' surface-finish, as well as the clamp design's integrated ribbing, no sanding was deemed necessary for the preparation process. In order to minimize slipping of the samples during tensile testing, a piece of VHB 4905 tape was applied to both surfaces of clamps (Figure A.28 (c)). VHB 4905 tape was chosen for all experiments to minimize the clamping width, since it is the thinner of the two tapes.

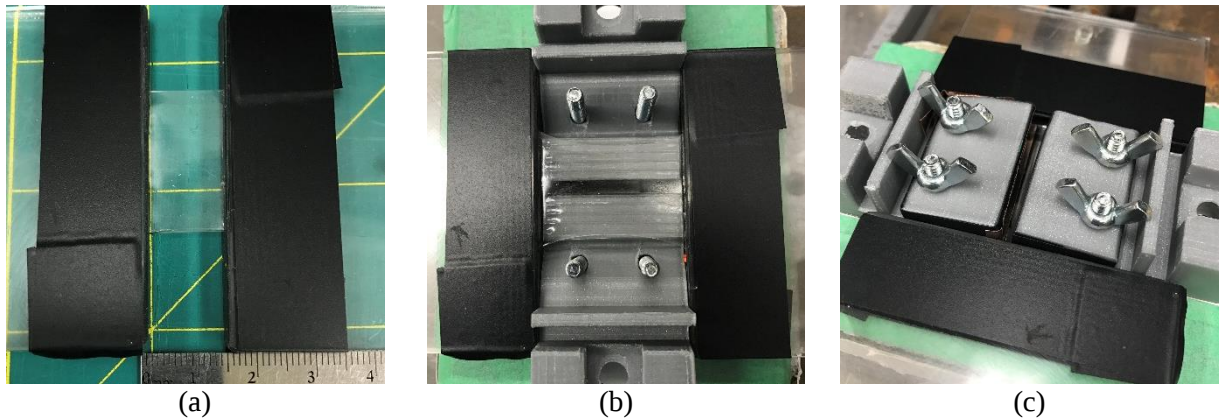


Figure A.29: Application of pre-stretched specimen to clamps

Once the clamp surfaces have been lined, the pre-stretched specimen was then applied to the top portion of the clamps, in the bench vise. The sample was first cut to the appropriate size to achieve the desired λ_2 width pre-stretch ratio. This was determined based on the clamps' jaw widths, as described earlier. In order to stretch the material to the desired ratio, the edges of the specimen were pinched between two pairs of acrylic plates, manually elongated, and applied to the clamps (as seen in Figure A.29). These acrylic plates were first prepped using solvent wipes, in order to ensure proper adhesion of the VHB tape. Samples were cut down to size, using the same cutting mat/ruler technique described for biaxial mechanical tests in Appendix A.1. Each was cut with an

additional 2 mm in width (e.g. for a desired 10 mm sample, a strip with an actual width of 12 mm was cut). This was done in order to give a 1 mm tape-edge on either side, to be used as the grip site for subsequent stretching.

By very carefully measuring the 1 mm width on either edge of the sample, and using the lines of the cutting mat, two acrylic plates were pressed onto the opposing sides of the specimen. The plates were taped with a straight piece of electrical tape, at 1 mm from their outer edge, to act as additional guides for this step. Once the first two plates were attached to the sample, the assembly was then flipped over, exposing the backside of the tape with the protective red film still attached. This film was then removed using a precision blade, and forceps, similarly to the process described in Appendix A.1. The two other acrylic plates were carefully pressed down on their respective sides, ensuring that the edges of adjacent plates aligned properly.

Once the sample was pinched between the plates, it was brought over to the bench vise, where it was then swiftly stretched above the clamp faces, centred, and brought down to make contact with them (Figure A.29 (b)). The edges of either acrylic plate pairs were slid down the side surfaces of the clamps, to ensure that the desired stretch ratio was achieved. The bottom jaws of the clamps were then applied to the assembly, using the exposed machine screws as alignment guides, and pressed down to ensure full clamping of the pre-stretched sample (Figure A.29 (c)). Wing nuts were screwed on, to complete the assembly. The acrylic plates were pried off of the sample, releasing its edges and allowing it to relax between the clamps. It should be noted that cutting the sample's edges along the acrylic plates was attempted. This process, however, left the samples with jagged edges, which resulted in tear propagation during tensile testing. For this reason, the 1 mm edge on either side of the pre-stretched specimen was kept as part of the assembly. Since the intended results of these experiments are to be used to characterize the electro-mechanical behavioural trends of the elastomer, the additional material left on the sample was deemed negligible.

Once the sample has been properly applied and secured, the clamps were released from the bench vise, and the specimen assembly was left to rest for 30 minutes. A fully assembled specimen can be seen in Figure A.30. As seen in the results of the previous section, a stress-relaxation response within the VHB tape ensues from being stretched and held, due to its viscoelastic nature.

This waiting period was therefore enforced in order to allow the pre-stretched specimen to settle, ensuring that the stresses within the material converge to a constant state.

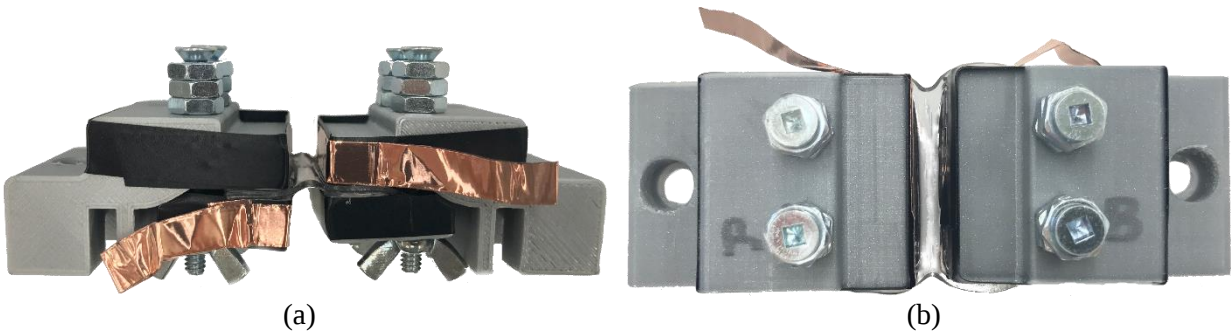
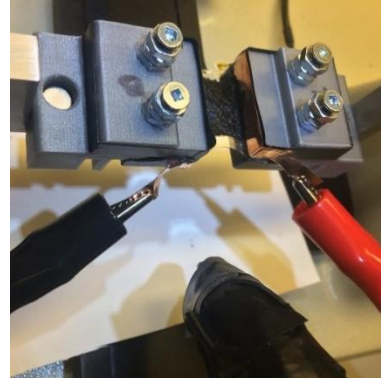


Figure A.30: Fully assembled uniaxial electro-mechanical testing specimen (excluding grease electrodes)

Following the resting period, electrodes were applied on either face of the tape, by painting the conductive grease solution with a brush. Due to the small distance between the clamps, sample painting was not possible from its initial state. In order to apply the grease to the specimen, the clamps were thus temporarily stretched apart. To keep the process consistent between all samples, the clamps were reinserted into the bench vise, at a distance of 10 mm (or $\lambda_1 = 2$). This was done using the same technique as the sample application process, where the ruler scale that was etched on the edge of the vise jaws was used in combination with a square piece of acrylic with a 10-mm width as a guide. In order to ensure consistency between all samples, the time during which the sample is stretched was also measured for the painting process. Each sample was held for an overall painting time of 10 minutes. The grease was carefully painted onto the sample with a fine-point brush, on both faces, ensuring a consistent thickness throughout. The paint was also liberally applied to the edges that were in contact with the copper tape, in order to ensure absolute connection with the voltage source. When the sample was turned over to paint the second electrode, extra care was taken to ensure that the electrodes were symmetrical.



(a)



(b)

Figure A.31: Uniaxial testing specimen electrode application and machine mounting

Due to the small size of the sample, and the material's high deformability, it was observed that, if the electrodes were painted to the edge, the grease would eventually bleed over (while being extended) and make contact with the opposing face. This ultimately led to the breakdown of the material and failure of the experiment. For this reason, a 2-mm edge was left unpainted on both free-stranding edges of the tape, as seen in Figure A.31. Once the 10-minute timer had ended, the sample was then released from the vise and placed onto the CellScale machine for testing.

Appendix A.7 – Results of Electro-Mechanical Experiments

A.7.1 Multi-Step Isostrain Electro-Mechanical Experiments

VHB 4905 tape

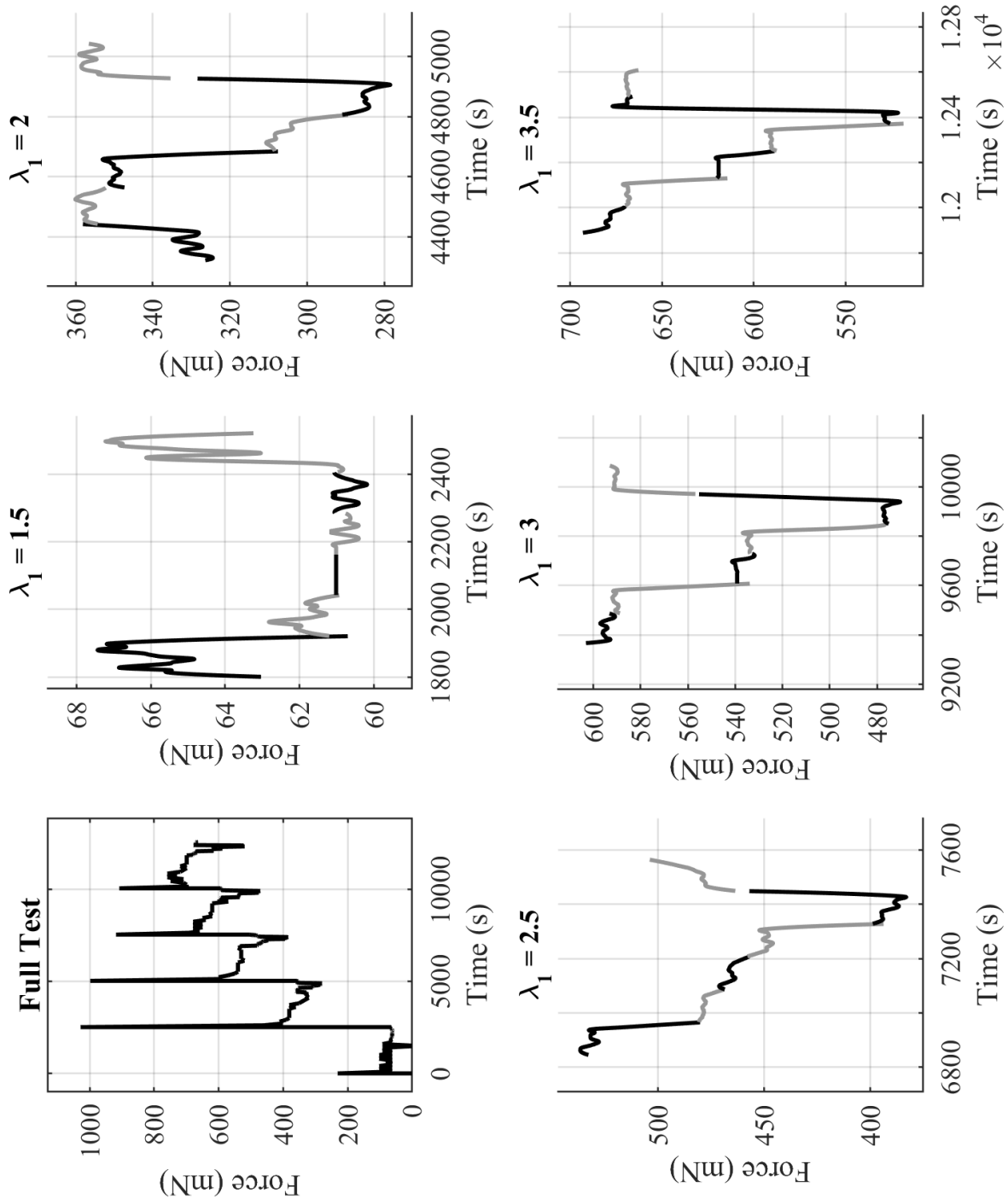


Figure A.32: Multi-step isostrain electro-mechanical test for VHB 4905 tape at fixed $\lambda_2 = 1.5$

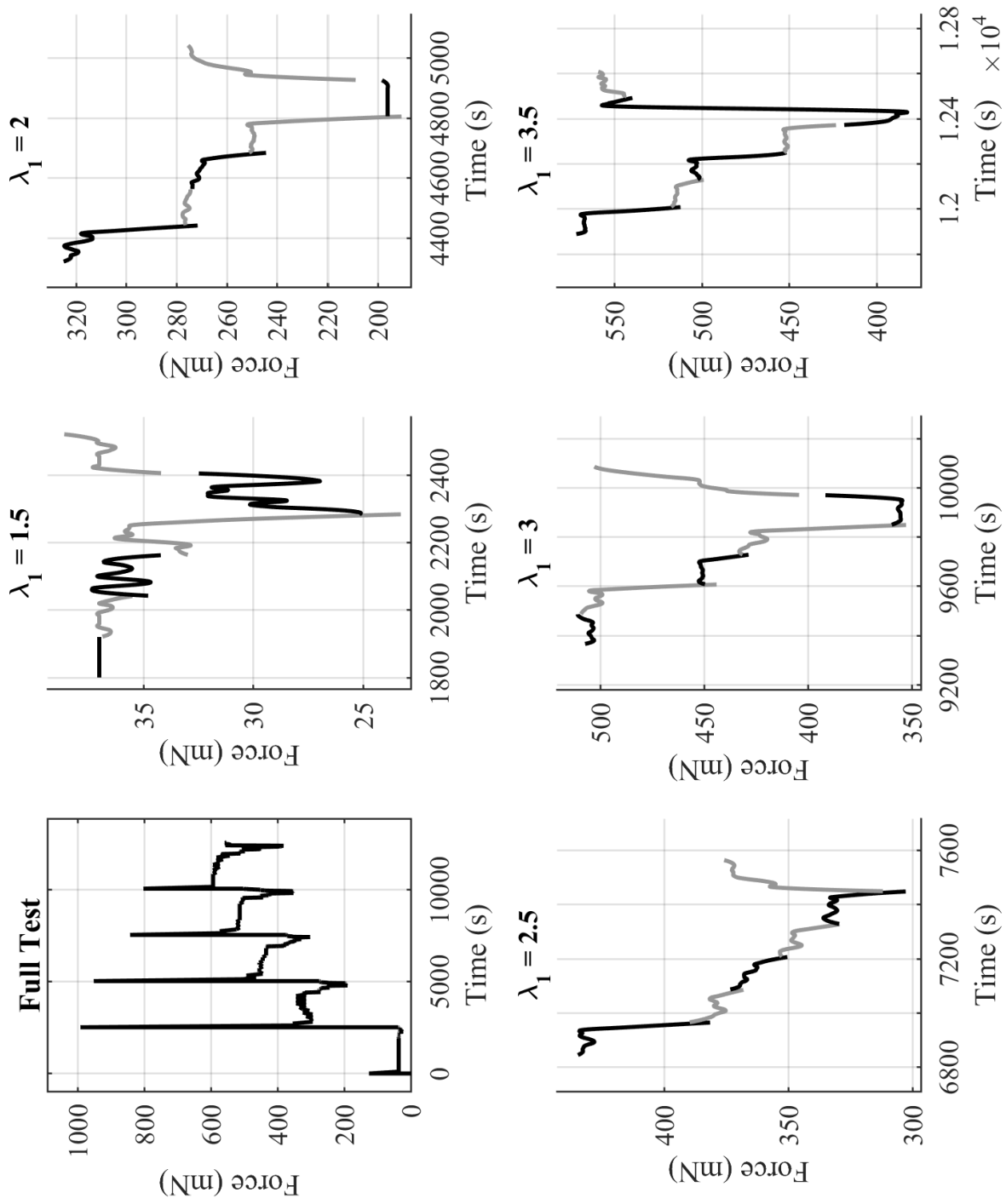


Figure A.33: Multi-step isostrain electro-mechanical test for VHB 4905 tape at fixed $\lambda_2 = 2$

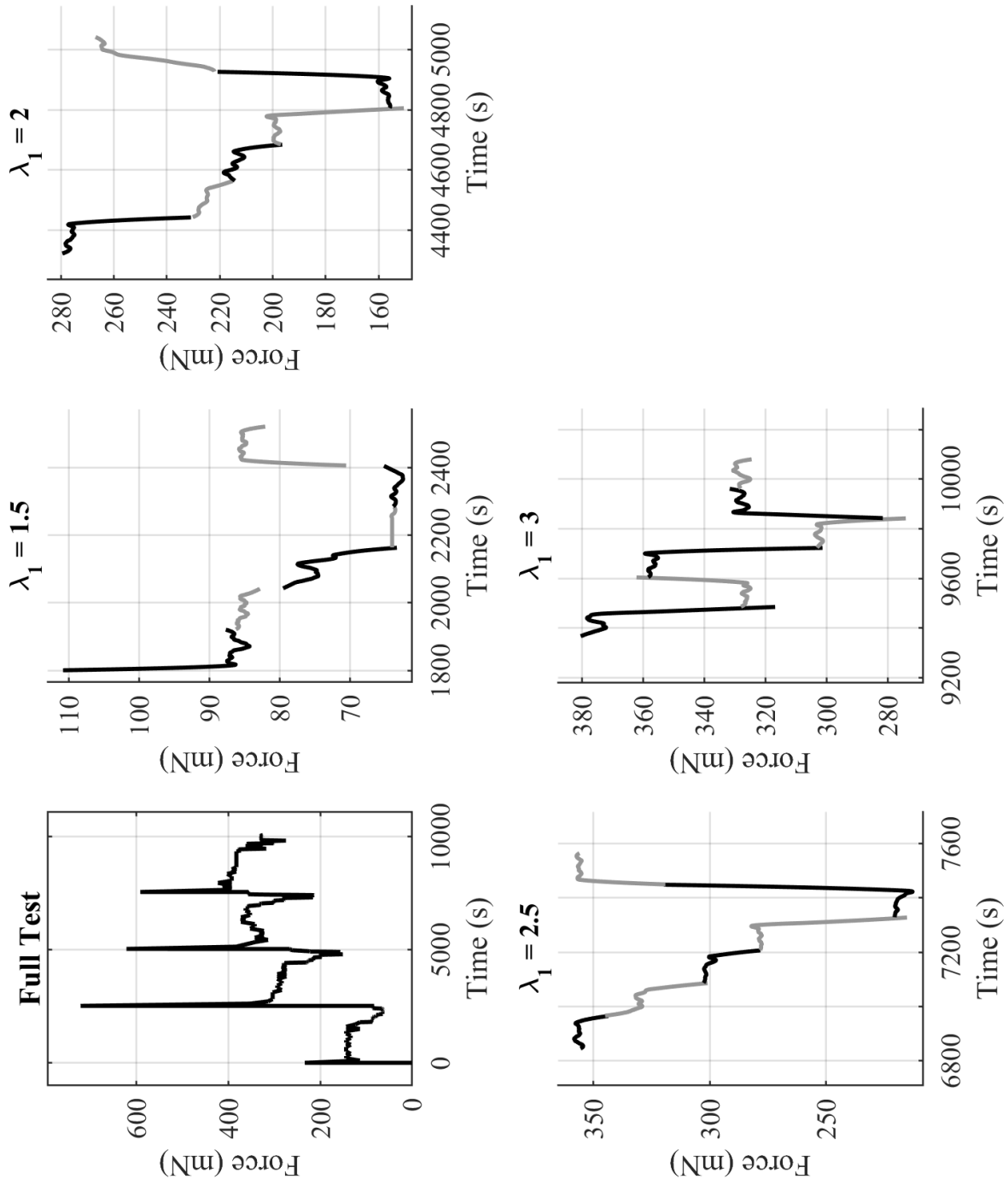


Figure A.34: Multi-step isostrain electro-mechanical test for VHB 4905 tape at fixed $\lambda_2 = 1.5$

VHB 4910 tape

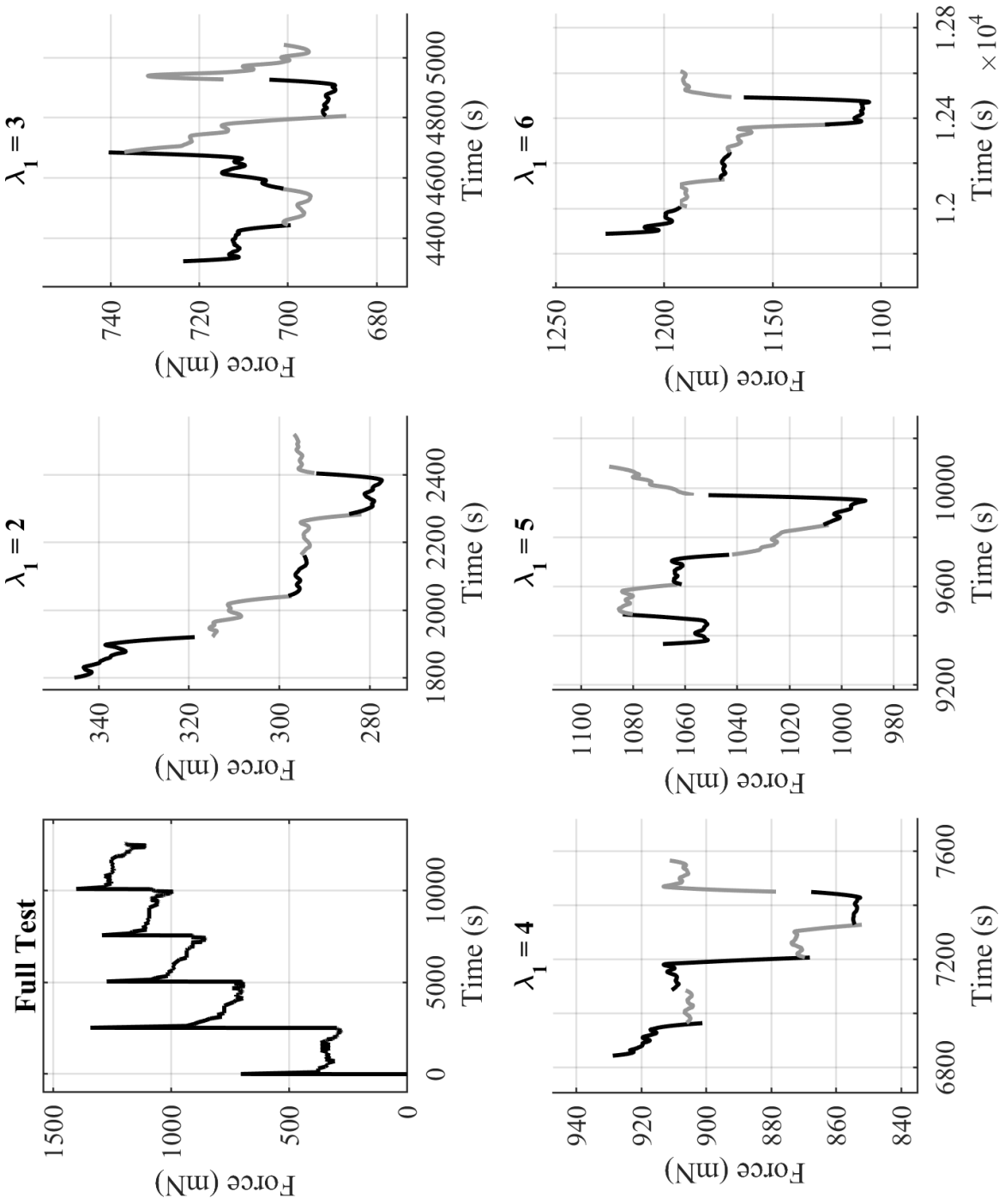


Figure A.35: Multi-step isostrain electro-mechanical test for VHB 4910 tape at fixed $\lambda_2 = 2$

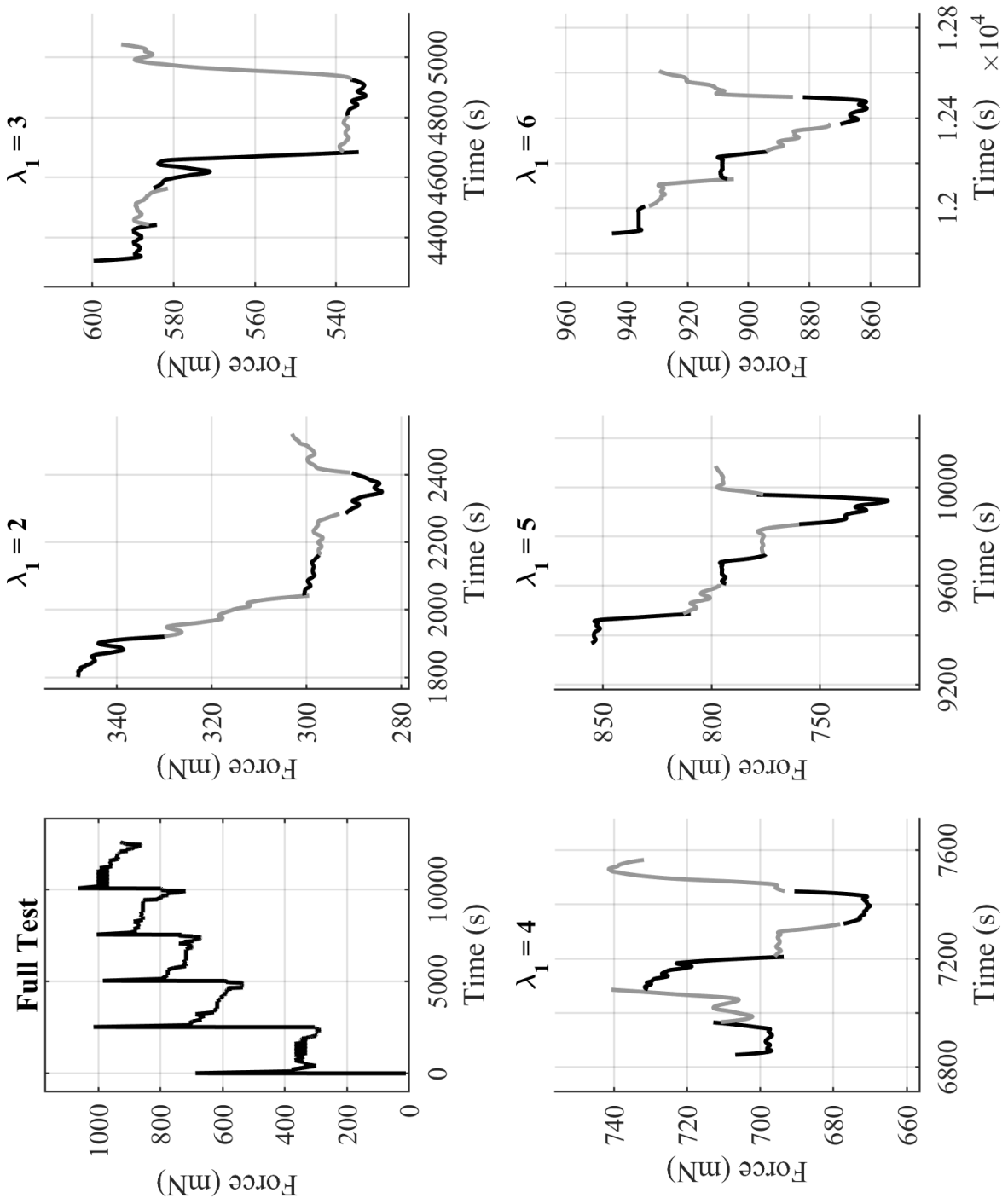


Figure A.36: Multi-step isostrain electro-mechanical test for VHB 4910 tape at fixed $\lambda_2 = 3$

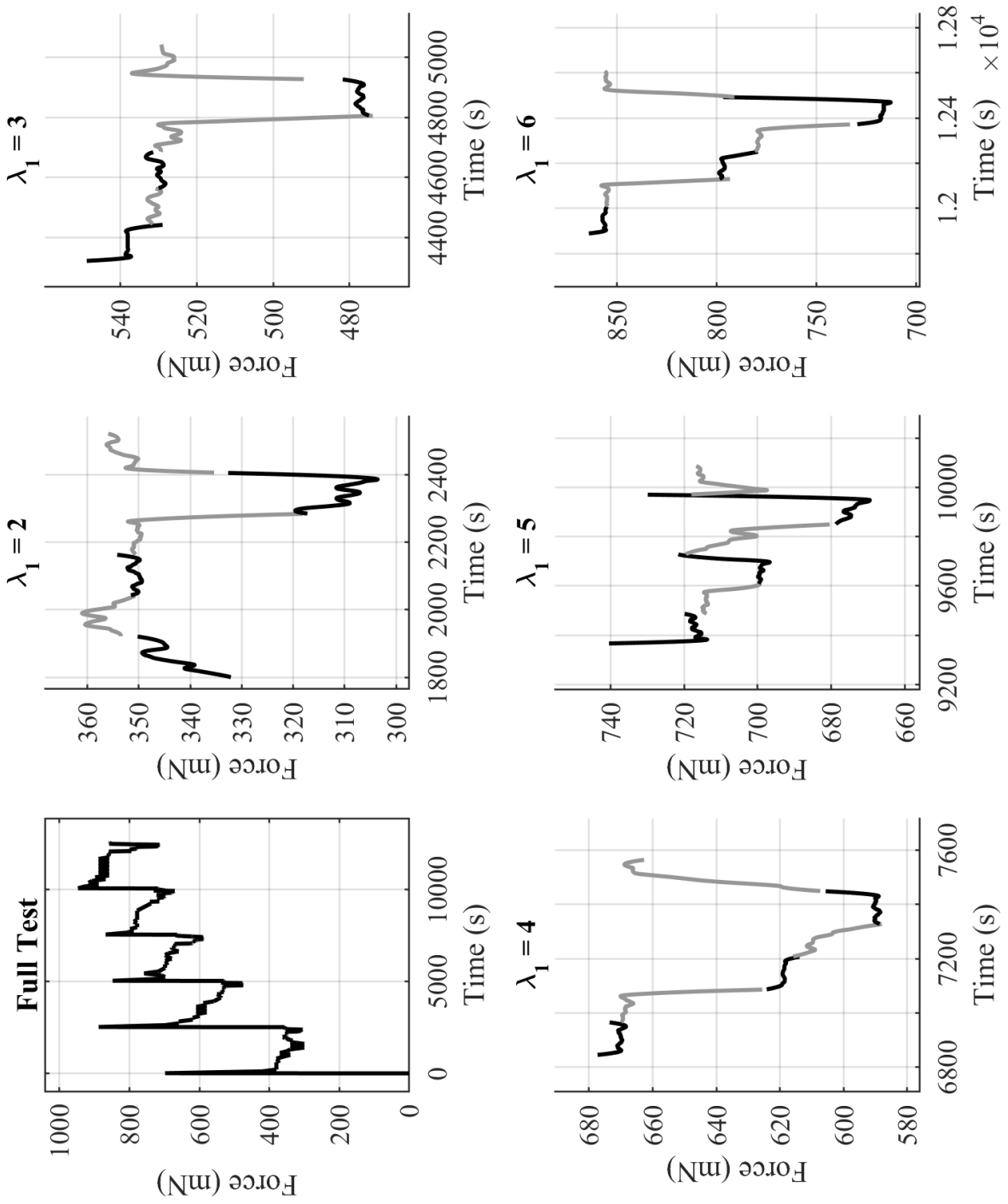


Figure A.37: Multi-step isostrain electro-mechanical test for VHB 4910 tape at fixed $\lambda_2 = 4$

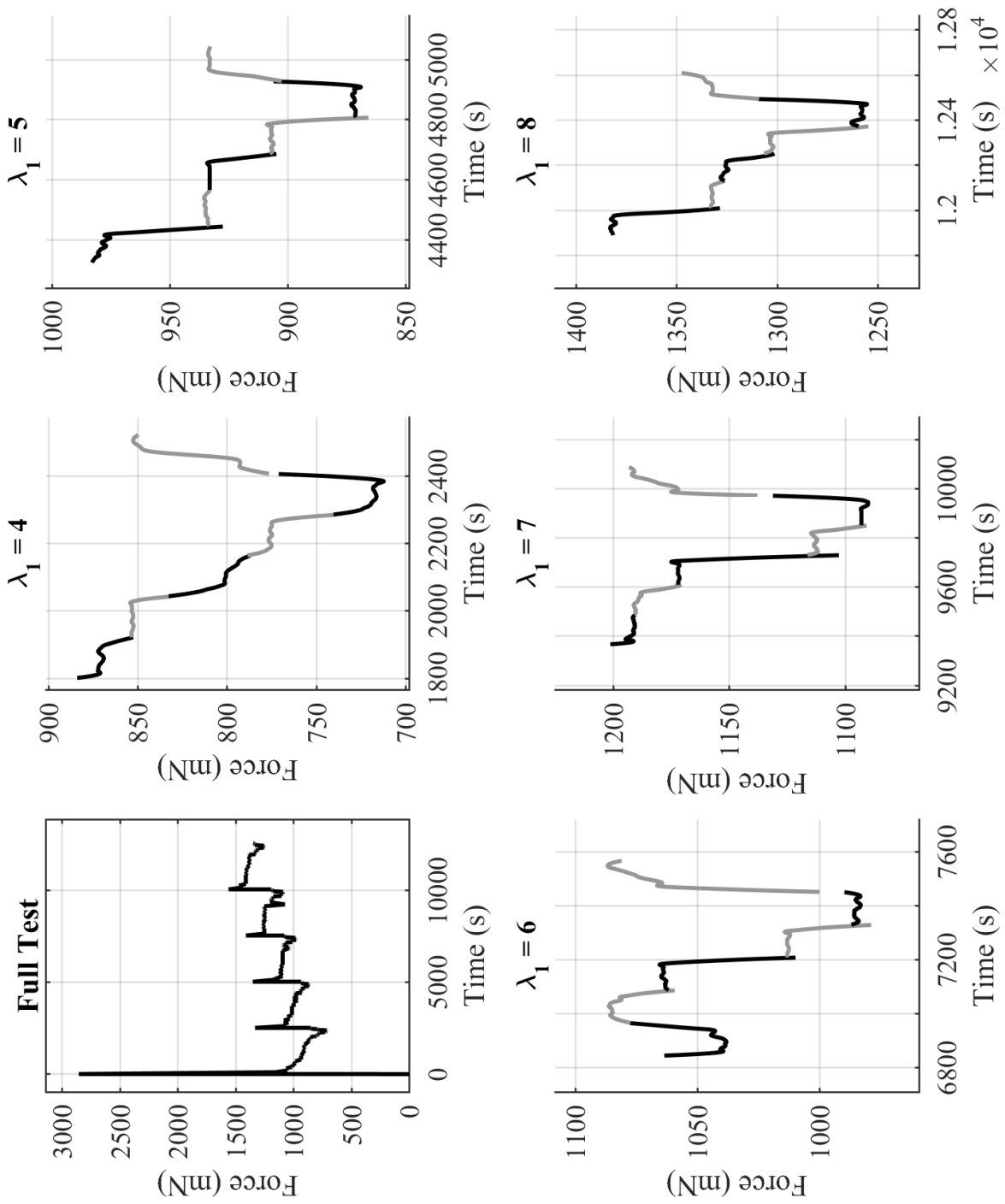


Figure A.38: Multi-step isostrain electro-mechanical test for VHB 4910 tape at fixed $\lambda_2 = 4$ with λ_1 values exceeding optimal theorized stretch ratio combination

A.7.2 Load-Unload Electro-Mechanical Experiments

VHB 4905 tape

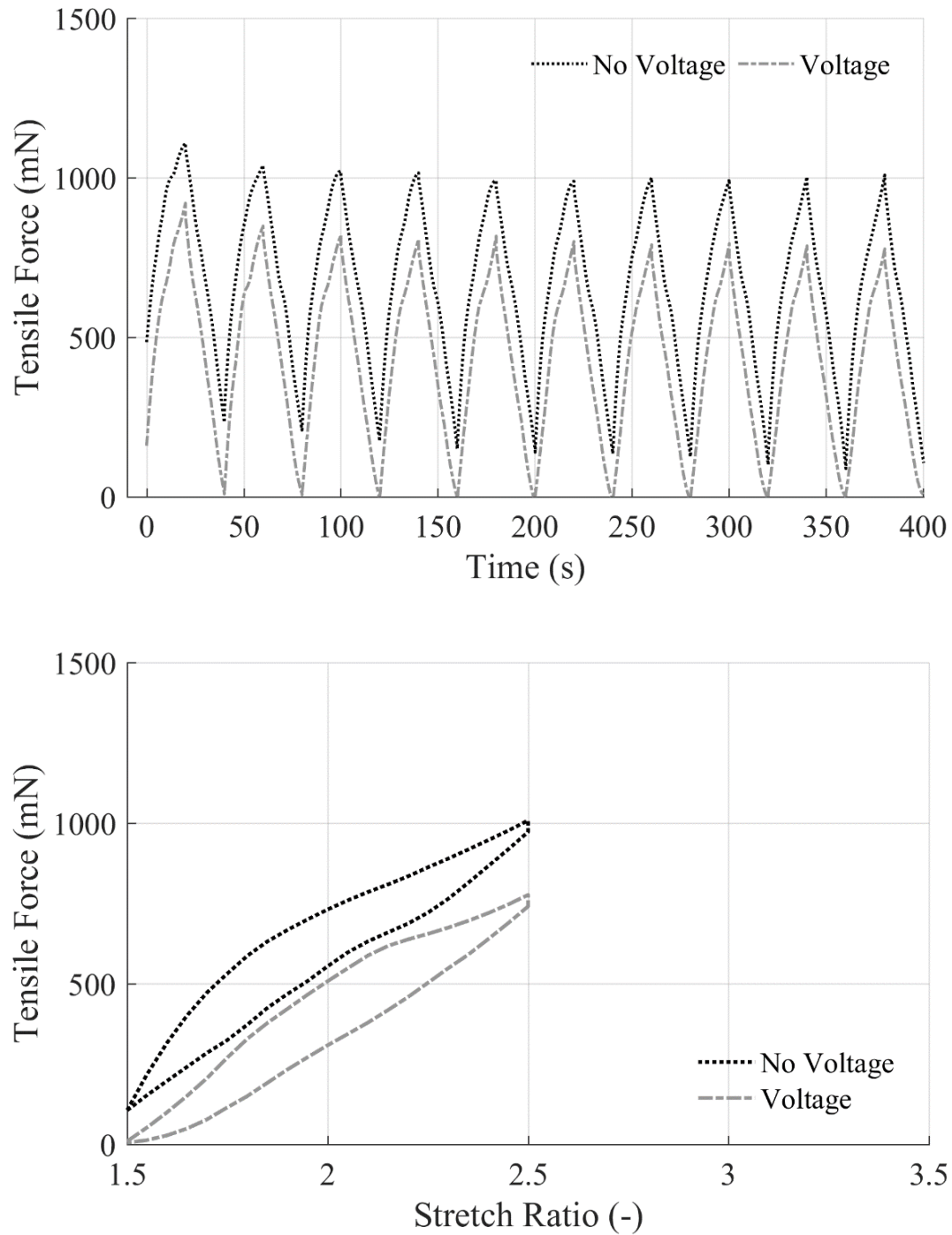


Figure A.39: Comparison of electro-mechanical load-unload curves for VHB 4905 tape at $\lambda_2 = 1.5$ for $1.5 \leq \lambda_1 \leq 2.5$

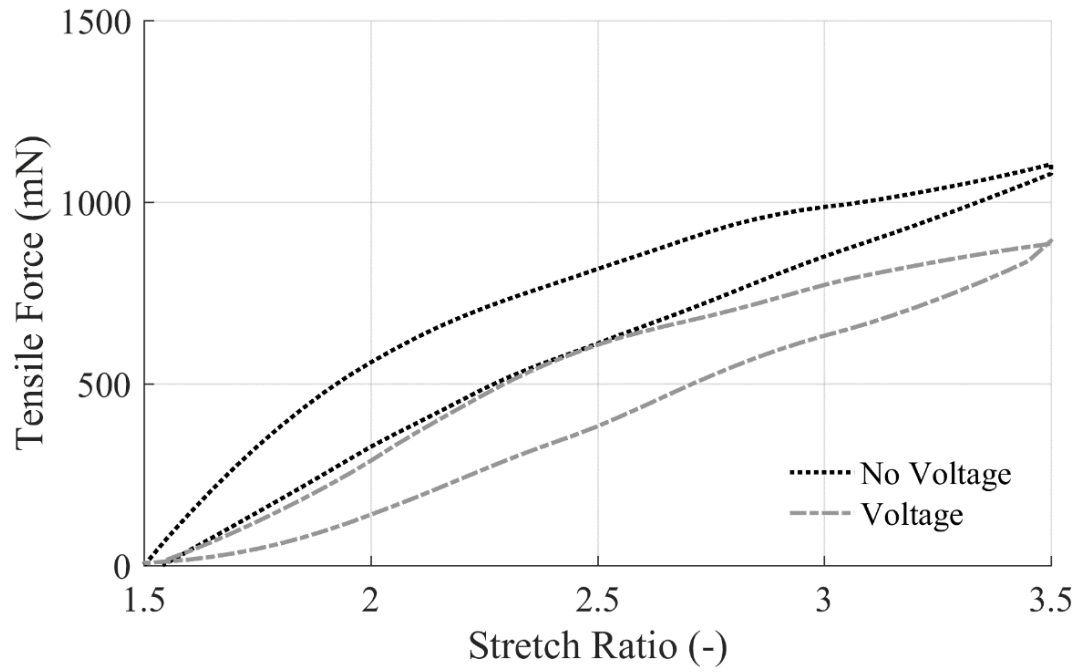
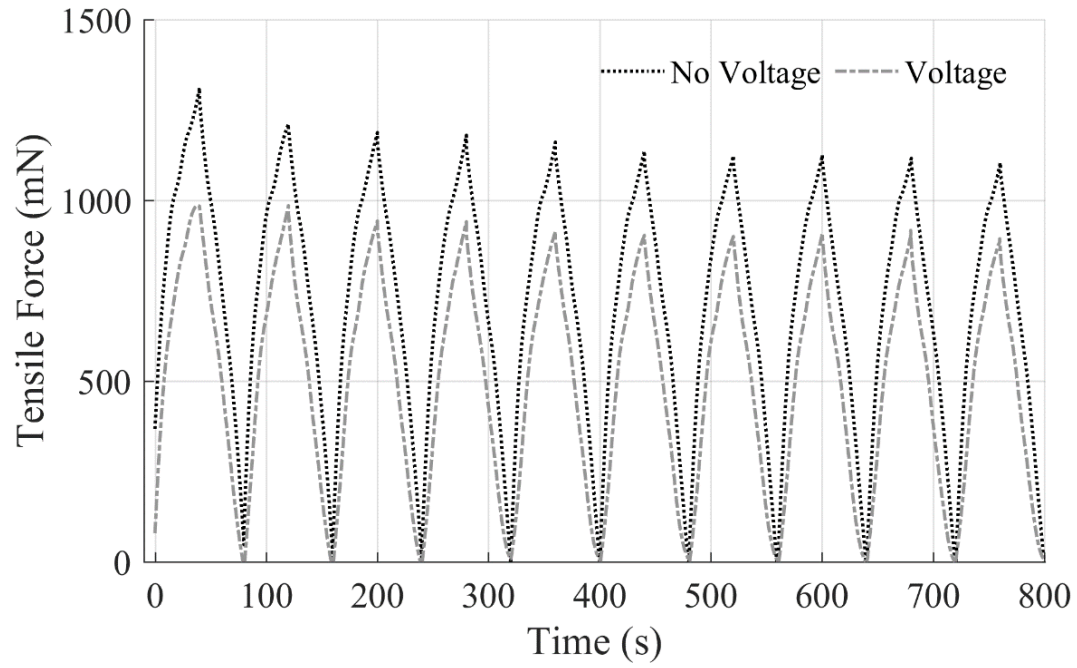


Figure A.40: Comparison of electro-mechanical load-unload curves for VHB 4905 tape at $\lambda_2 = 1.5$ for $1.5 \leq \lambda_1 \leq 3.5$

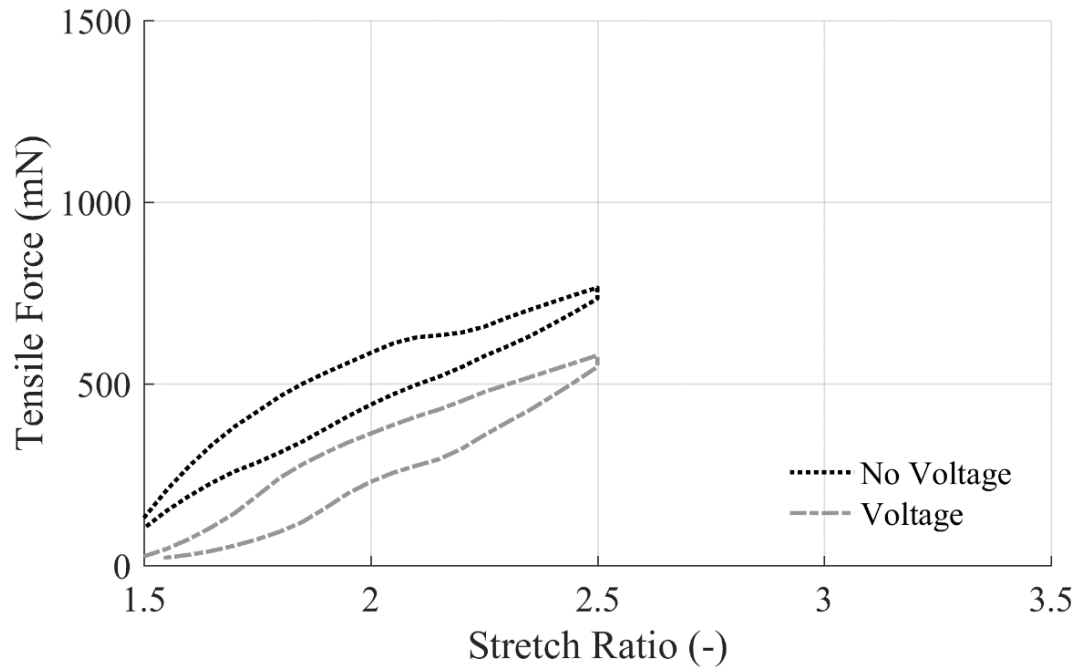
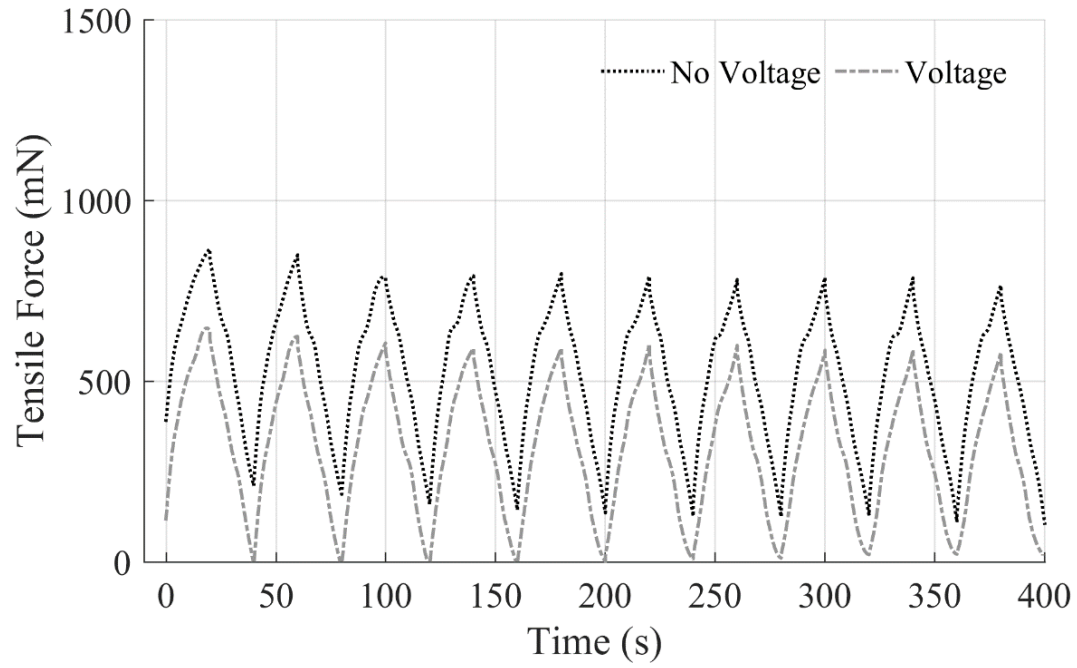


Figure A.41: Comparison of electro-mechanical load-unload curves for VHB 4905 tape at $\lambda_2 = 2$ for $1.5 \leq \lambda_1 \leq 2.5$

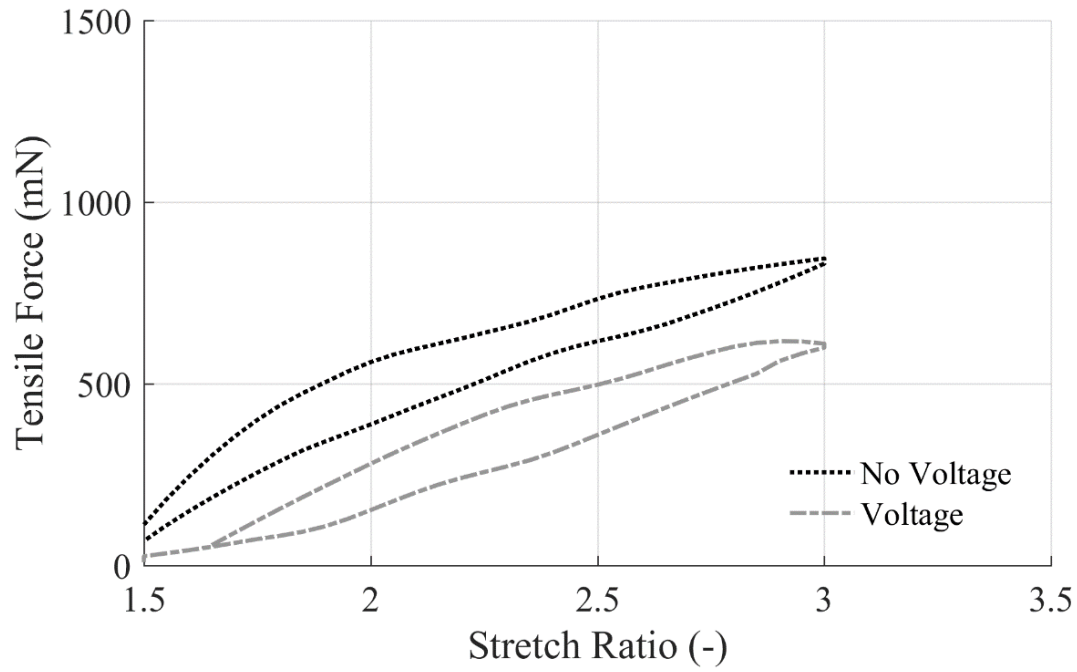
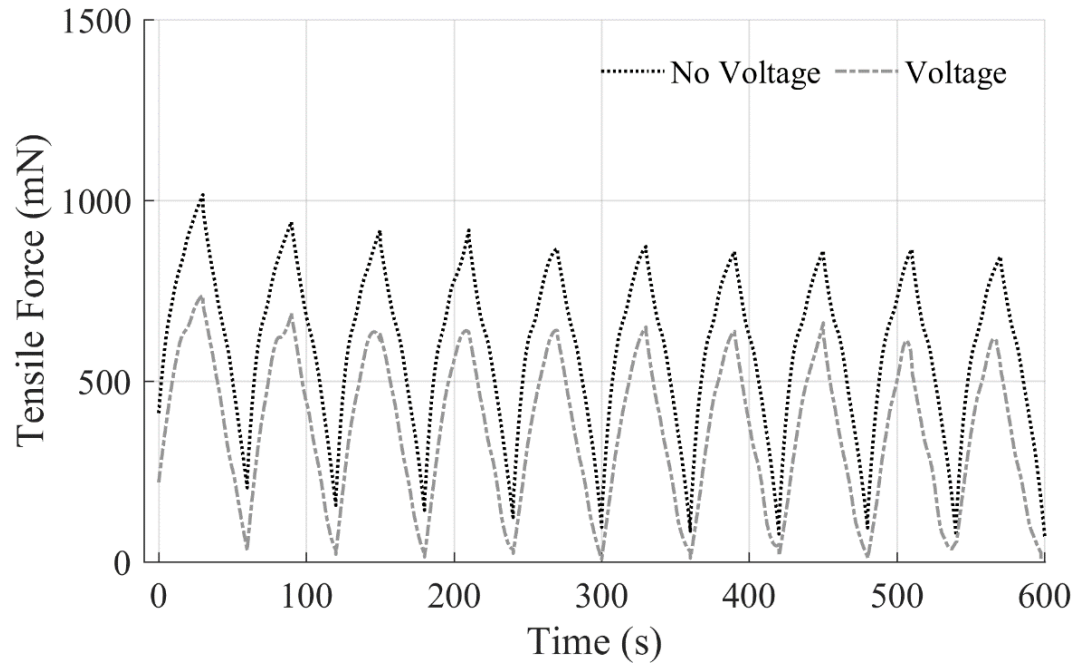


Figure A.42: Comparison of electro-mechanical load-unload curves for VHB 4905 tape at $\lambda_2 = 2$ for $1.5 \leq \lambda_1 \leq 3$

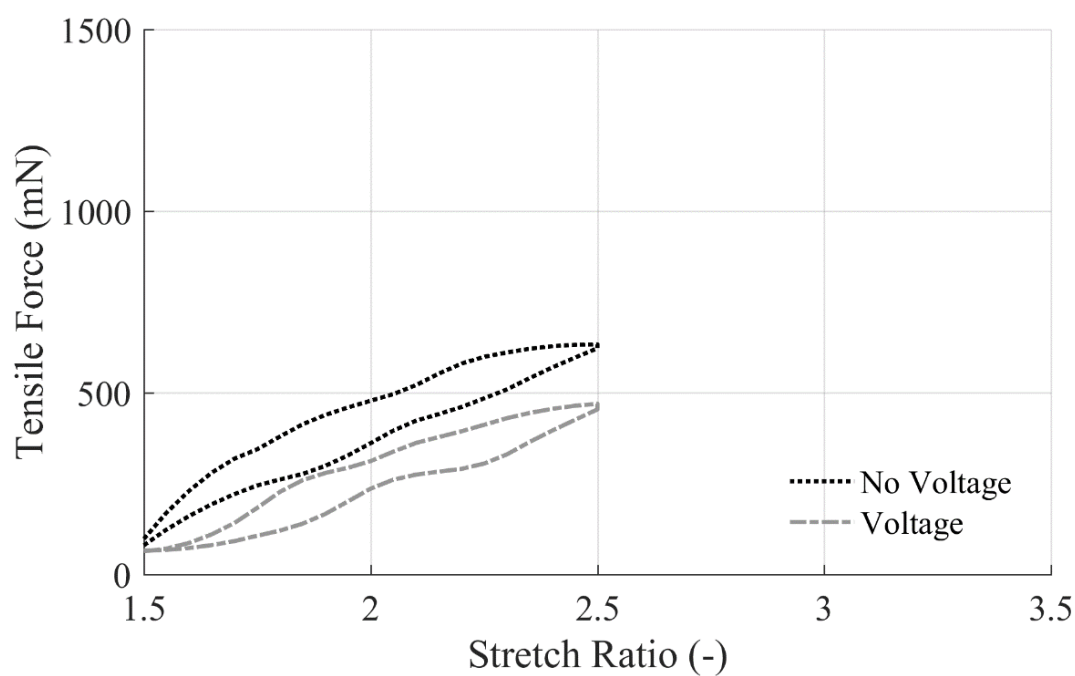
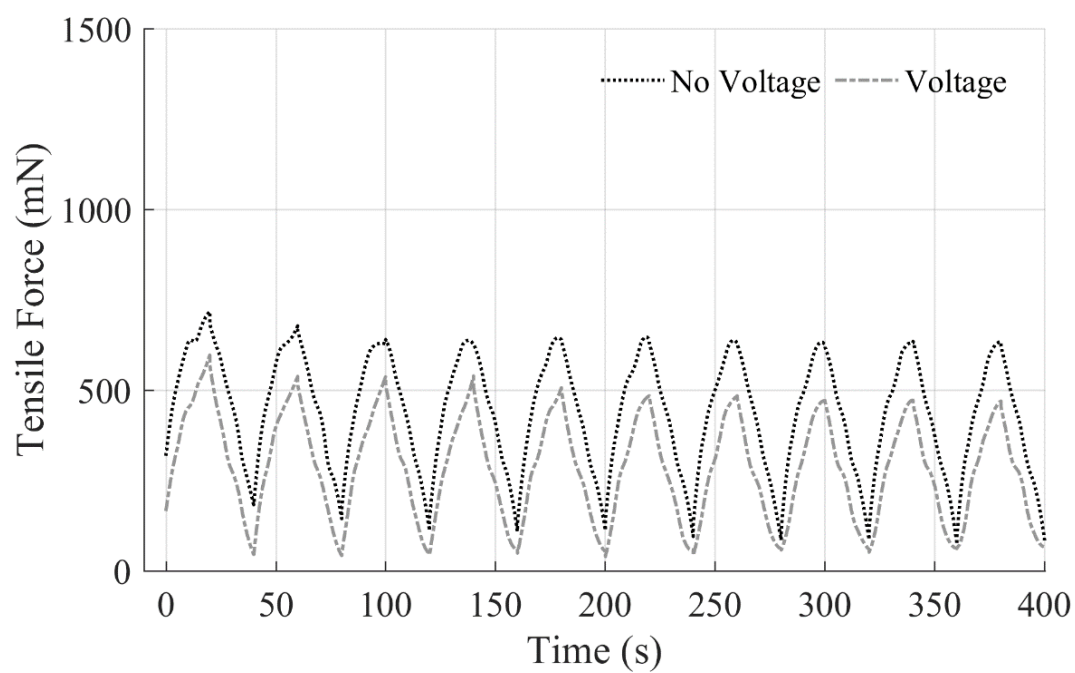


Figure A.43: Comparison of electro-mechanical load-unload curves for VHB 4905 tape at $\lambda_2 = 2.5$ for $1.5 \leq \lambda_1 \leq 2.5$

VHB 4910 tape

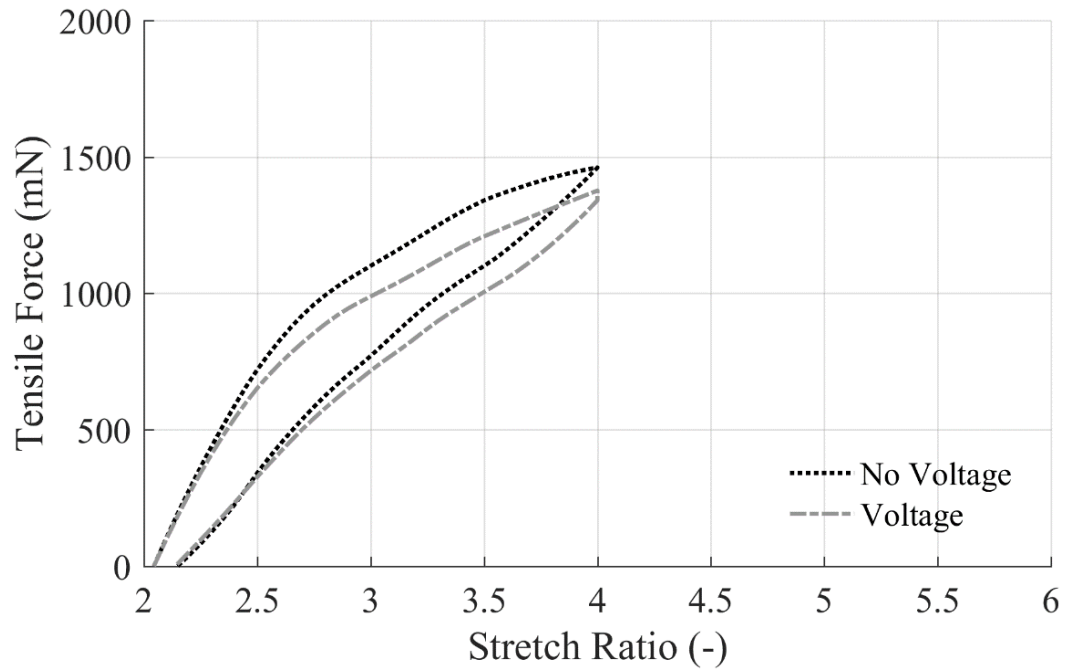
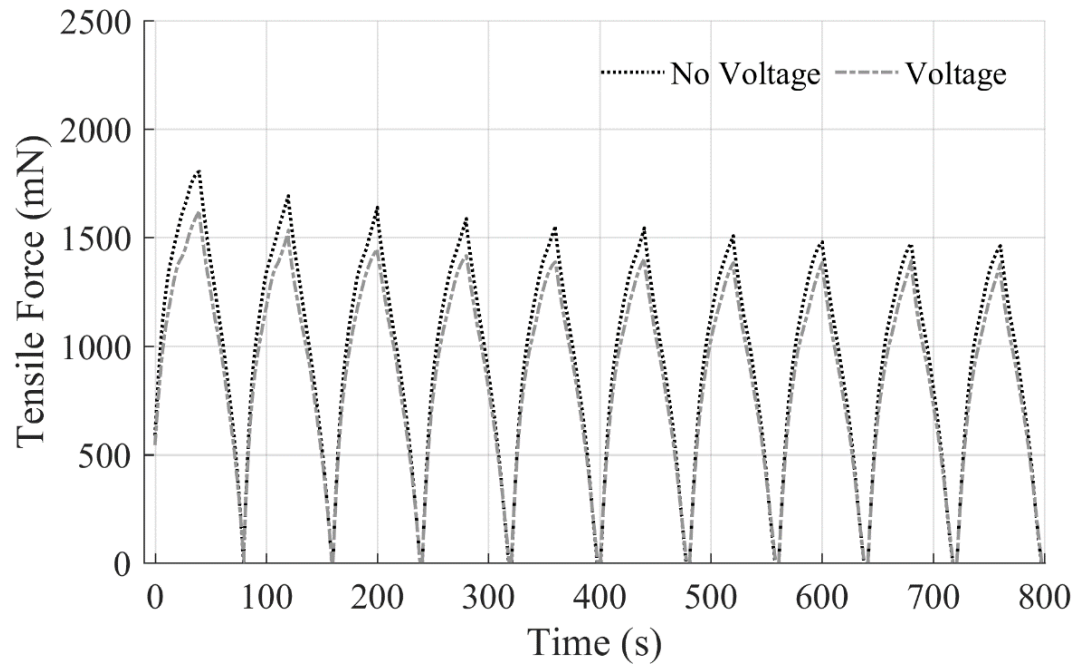


Figure A.44: Comparison of electro-mechanical load-unload curves for VHB 4910 tape at $\lambda_2 = 2$ for $2 \leq \lambda_1 \leq 4$

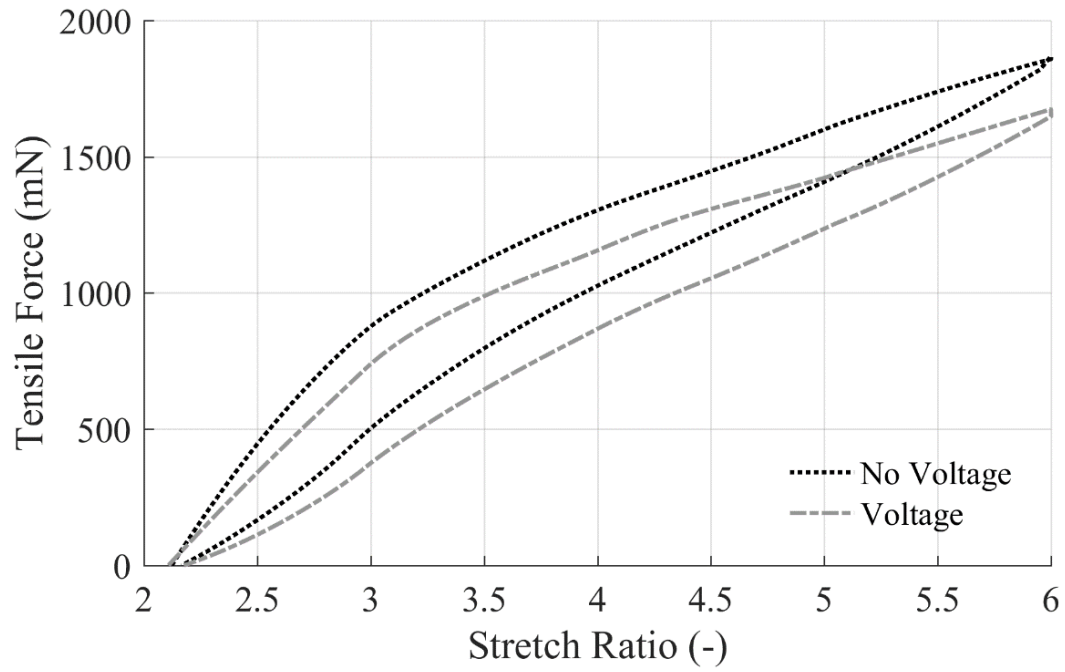
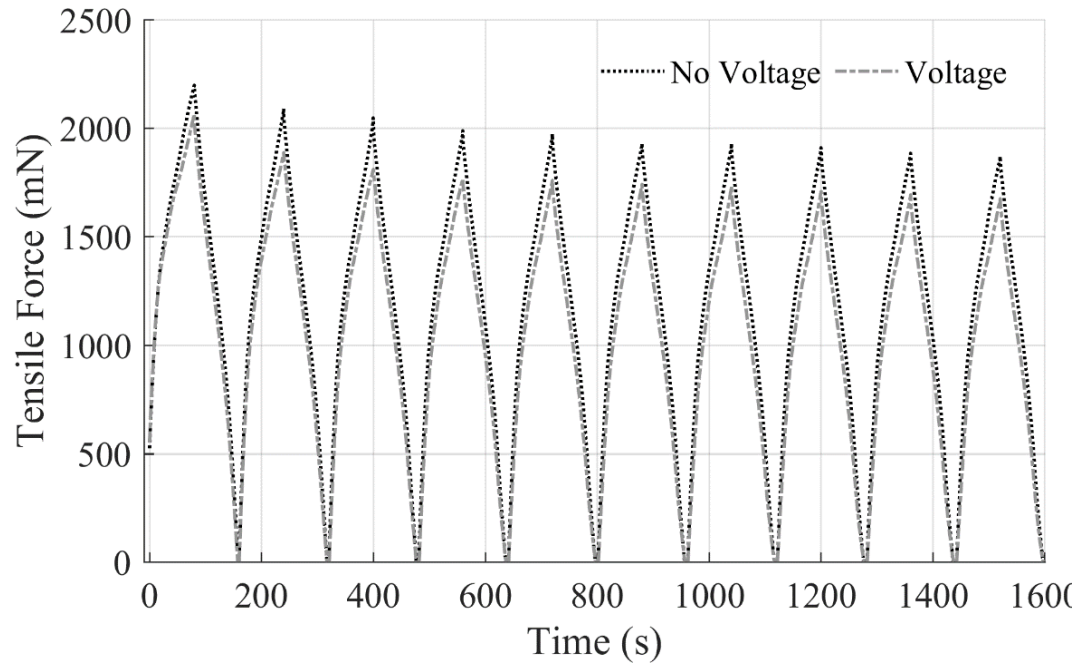


Figure A.45: Comparison of electro-mechanical load-unload curves for VHB 4910 tape at $\lambda_2 = 2$ for $2 \leq \lambda_1 \leq 6$

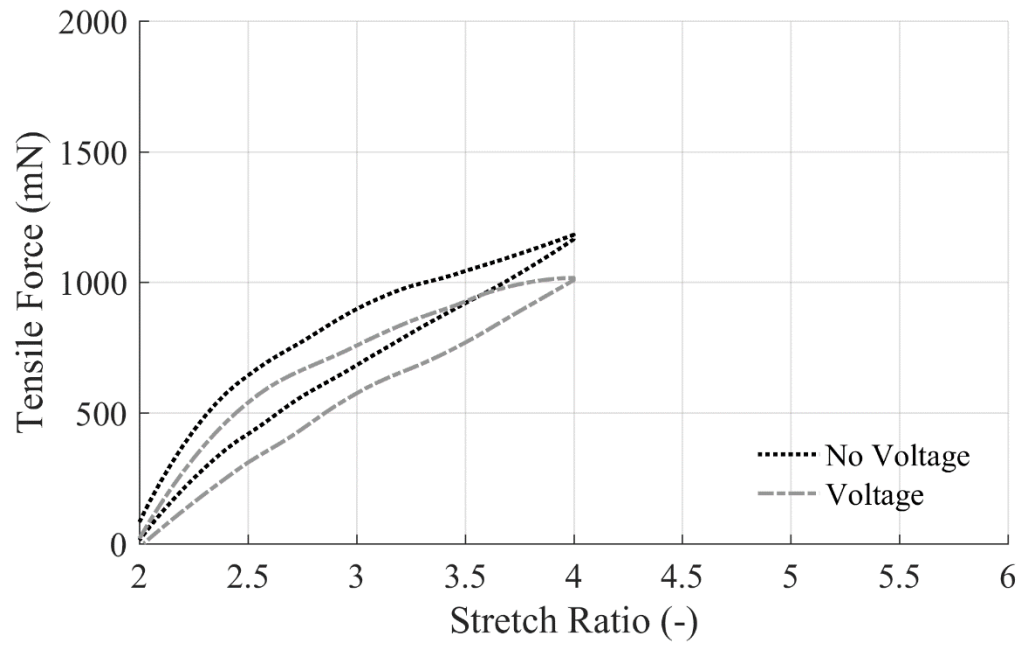
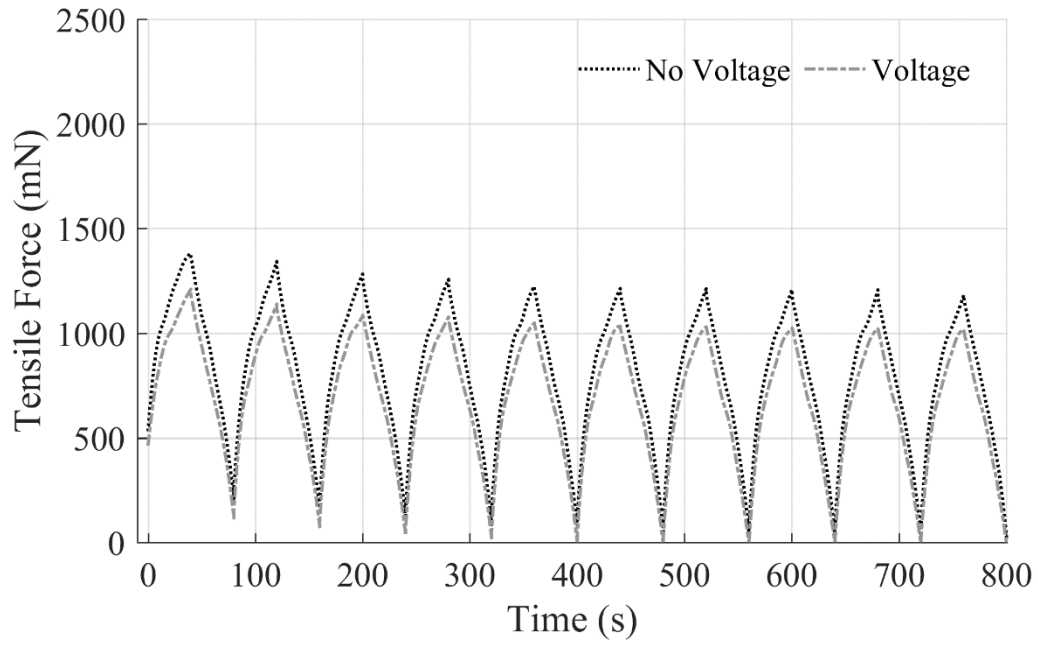


Figure A.46: Comparison of electro-mechanical load-unload curves for VHB 4910 tape at $\lambda_2 = 3$ for $2 \leq \lambda_1 \leq 4$

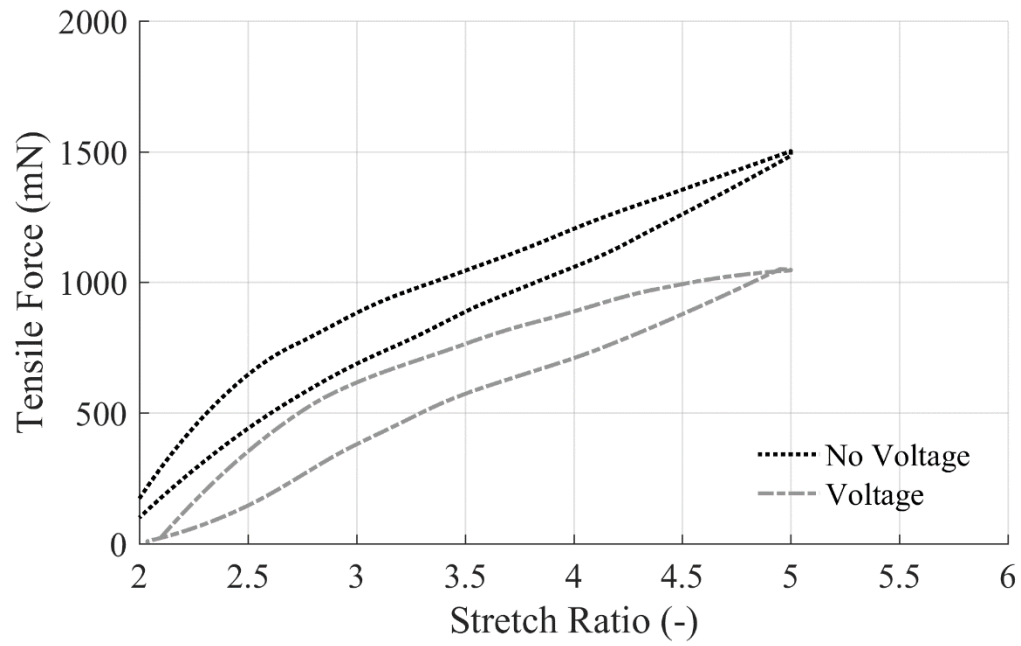
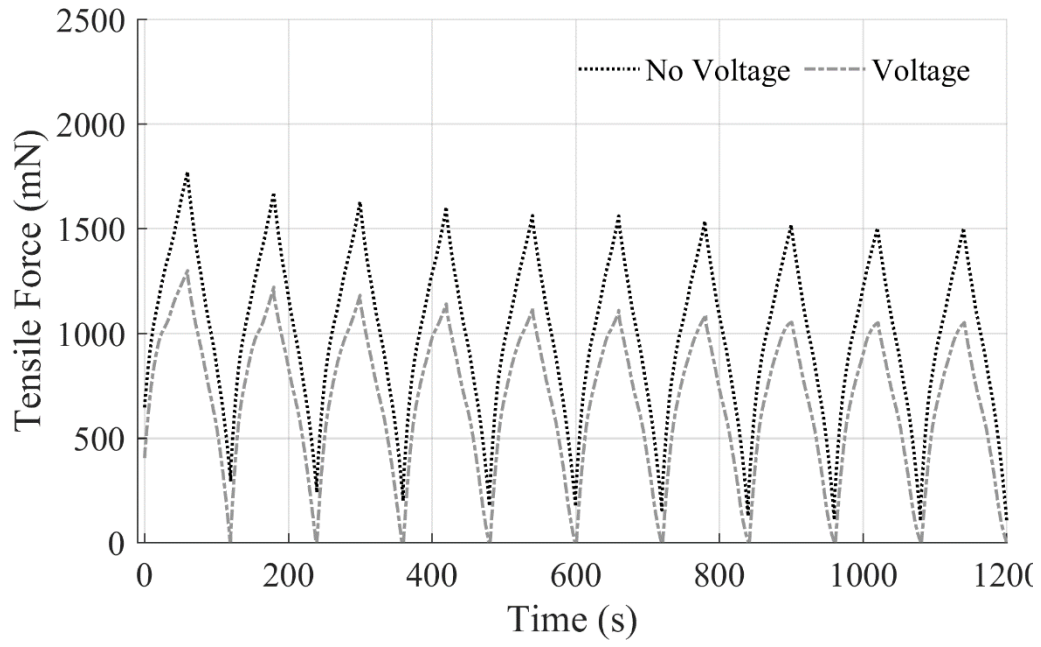


Figure A.47: Comparison of electro-mechanical load-unload curves for VHB 4910 tape at $\lambda_2 = 3$ for $2 \leq \lambda_1 \leq 5$

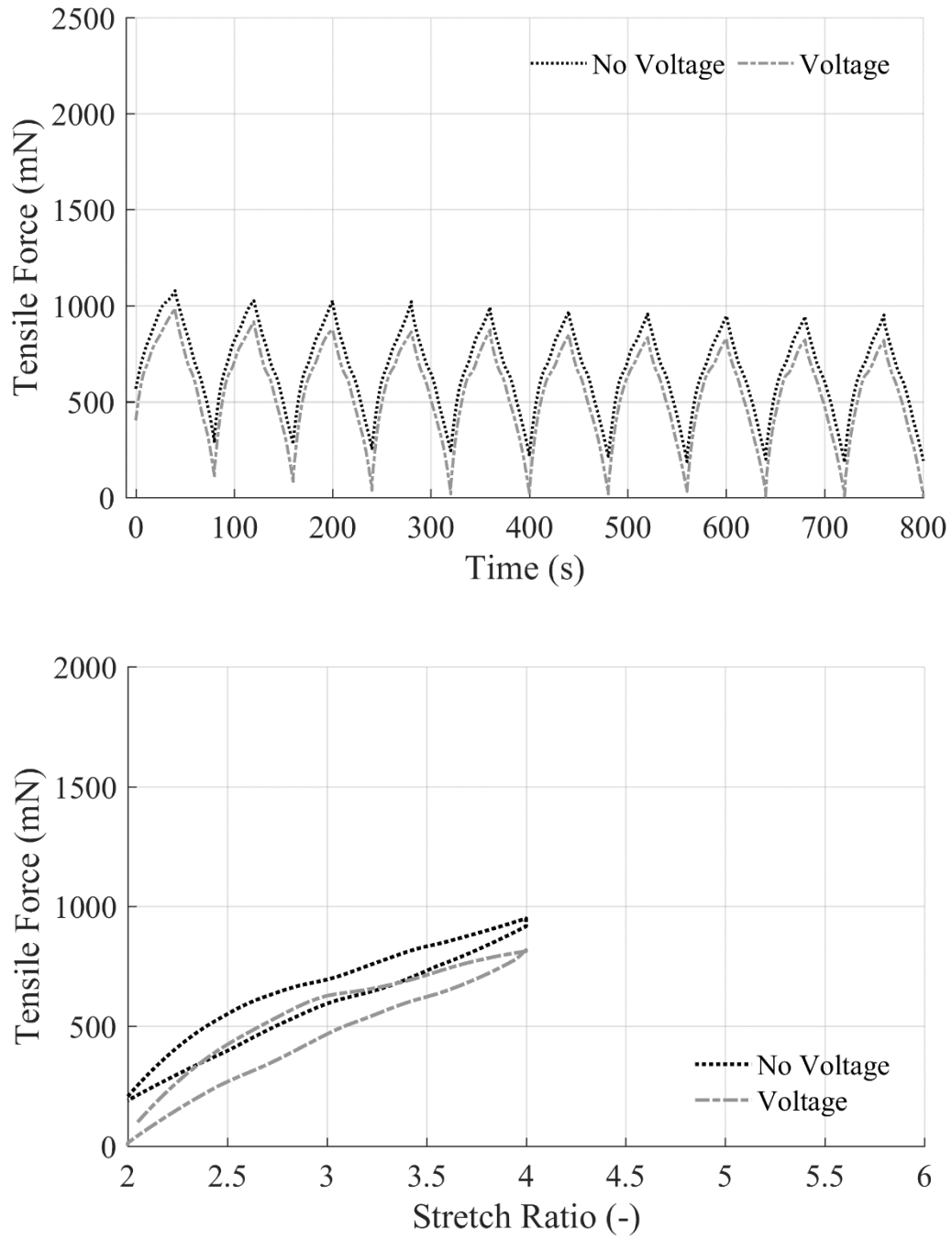


Figure A.48: Comparison of electro-mechanical load-unload curves for VHB 4910 tape at $\lambda_2 = 4$ for $2 \leq \lambda_1 \leq 4$

Appendix B

Appendix B.1 – Optimization Algorithm Process Description

Steps 0 to 3 are applied to each individual experiment separately:

Step 0 – Preliminaries

The first step of the program achieves the preliminary steps for data manipulation. Within this step, the data file is read, and values are assigned to their respective variables. The optimization parameters are then placed into an options structure, using the `optimset` function, in order for them to be passed on to the optimization functions in Step 3.

Step 1 – Stress (σ) Function

This step calculates values for the axial stresses σ based on (4.17). The values for the angular frequency ω and equivalent complex modulus E_{eq}^* are calculated using the experimental stretch ratio values λ_1 and initial guesses for spring and damper constants selected.

Step 2 – Stress (σ) Error

From the values obtained in Step 1, the error between calculated and experimental σ is calculated, in order to be used for optimization in the following steps.

Step 3 – Optimize Material Constants (For Individual Experiments)

Initial values for the constants are given as a datum (see program in Appendix B.2 for initial guesses). This step then uses the `lsqnonlin` function to optimize the constants for the experiment, by reducing the error found in Step 2 (the `lsqnonlin` function will be explained later in this section). Once they are fully optimized (and errors reduced), the final constant values are printed, and sent to Step 4 for further complete model optimization.

Once each experiment has been optimized independently, the values of their angular frequencies (calculated in Step 1) and dynamic complex moduli are grouped by corresponding experimental stretch rates. These values are then averaged to find a single value of ω and E_{eq}^* for each stretch rate. In order to find the final set of constants that apply to all experimental stretch rates, a correlation is then drawn between them by making use of equation (4.7), and optimizing the spring and damper coefficients (E_s , E_p , and D_p) for all cases simultaneously.

Steps 4 to 6 are applied to all experiments collectively:

Step 4 – Complex Modulus (E_{eq}^*) Function

This step calculates the absolute values of E_{eq}^* using (4.7). The complex moduli are calculated for every respective (averaged) angular frequency ω , that were previously determined.

Step 5 – Complex Modulus (E_{eq}^*) Error

From Step 4, the error between the calculated theoretical E_{eq}^* and averaged experimental E_{eq}^* values are then calculated for each of the averaged angular frequencies (ω).

Step 6 – Optimize Material Constants (For All Experiments)

The same initial values (“estimated”) for the constants as Step 3 are given as a datum. The same optimisation parameters as Step 0 were input into `optimset`. This step then uses the `lsqnonlin` function to optimize the constants for all of the experiments collectively, by reducing the error found in Step 5. Once the constants are fully optimized (and errors reduced), the final constant values are printed, and then used for subsequent theoretical stress plotting.

lsqnonlin function

The `lsqnonlin` function is a data fitting sub-function within MATLAB that allows to solve nonlinear least-squares problems [102]. The function uses the following form:

$$\min_x \|f(x)\|_2^2 = \min_x (f_1(x)^2 + f_2(x)^2 + \dots + f_n(x)^2)$$

This function looks to minimize the value of x in $f(x)$, where x and $f(x)$ are vectors/matrices [102]. The current model parameter fitting made use of the Levenberg-Marquardt algorithm (or damped least-squares method) in order to obtain the values of the material properties. In Steps 3 and 6, this function is used to minimize the error function of Steps 2 and 5 respectively. For both cases, the x variable is the *constants* matrix for the fitting model, containing the values of E_s , E_p , and D_p .

Appendix B.2 – MATLAB Optimization Algorithm for Biaxial Consideration

```
%-----  
% This is the main function to fit biaxial tensile mechanical  
% experiments to analytical model, and find final constants to be input in  
% model. Function should be placed in a folder with all "[...]Data.xlsx"  
% files (post iso-mapping/stress calculations) for only one type of tape at  
% a time. Function will automatically run through all files and then group  
% files by similar names to average their values for equivalent stretch  
% rates.  
%-----  
function main_program_biaxial()  
  
beep on; tic;  
  
clc; % clear MATLAB interface  
clear % clear variables  
format long % data output format  
  
%% ----- STEP 0 (PRELIMINARIES) -----  
  
% Find all excel file names within current folder  
all_files(:,1) = dir('*.xlsx');  
files = length(all_files);  
  
% Create array of all file names  
for k=1:files  
file_name{k,1} = all_files(k).name;  
end  
  
% Sort alphabetically  
file_name = sort(file_name);  
  
% Analysis loop (automated)  
for p = 1:files  
  
% Clear all variables for each loop except select variables which will be  
% averaged and displayed later  
clearvars -except files p file_name Eeq_x ang_freq_x str_ratio_x_exp_all...  
stress_x_exp_all str_ratio_x_theo_all stress_x_theo_all Eeq_y ...  
ang_freq_y str_ratio_y_exp_all stress_y_exp_all str_ratio_y_theo_all...  
stress_y_theo_all r2_x r2_y  
  
% EXTRACT DATA FROM EXCEL FILE  
% Determine file to be analyzed  
file_name_current = file_name{p};  
fprintf('Data File name : ');  
disp(file_name_current);  
file_path = which(file_name_current);  
numData = xlsread(file_name_current,2);  
rows = length(numData);
```

```

% Sometimes processing adds additional row to time, but no stress value.
% This is a fail-safe to ensure all rows are the same length, or else
% program freezes and won't continue computing
last_value = numData(rows,2);
if isnan(last_value); numData = numData(1:rows-1,:); end

% Determine the end of load cycle (the peak)
rows = length(numData); loadcycle_peak = ceil(rows/2);

% Index time, stretch ratio, and stress columns
time_exp          = numData(:,1); % in s
str_ratio_x_exp   = numData(:,2);
str_ratio_y_exp   = numData(:,3);
stress_x_exp      = numData(:,4); % in MPa
stress_y_exp      = numData(:,5); % in MPa
stress_x_smooth_exp = numData(:,6); % in MPa
stress_y_smooth_exp = numData(:,7); % in MPa

% OPTIMIZE MATERIAL CONSTANTS USING "optimset"
options = optimset('largescale','off','MaxFunEvals',1e100,'tolFun',1e-30...
    'TolX',1e-30,'MaxIter',5e3,'Algorithm','levenberg-marquardt',...
    'Display','off');

%% ----- STEP 2 (OPTIMIZE MATERIAL CONSTANTS) -----

% INITIAL GUESSES FOR MATERIAL CONSTANTS
Es = 0.1; Ep = 0.1; Dp = 0.1;
initialconst = [Es Ep Dp];

% FIND THE CONSTANTS USING "lsqnonlin"

% Use the lsqnonlin function to optimize constants vector
constants_x = lsqnonlin(@(x) error_stress(x,str_ratio_x_exp,...
    str_ratio_y_exp,time_exp,loadcycle_peak,stress_x_smooth_exp),...
    initialconst,[],[],options);
constants_y = lsqnonlin(@(y) error_stress(y,str_ratio_y_exp,...
    str_ratio_x_exp,time_exp,loadcycle_peak,stress_y_smooth_exp),...
    initialconst,[],[],options);

% Set theoretical stretch ratios to be the same as experimental
str_ratio_x_theo = str_ratio_x_exp;
str_ratio_y_theo = str_ratio_y_exp;

% Find complex modulus and angular frequency
[Eeq_x(p,1),ang_freq_x(p,1),str_rate_x,str_ratio_max_x] = Eeq_Angfreq...
    (constants_x,str_ratio_x_theo,time_exp,loadcycle_peak);
[Eeq_y(p,1),ang_freq_y(p,1),str_rate_y,str_ratio_max_y] = Eeq_Angfreq...
    (constants_y,str_ratio_y_theo,time_exp,loadcycle_peak);

% Recalculate stress based on theoretical data for loading cycle
stress_x_theor_cycle = stress_theor_cycle(constants_x,str_ratio_x_theo,...
    str_ratio_y_exp,time_exp,loadcycle_peak);
stress_y_theor_cycle = stress_theor_cycle(constants_y,str_ratio_y_theo,...
    str_ratio_x_exp,time_exp,loadcycle_peak);

```

```

% Calculate R-Square value
r2_x(p,1) = rsq(stress_x_smooth_exp(1:loadcycle_peak),...
    stress_x_theor_cycle);
r2_y(p,1) = rsq(stress_y_smooth_exp(1:loadcycle_peak),...
    stress_y_theor_cycle);

% Print final results
fprintf('Constants X \n');
fprintf('Es (MPa) = %f \n', constants_x(1));
fprintf('Ep (MPa) = %f \n', constants_x(2));
fprintf('Dp (MPa) = %f \n', constants_x(3)); fprintf('\n');
fprintf('|Eeq*| (MPa) = %f \n', (Eeq_x(p,1)));
fprintf('lambda` (s^-1) = %f \n', str_rate_x);
fprintf('omega (rad s^-1) = %f \n', ang_freq_x(p,1));
fprintf('r2 = %f \n', r2_x(p)); fprintf('\n');
fprintf('Constants Y \n');
fprintf('Es (MPa) = %f \n', constants_y(1));
fprintf('Ep (MPa) = %f \n', constants_y(2));
fprintf('Dp (MPa) = %f \n', constants_y(3)); fprintf('\n');
fprintf('|Eeq*| (MPa) = %f \n', (Eeq_y(p,1)));
fprintf('lambda` (s^-1) = %f \n', str_rate_y);
fprintf('omega (rad s^-1) = %f \n', ang_freq_y(p,1));
fprintf('r2 = %f \n', r2_y(p));

%% ----- PLOT CURVE FITTING -----

% Reduce number of experimental data points in order to plot a dotted line
% Set first value in data vector
str_ratio_x_exp_plot(1,1) = str_ratio_x_exp(1);
str_ratio_y_exp_plot(1,1) = str_ratio_y_exp(1);
stress_x_smooth_exp_plot(1,1) = stress_x_smooth_exp(1);
stress_y_smooth_exp_plot(1,1) = stress_y_smooth_exp(1);

% Set interval for skipping points (in this case, data set was divided by
% a factor of 5)
l = 1;
if loadcycle_peak > 14; jump = 14;
else jump = loadcycle_peak; end;

% Create the new vector with less data points
for k=1:(jump-2)
l = l+ceil(loadcycle_peak/jump);
str_ratio_x_exp_plot((k+1),1) = str_ratio_x_exp(l);
stress_x_smooth_exp_plot((k+1),1) = stress_x_smooth_exp(l);
str_ratio_y_exp_plot((k+1),1) = str_ratio_y_exp(l);
stress_y_smooth_exp_plot((k+1),1) = stress_y_smooth_exp(l);
end

% Set last point in data vector
str_ratio_x_exp_plot(jump,1) = str_ratio_x_exp(loadcycle_peak);
str_ratio_y_exp_plot(jump,1) = str_ratio_y_exp(loadcycle_peak);
stress_x_smooth_exp_plot(jump,1) = stress_x_smooth_exp(loadcycle_peak);
stress_y_smooth_exp_plot(jump,1) = stress_y_smooth_exp(loadcycle_peak);

```

```

% Plotting
file_name_plot = [file_name_current(1:end-5)];
file_name_save = [file_name_plot, '_CurveFitting.png'];

fig = figure('Name','Curve Fitting','NumberTitle','off');
set(gcf,'DefaultTextFontSize',9, ...
'DefaultTextFontname','Times New Roman', ...
'DefaultTextFontWeight','bold', ...
'DefaultAxesFontSize',13, ...
'DefaultAxesFontname','Times New Roman');
set(gcf,'visible','off')

hold on
plot(str_ratio_x_exp_plot, stress_x_smooth_exp_plot, '.', ...
'Color',[0/255 0/255 0/255], 'MarkerSize',7)
plot(str_ratio_x_theo(1:loadcycle_peak), stress_x_theor_cycle, '-', ...
'Color',[100/255 100/255 100/255], 'LineWidth',1.3)
plot(str_ratio_y_exp_plot, stress_y_smooth_exp_plot, '^', ...
'Color',[50/255 50/255 50/255], 'MarkerSize',3)
plot(str_ratio_y_theo(1:loadcycle_peak), stress_y_theor_cycle, ':', ...
'Color',[150/255 150/255 150/255], 'LineWidth',1.3)
hold off

aspect_x = 5;
aspect_y = 3;
pbaspect([aspect_x aspect_y 1])
grid on
axis([1 1.8 0 0.5])
set(gcf,'visible','off')
l = legend('Experimental \sigma_1','Fitted Curve \sigma_1',...
'Experimental \sigma_2','Fitted Curve \sigma_2','Location','NW');
set(l,'FontSize',8);
xlabel('Stretch Ratio (-)')
ylabel('Stress (MPa)')

r2_x_text = ['R^2 (\sigma_1) = ', num2str(r2_x(p,1))];
text(1.03,0.3,r2_x_text,...
'HorizontalAlignment','left','FontSize',9,'FontAngle','italic');
r2_y_text = ['R^2 (\sigma_2) = ', num2str(r2_y(p,1))];
text(1.03,0.27,r2_y_text,...
'HorizontalAlignment','left','FontSize',9,'FontAngle','italic');

print(file_name_save, '-dpng', '-r350');

%% ----- SAVE DATA -----

% Calculate theoretical stress curve based on new found values
[stress_x_theor, str_ratio_x_theor] = stress_theor(constants_x,...
str_ratio_max_x, str_ratio_max_y, time_exp, ang_freq_x(p,1), ...
Eq_x(p,1), rows);
[stress_y_theor, str_ratio_y_theor] = stress_theor(constants_y,...
str_ratio_max_y, str_ratio_max_y, time_exp, ang_freq_y(p,1), ...
Eq_y(p,1), rows);

```

```

% Write Data to Excel File
xlswrite(file_path,{'Time (s)'},3,'A1');
xlswrite(file_path,time_exp,3,'A2');
xlswrite(file_path,{'Str Ratio X (um/um)'},3,'B1');
xlswrite(file_path,str_ratio_x_theor,3,'B2');
xlswrite(file_path,{'Str Ratio Y (um/um)'},3,'C1');
xlswrite(file_path,str_ratio_y_theor,3,'C2');
xlswrite(file_path,{'Stress X (MPa)'},3,'D1');
xlswrite(file_path,stress_x_theor,3,'D2');
xlswrite(file_path,{'Stress Y (MPa)'},3,'E1');
xlswrite(file_path,stress_y_theor,3,'E2');
xlswrite(file_path,{'|Eeq*|_X (MPa)'},3,'F1');
xlswrite(file_path,Eeq_x(p,1),3,'G1');
xlswrite(file_path,{'lambda`_X (s^-1)'},3,'F2');
xlswrite(file_path,str_rate_x,3,'G2');
xlswrite(file_path,{'omega_X (rad s^-1)'},3,'F3');
xlswrite(file_path,ang_freq_x(p,1),3,'G3');
xlswrite(file_path,{'r^2_X'},3,'F4');
xlswrite(file_path,r2_x(p),3,'G4');
xlswrite(file_path,{'Es_X (MPa)'},3,'F5');
xlswrite(file_path,constants_x(1),3,'G5');
xlswrite(file_path,{'Ep_X (MPa)'},3,'F6');
xlswrite(file_path,constants_x(2),3,'G6');
xlswrite(file_path,{'Dp_X (MPa)'},3,'F7');
xlswrite(file_path,constants_x(3),3,'G7');
xlswrite(file_path,{'---'},3,'F8');
xlswrite(file_path,{'---'},3,'G8');
xlswrite(file_path,{'|Eeq*|_Y (MPa)'},3,'F9');
xlswrite(file_path,Eeq_y(p,1),3,'G9');
xlswrite(file_path,{'lambda`_Y (s^-1)'},3,'F10');
xlswrite(file_path,str_rate_y,3,'G10');
xlswrite(file_path,{'omega_Y (rad s^-1)'},3,'F11');
xlswrite(file_path,ang_freq_y(p,1),3,'G11');
xlswrite(file_path,{'r^2_Y'},3,'F12');
xlswrite(file_path,r2_y(p),3,'G12');
xlswrite(file_path,{'Es_Y (MPa)'},3,'F13');
xlswrite(file_path,constants_y(1),3,'G13');
xlswrite(file_path,{'Ep_Y (MPa)'},3,'F14');
xlswrite(file_path,constants_y(2),3,'G14');
xlswrite(file_path,{'Dp_Y (MPa)'},3,'F15');
xlswrite(file_path,constants_y(3),3,'G15');

close all
fprintf('\n-----\n\n');
end

p = 0;
toc
fprintf('\n');

```

```

% Create matrix with values found for angular frequency, modulus and R2
% values to input in excel file
constants_x_csv = [ang_freq_x Eeq_x r2_x];
constants_y_csv = [ang_freq_y Eeq_y r2_y];

```

```

% Write values into CSV file for constants compilation
csvwrite('constants_x.csv',constants_x_csv);
csvwrite('constants_y.csv',constants_y_csv);

% Determine how many sets there are with different parameters

% First cut down names of files to only reflect the testing parameters
% (i.e. removing number iterations '001' at end of each file name)
for k=1:files
file_name_short{k} = file_name{k}(1:end-13);
end

% Find all unique names, and how many there are
set_names = unique(file_name_short); sets = length(set_names);

% Find all similar names in order to determine how many repeat experiments
% there are per test
for k=1:sets
I = find(ismember(file_name_short,set_names{k}));
tests_per_set(k,1) = length(I);
end

if sets == 1; fprintf('Cannot optimize for only 1 stretch rate.');
```

```
return
else

% Find intervals of indices. test_array(k,1) is the start of the array
% portion for the set and test_array(k,1)+tests_per_set(k) is the end of
% the array.
for k = 1:sets
if k == 1; test_array(k,1) = 1;
else test_array(k,1) = (test_array(k-1,1)+tests_per_set(k-1));
end; test_array(k,2) = (test_array(k,1)+tests_per_set(k)-1); end; end;

%% ----- STEP 7 (OPTIMIZE MATERIAL CONSTANTS FOR ALL CASES) -----

format short

% OPTIMIZE MATERIAL CONSTANTS USING "optimset"
options = optimset('largescale','off','MaxFunEvals',1e100,'tolFun',1e-30...
    , 'TolX',1e-30,'MaxIter',5e3,'Algorithm','levenberg-marquardt',...
    'Display','off');
```

```
% INITIAL GUESSES FOR MATERIAL CONSTANTS
Es = 0.1; Ep = 0.1; Dp = 0.1;
initialconst = [Es Ep Dp];

% Take average value for angular frequency and for complex modulus for each
% set, and find standard deviation for all

for k = 1:sets
% Calculate Mean values for ang freq, Eeq, and r2 for each set type
ang_freq_Eeq_x_avg{k,1} = mean(ang_freq_x(test_array(k,1):test_array(k,2)));
ang_freq_Eeq_y_avg{k,1} = mean(ang_freq_y(test_array(k,1):test_array(k,2)));

```

```

ang_freq_Eeq_x_avg{k,2} = mean(Eeq_x(test_array(k,1):test_array(k,2)));
ang_freq_Eeq_y_avg{k,2} = mean(Eeq_y(test_array(k,1):test_array(k,2)));
r2_x_avg{k,1} = mean(r2_x((test_array(k,1):test_array(k,2))));
r2_y_avg{k,1} = mean(r2_y((test_array(k,1):test_array(k,2))));

% Calculate sample standard deviation
ang_freq_Eeq_x_avg{k,3} = std(ang_freq_x(test_array(k,1):test_array(k,2)));
ang_freq_Eeq_y_avg{k,3} = std(ang_freq_y(test_array(k,1):test_array(k,2)));
ang_freq_Eeq_x_avg{k,4} = std(Eeq_x(test_array(k,1):test_array(k,2)));
ang_freq_Eeq_y_avg{k,4} = std(Eeq_y(test_array(k,1):test_array(k,2)));
end

ang_freq_Eeq_x_avg = cell2mat(ang_freq_Eeq_x_avg);
ang_freq_Eeq_y_avg = cell2mat(ang_freq_Eeq_y_avg);
r2_x_avg = cell2mat(r2_x_avg);
r2_y_avg = cell2mat(r2_y_avg);

% Outlier loop for final fitting
while p == 0

ang_freq_Eeq_x_avg_no_outlier = ang_freq_Eeq_x_avg;
ang_freq_Eeq_y_avg_no_outlier = ang_freq_Eeq_y_avg;

beep
m = 1;

% Ask if there are any outliers to be removed from curve fitting for all
% sets (in case certain outliers occur and prevent lsqnonlin from
% converging).
while m == 1
prompt = ['Any Outliers in X? (0 or [1-' num2str(sets) ']) : '];
outliers_x = input(prompt);
outliers_x = sort(unique(outliers_x)); plot_outliers = 0;

if outliers_x ~= 0 && length(outliers_x) >= (sets-1)
fprintf('Cannot optimize with this many points removed. ');
elseif sum(outliers_x>sets) > 0
fprintf('One (or more) of your entries exceeds the number of sets. ');
elseif outliers_x == 0; m = 0;
elseif outliers_x ~= 0

% Remove rows of outliers from data set and place them in separate array to
% be plotted as smaller points on final graph
rows = length(outliers_x);
for k=1:rows
ang_freq_Eeq_x_avg_outlier(k,:) = ang_freq_Eeq_x_avg_no_outlier...
(outliers_x(k),:);
ang_freq_Eeq_x_avg_no_outlier(outliers_x(k),:) = [];
outliers_x = outliers_x-1; end;

plot_outliers = 1; m = 0; end; end;

```

```

% Ask the same for y-axis
m=1;
while m == 1
prompt = ['Any Outliers in Y? (0 or [1-' num2str(sets) ']) : '];
outliers_y = input(prompt);
outliers_y = sort(unique(outliers_y)); plot_outliers = 0;
if outliers_y ~= 0 && length(outliers_y) >= (sets-1)
fprintf('Cannot optimize with this many points removed. ');
elseif sum(outliers_y>sets) > 0
fprintf('One (or more) of your entries exceeds the number of sets. ');
elseif outliers_y == 0; m = 0;
elseif outliers_y ~= 0
rows = length(outliers_y);
for k=1:rows
ang_freq_Eeq_y_avg_outlier(k,:) = ang_freq_Eeq_y_avg_no_outlier...
(outliers_y(k),:);
ang_freq_Eeq_y_avg_no_outlier(outliers_y(k),:) = [];
outliers_y = outliers_y-1; end;
plot_outliers = 1; m = 0; end; end;

% Display table with average values found
T_x = table(ang_freq_Eeq_x_avg(:,1),ang_freq_Eeq_x_avg(:,2),...
ang_freq_Eeq_x_avg(:,3), ang_freq_Eeq_x_avg(:,4),r2_x_avg,...
'VariableNames',{'AngFreqX' 'EeqX' 'StdDevAngFreqX' 'StdDevEeqX'...
'r2AvgX'});
T_y = table(ang_freq_Eeq_y_avg(:,1),ang_freq_Eeq_y_avg(:,2),...
ang_freq_Eeq_y_avg(:,3), ang_freq_Eeq_y_avg(:,4),r2_y_avg,...
'VariableNames',{'AngFreqY' 'EeqY' 'StdDevAngFreqY' 'StdDevEeqY'...
'r2AvgY'});
display(T_x)
display(T_y)

% FIND THE CONSTANTS USING "lsqnonlin"

% use the lsqnonlin function to optimize constant vector
constants_x_all = lsqnonlin(@(x) error_modulus(x,...
ang_freq_Eeq_x_avg(:,1),ang_freq_Eeq_x_avg(:,2)),...
initialconst,[],[],options);
constants_y_all = lsqnonlin(@(y) error_modulus(y,...
ang_freq_Eeq_y_avg(:,1),ang_freq_Eeq_y_avg(:,2)),...
initialconst,[],[],options);

% print final results
fprintf('Constants X Overall\n');
fprintf('Es (MPa) = %f \n', constants_x_all(1));
fprintf('Ep (MPa) = %f \n', constants_x_all(2));
fprintf('Dp (MPa) = %f \n', constants_x_all(3)); fprintf('\n');
fprintf('Constants Y Overall\n');
fprintf('Es (MPa) = %f \n', constants_y_all(1));
fprintf('Ep (MPa) = %f \n', constants_y_all(2));
fprintf('Dp (MPa) = %f \n', constants_y_all(3)); fprintf('\n');
fprintf('Constants Avg Overall\n');
fprintf('Es (MPa) = %f \n', (constants_x_all(1)+constants_y_all(1))/2);
fprintf('Ep (MPa) = %f \n', (constants_x_all(2)+constants_y_all(2))/2);
fprintf('Dp (MPa) = %f \n', (constants_x_all(3)+constants_y_all(3))/2);

```

```

%% ----- PLOT PARAMETER FITTING -----

% Create a theoretical set of data points in order to plot a smooth curve
% based on newly found constants

n = 100; % to split interval between min and max into 100 data points
interval = (ang_freq_Eeq_x_avg(sets,1)-ang_freq_Eeq_x_avg(1,1))/n;

% Calculate theoretical angular frequencies for each data point for smooth
% curve plot
for k = 1:n
    ang_freq_x_theo(k,1) = ang_freq_Eeq_x_avg(1,1) + (interval*(k-1));
    ang_freq_y_theo(k,1) = ang_freq_Eeq_y_avg(1,1) + (interval*(k-1));
end

% Calculate corresponding complex modulus for each ang freq
for k = 1:n
    Eeq_theo_x(k,1) = (constants_x_all(1)*sqrt(constants_x_all(2)^2+...
        ang_freq_x_theo(k,1)^2*constants_x_all(3)^2))/sqrt((...
        constants_x_all(1)+constants_x_all(2))^2+ang_freq_x_theo(k,1)...
        ^2*constants_x_all(3)^2);
    Eeq_theo_y(k,1) = (constants_y_all(1)*sqrt(constants_y_all(2)^2+...
        ang_freq_y_theo(k,1)^2*constants_y_all(3)^2))/sqrt((...
        constants_y_all(1)+constants_y_all(2))^2+ang_freq_y_theo(k,1)...
        ^2*constants_y_all(3)^2);
end

% Plot for X-Axis
fig = figure('Name','Angular Freq vs Modulus X','NumberTitle','off');

set(gcf,'DefaultTextFontSize',11, ...
'DefaultTextFontname','Times New Roman', ...
'DefaultTextFontWeight','bold', ...
'DefaultAxesFontSize',13, ...
'DefaultAxesFontname','Times New Roman');
set(gcf,'visible','off')

hold on
errorbar(ang_freq_Eeq_x_avg_no_outlier(:,1),...
    ang_freq_Eeq_x_avg_no_outlier(:,2),...
    ang_freq_Eeq_x_avg_no_outlier(:,4),...
    'ko','MarkerSize',6,'MarkerEdgeColor',[0/255 0/255 0/255],...
    'MarkerFaceColor',[1 1 1])
plot(ang_freq_x_theo,Eeq_theo_x,'Color',...
    [100/255 100/255 100/255],'LineWidth',1.2)

if plot_outliers == 0
    legend('Experimental (\lambda_1)','Fitted Parameter','Location','NW')
elseif plot_outliers == 1
    errorbar(ang_freq_Eeq_x_avg_outlier(:,1),...
        ang_freq_Eeq_x_avg_outlier(:,2),...
        ang_freq_Eeq_x_avg_outlier(:,4),...
        'b^','MarkerSize',4,'MarkerEdgeColor',...
        'blue','MarkerFaceColor',[1 1 1])
    legend('Experimental (\lambda_1)','Fitted Parameter','Outliers',...

```

```

        'Location','NW')
end
hold off

grid on
aspect_x = 5; aspect_y = 3;
pbaspect([aspect_x aspect_y 1])
set(gcf,'visible','off')
xlabel('Angular Frequency (rad/s)')
ylabel('Dynamic Modulus (MPa)')
print('Modulus_Fitting_X.png','-dpng','-r350');

% Plot for Y-Axis
fig = figure('Name','Angular Freq vs Modulus Y','NumberTitle','off');

set(gcf,'DefaultTextFontSize',11, ...
'DefaultTextFontname','Times New Roman', ...
'DefaultTextFontWeight','bold', ...
'DefaultAxesFontSize',13, ...
'DefaultAxesFontname','Times New Roman');
set(gcf,'visible','off')

hold on
errorbar(ang_freq_Eeq_y_avg_no_outlier(:,1),...
    ang_freq_Eeq_y_avg_no_outlier(:,2),...
    ang_freq_Eeq_y_avg_no_outlier(:,4),...
    'ko','MarkerSize',6,'MarkerEdgeColor',[0/255 0/255 0/255],...
    'MarkerFaceColor',[1 1 1])
plot(ang_freq_y_theo,Eeq_theo_y,'Color',...
    [100/255 100/255 100/255],'LineWidth',1.2)

if plot_outliers == 0
legend('Experimental (\lambda_2)','Fitted Parameter','Location','NW')
elseif plot_outliers == 1
errorbar(ang_freq_Eeq_y_avg_outlier(:,1),...
    ang_freq_Eeq_y_avg_outlier(:,2),...
    ang_freq_Eeq_y_avg_outlier(:,4),...
    'b^','MarkerSize',4,'MarkerEdgeColor',...
    'blue','MarkerFaceColor',[1 1 1])
legend('Experimental (\lambda_2)','Fitted Parameter','Outliers',...
    'Location','NW')
end
hold off

grid on
aspect_x = 5; aspect_y = 3;
pbaspect([aspect_x aspect_y 1])
set(gcf,'visible','off')
xlabel('Angular Frequency (rad/s)')
ylabel('Dynamic Modulus (MPa)')
print('Modulus_Fitting_Y.png','-dpng','-r350');

```

```

prompt    = 'Good? [y/n] : '; better = input(prompt,'s');

if better == 'y'; p = 1;
else p = 0; end;
close all
end
end

%% ----- STEP 1 (Theoretical Stress) -----

function stress_theor_cycle = stress_theor_cycle(constants,...
    str_ratio_primary_exp,str_ratio_secondary_exp,time_exp,loadcycle_peak)

% Calculate theoretical stresses for initial constants, using complex
% modulus of experiment. These values can be found by referring to
% Equation (4.22)

poiss = 0.49;

% Find absolute modulus using function
[Eeq]= Eeq_Angfreq(constants,str_ratio_primary_exp,time_exp,loadcycle_peak);

% Define the stretch ratio to run from 0 to load peak
str_ratio_primary_exp_cycle = str_ratio_primary_exp(1:loadcycle_peak);
str_ratio_secondary_exp_cycle = str_ratio_secondary_exp(1:loadcycle_peak);

for k = 1:loadcycle_peak

    lambdai(k,1) = str_ratio_primary_exp_cycle(k,1); % axis of interest
    lambdaj(k,1) = str_ratio_secondary_exp_cycle(k,1); % secondary axis
    lambda3(k,1) = 1/(lambdai(k,1)*lambdaj(k,1)); % z axis (tape thickness)

    coeff = Eeq/(1-poiss^2); % E/(1-v^2)
    p(k,1) = Eeq*lambda3(k,1)*(lambda3(k,1)-1);
    stress_theor_cycle(k,1) = lambdai(k,1)*coeff*(lambdai(k,1)-1+...
        lambdaj(k,1)*poiss-poiss)-p(k,1);
end
end

%% ----- STEP 2 (Stress Error) -----

function error_stress = error_stress(constants,str_ratio_primary_exp,...
    str_ratio_secondary_exp,time_exp,loadcycle_end,stress_primary_exp)

% Calculate error between theoretical and experimental values, in order to
% minimize with optimization function

% Call function to calculate theoretical values
stress_theor_cycle = stress_theor_cycle(constants,str_ratio_primary_exp,...
    str_ratio_secondary_exp,time_exp,loadcycle_end);

% Define experimental stress to run from 0 to load peak
stress_primary_exp_cycle = stress_primary_exp(1:loadcycle_end);

```

```

% Find error
error_stress = (stress_theor_cycle-stress_primary_exp_cycle);
end

%% ----- Calculate Theoretical Stress with lag -----
function [stress_theor,str_ratio_theor_prim] = stress_theor(constants,...
    str_ratio_max_prim,str_ratio_max_sec,time_exp,ang_freq,Eeq,rows)

% Calculate the theoretical stress curve based on previously calculated
% modulus parameters. Find lag angle 'del' using Equation (4.8) and then
% calculate the final stress values using Equation (4.22).

% Poisson's Ratio for VHB 4905/4910 tape
poiss = 0.49;

% Calculate imaginary and real parts of the complex modulus
Im_Eeq = constants(1)^2*constants(3)*ang_freq;
Re_Eeq = constants(1)^2*constants(2)+constants(1)*constants(2)^2+...
    constants(1)*constants(3)^2*ang_freq^2;

% Calculate the lag angle of the strain
del = atan(Im_Eeq/Re_Eeq);

strain_max_prim = str_ratio_max_prim-1;
strain_max_sec = str_ratio_max_sec-1;

omega_t = ang_freq.*time_exp;

for k=1:rows
    str_ratio_theor_prim(k,1) = strain_max_prim*sin(omega_t(k))+1;
    str_ratio_theor_sec(k,1) = strain_max_sec*sin(omega_t(k))+1;
end

for k=1:rows
    str_ratio_theor_lag_prim(k,1) = strain_max_prim*sin(omega_t(k)+del)+1;
    str_ratio_theor_lag_sec(k,1) = strain_max_sec*sin(omega_t(k)+del)+1;
end

% Calculate the stress
for k=1:rows

    lambdai = str_ratio_theor_lag_prim(k,1); % axis of interest
    lambdaj = str_ratio_theor_lag_sec(k,1); % secondary axis
    lambda3 = 1/(lambdai*lambdaj); % z axis (tape thickness)

    coeff = Eeq/(1-poiss^2); % E/(1-v^2)
    p = lambda3*Eeq*(lambda3-1);
    stress_theor(k,1) = lambdai*coeff*(lambdai-1+lambdaj*poiss-poiss)-p;
end
end

```

```

%% ----- STEP 6 (Modulus Error) -----

function error_modulus = error_modulus(constants,ang_freq,Eeq)

rows = length(ang_freq);

% Calculate error between theoretical and experimental values, in order to
% minimize with optimization function

% Calculate theoretical values
for k = 1:rows
Eeq_theo(k,1) = (constants(1)*sqrt(constants(2)^2+ang_freq(k)^2*...
    constants(3)^2))/sqrt((constants(1)+constants(2))^2+ang_freq(k)...
    ^2*constants(3)^2);
end

% Find error
error_modulus = (Eeq_theo-Eeq);
end

%% ----- Complex Modulus and Angular Freq -----

function [Eeq,ang_freq,str_rate,str_ratio_max] = Eeq_Angfreq(constants,...
    str_ratio_primary_exp,time_exp,loadcycle_peak)

% Find the equivalent angular frequency, based on Equation (4.4).
% First, the maximum stretch achieved is found from
% experimental value. Second, the stretch rate is calculated by dividing
% the maximum stretch ratio by the time it takes to reach it. This value
% should be close to the true value of the stretch rate set for the
% experiment. Finally, the angular frequency is found with these two
% values.

% Find maximum experimental stretch ratio
str_ratio_max = str_ratio_primary_exp(loadcycle_peak);
% Find strain rate based on max stretch ratio
str_rate = (str_ratio_max-1)/time_exp(loadcycle_peak);
% Calculate angular frequency
ang_freq = (pi()*str_rate)/(2*(str_ratio_max-1));

% Calculate magnitude of complex modulus expression, based on Equation (4.7).
% Note that the matrix containing constants has the form
% constants = [Es Ep Dp]

Eeq = (constants(1)*sqrt(constants(2)^2+ang_freq^2*constants(3)^2))/...
    sqrt((constants(1)+constants(2))^2+ang_freq^2*constants(3)^2);
end

```

```

%% ----- R-Squared Value -----

function r2 = rsq(experimental,theoretical)

if length(experimental)~=length(theoretical)
error 'Experimental and Theoretical must be same length';
else

% Check for NaN
remove = ~or(isnan(experimental),isnan(theoretical));
experimental = experimental(remove);
theoretical = theoretical(remove);

A = (experimental-mean(experimental)); SS_tot = (sum(A(:).^2));
B = (experimental-theoretical); SS_res = (sum(B(:).^2));
r2 = 1 - SS_res/SS_tot;
end
end

```

Appendix B.3 – Results of Uniaxial Analytical Parameter Fitting

B.3.1 VHB 4905 Tape Uniaxial Parameter Optimization Results

Experimental Stretch Ratio $\dot{\lambda}_1(\text{s}^{-1})$	Angular Frequency ω_1 (rad s ⁻¹)	Complex Modulus E_{eq}^* (MPa)	R ² Value
0.025	0.006545	0.03081	0.97311
	0.006545	0.03231	0.97154
	0.006545	0.02920	0.97215
	0.006545	0.02916	0.97386
	0.006545	0.02982	0.97545
0.050	0.01309	0.03416	0.97668
	0.01309	0.03176	0.97242
	0.01309	0.03181	0.97854
	0.01309	0.03144	0.97359
	0.01309	0.03079	0.97459
0.075	0.01964	0.03402	0.9809
	0.01964	0.03320	0.97604
	0.01964	0.03635	0.97859
	0.01964	0.03608	0.97905
	0.01964	0.03431	0.97488
0.100	0.02618	0.03344	0.97206
	0.02618	0.03299	0.97794
	0.02618	0.03516	0.97579
	0.02618	0.03492	0.98151
	0.02618	0.03585	0.97861
0.200	0.05236	0.03840	0.97638
	0.05236	0.03807	0.97533
	0.05236	0.03737	0.9779
	0.05236	0.03894	0.97629
	0.05236	0.03657	0.9784
0.300	0.07905	0.03949	0.97635
	0.07854	0.03796	0.97481
	0.07854	0.04035	0.97812
	0.07854	0.04154	0.97741
	0.07854	0.04175	0.97619

B.3.2 VHB 4910 Tape Uniaxial Parameter Optimization Results

Experimental Stretch Ratio $\dot{\lambda}_1(\text{s}^{-1})$	Angular Frequency ω_1 (rad s ⁻¹)	Complex Modulus E_{eq}^* (MPa)	R ² Value
0.025	0.006545	0.02757	0.97343
	0.006545	0.02771	0.96971
	0.006545	0.02419	0.97633
	0.006545	0.02441	0.98017
	0.006545	0.02712	0.97276
0.050	0.01309	0.02675	0.98399
	0.01309	0.02896	0.97248
	0.01309	0.02994	0.97256
	0.01309	0.02865	0.97333
	0.01309	0.02822	0.97101
0.075	0.01964	0.02833	0.97364
	0.01964	0.02816	0.96944
	0.01964	0.02873	0.97683
	0.01964	0.02831	0.97802
	0.01964	0.02800	0.97088
0.100	0.02618	0.02979	0.9697
	0.02618	0.02959	0.97615
	0.02618	0.02937	0.98396
	0.02618	0.03263	0.9741
	0.02618	0.03318	0.97104
0.200	0.05236	0.03928	0.97297
	0.05236	0.03400	0.97498
	0.05236	0.03458	0.97324
	0.05236	0.03415	0.97294
	0.05236	0.03830	0.97255
0.300	0.07854	0.03906	0.9733
	0.07854	0.03832	0.97516
	0.07854	0.03955	0.97403
	0.07854	0.03832	0.9727
	0.07982	0.03777	0.976

Appendix B.4 – Uniaxial Model Comparison to Experimental Data

VHB 4905 tape

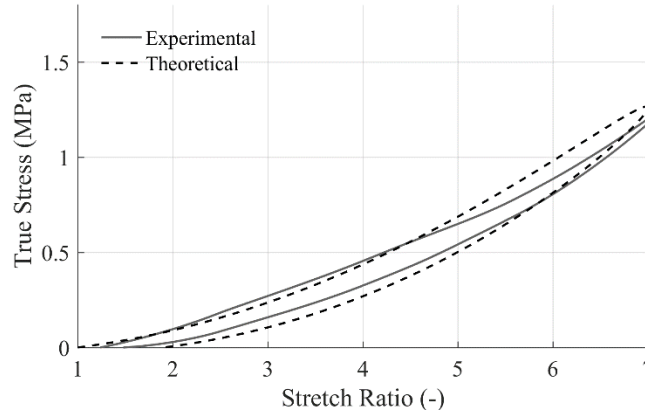


Figure B.1: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$

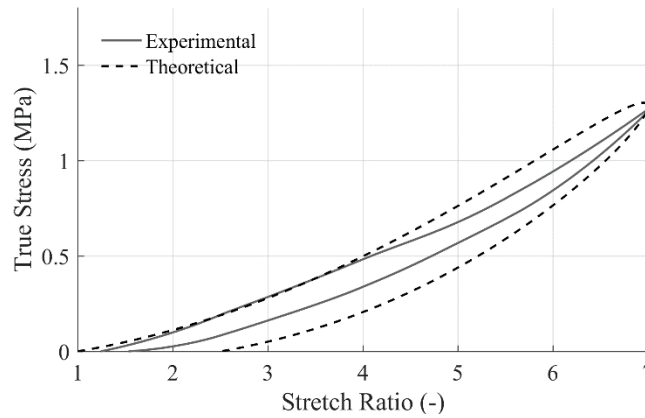


Figure B.2: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.050 \text{ s}^{-1}$

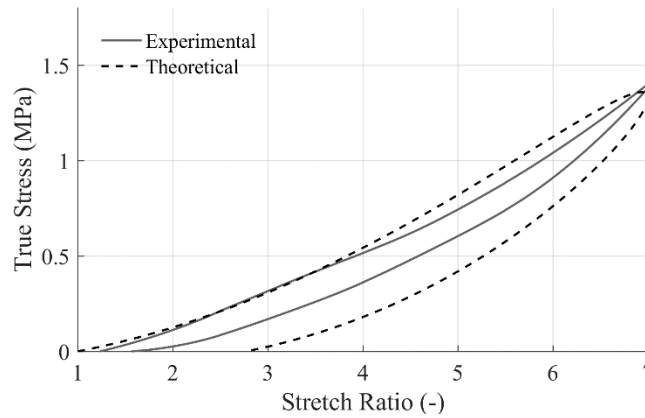


Figure B.3: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.075 \text{ s}^{-1}$

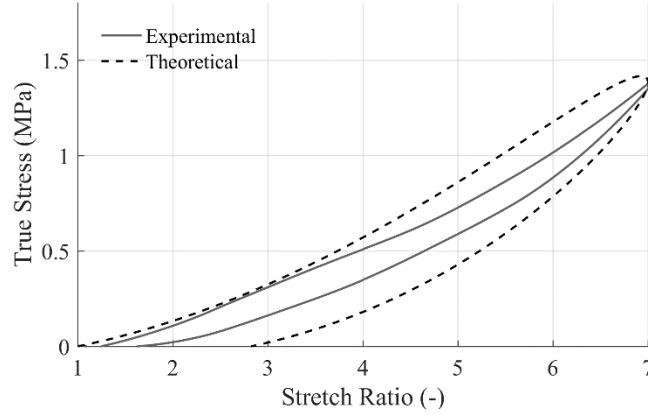


Figure B.4: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$

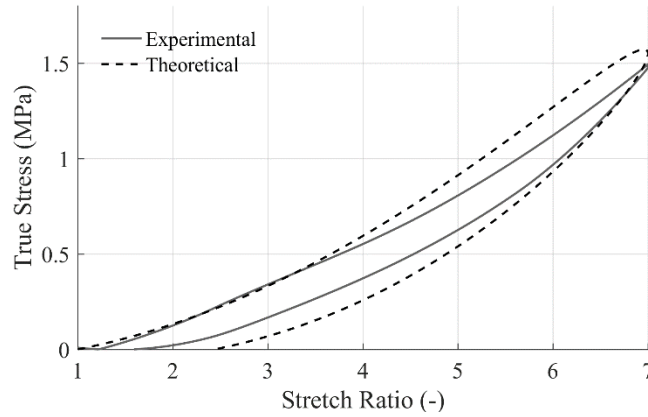


Figure B.5: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$

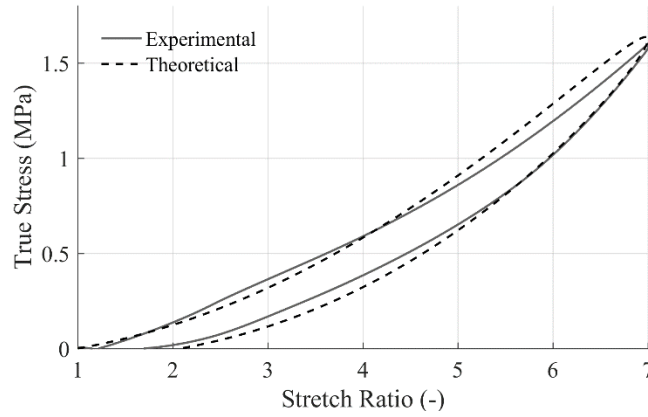


Figure B.6: Theoretical and experimental plots of uniaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$

VHB 4910 tape

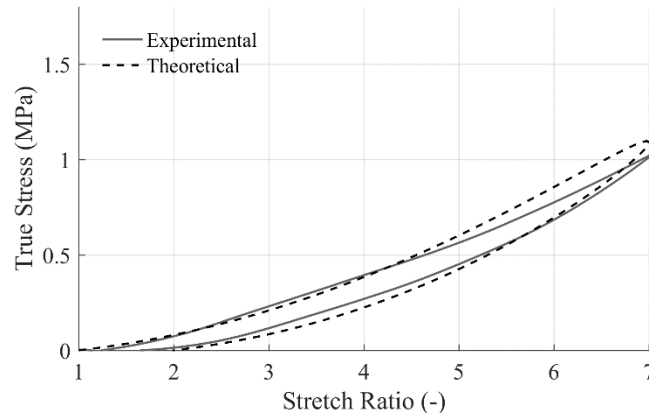


Figure B.7: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$

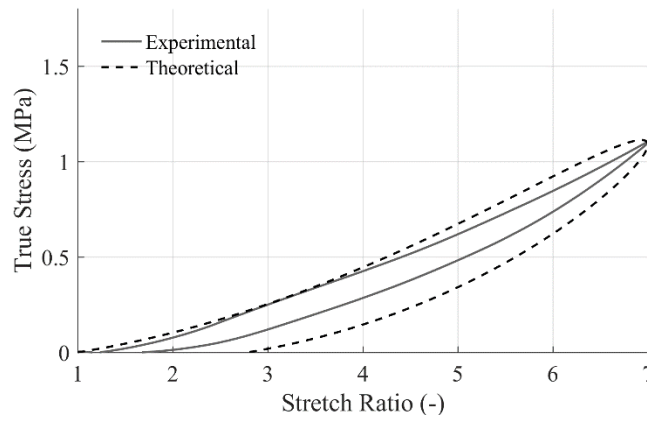


Figure B.8: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.050 \text{ s}^{-1}$

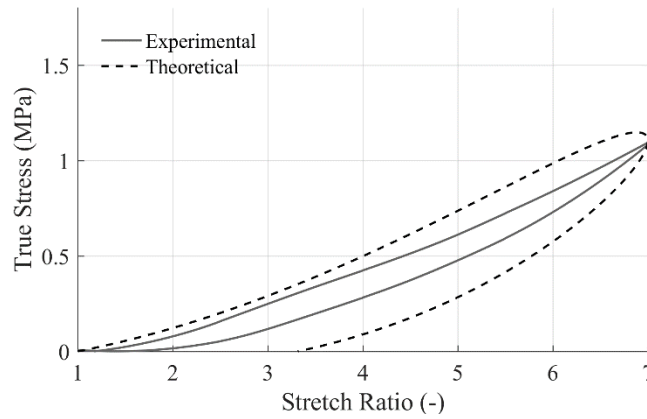


Figure B.9: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.075 \text{ s}^{-1}$

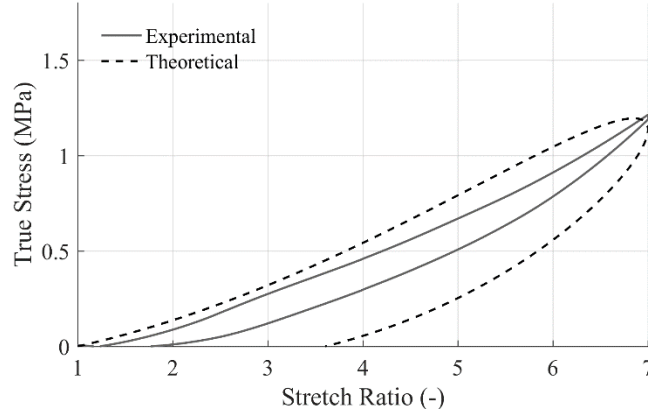


Figure B.10: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$

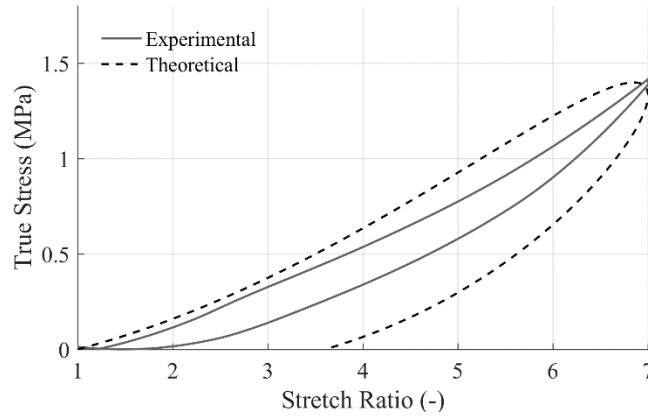


Figure B.11: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$

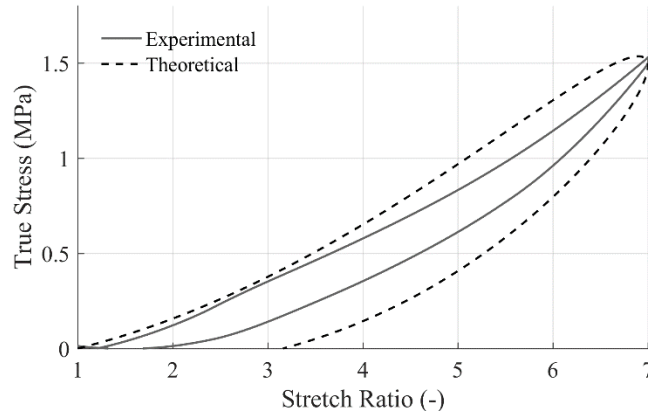


Figure B.12: Theoretical and experimental plots of uniaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$

Appendix B.5 – Results of Biaxial Analytical Parameter Fitting

B.5.1 VHB 4905 Tape Biaxial Parameter Optimization Results

Experimental Stretch Ratio $\dot{\lambda}(\text{s}^{-1})$	Angular Frequency $\omega_1 \text{ (rad s}^{-1}\text{)}$	Complex Modulus $E_{eq_1}^* \text{ (MPa)}$	R ² Value σ_1	Angular Frequency $\omega_2 \text{ (rad s}^{-1}\text{)}$	Complex Modulus $E_{eq_2}^* \text{ (MPa)}$	R ² Value σ_2
0.025	0.03927	0.08117	0.7843	0.03927	0.07255	0.90235
	0.03927	0.08787	0.9013	0.03927	0.08986	0.93143
	0.03927	0.09088	0.9254	0.03927	0.08742	0.89754
	0.03927	0.08706	0.9053	0.03927	0.08447	0.89597
	0.03927	0.08789	0.9061	0.03927	0.08493	0.89633
0.050	0.07854	0.08662	0.8324	0.07854	0.07793	0.89469
	0.07854	0.09942	0.8705	0.07854	0.09942	0.85245
	0.07854	0.09403	0.8859	0.07854	0.09505	0.88646
	0.07854	0.09992	0.8658	0.07854	0.09900	0.88135
	0.07854	0.09793	0.8594	0.07854	0.1043	0.86905
0.075	0.1178	0.08676	0.8808	0.1178	0.08798	0.88129
	0.1178	0.1061	0.8846	0.1178	0.1065	0.89365
	0.1178	0.1010	0.8998	0.1178	0.1002	0.91391
	0.1178	0.1073	0.8833	0.1178	0.1100	0.89325
	0.1178	0.09886	0.8818	0.1178	0.09580	0.88681
0.100	0.1571	0.08287	0.8513	0.1571	0.08812	0.86841
	0.1571	0.1065	0.8654	0.1571	0.1091	0.87071
	0.1571	0.1070	0.8750	0.1571	0.1095	0.88735
	0.1571	0.1177	0.9097	0.1571	0.1142	0.90769
	0.1571	0.1044	0.8658	0.1571	0.1077	0.88451
0.200	0.3142	0.09510	0.8352	0.3142	0.1024	0.83686
	0.3142	0.1244	0.8308	0.3142	0.1205	0.76597
	0.3142	0.1209	0.8949	0.3142	0.1224	0.85765
	0.3142	0.1230	0.8345	0.3142	0.1214	0.82714
	0.3142	0.1259	0.8666	0.3142	0.1242	0.81802
0.300	0.4717	0.1071	0.8278	0.4717	0.1005	0.83781
	0.4717	0.1303	0.8189	0.4717	0.1322	0.85086
	0.4717	0.1230	0.8319	0.4717	0.1228	0.87122
	0.4717	0.1334	0.8240	0.4717	0.1330	0.8483
	0.4717	0.1390	0.8183	0.4717	0.1403	0.82759

B.5.2 VHB 4910 Tape Biaxial Parameter Optimization Results

Experimental Stretch Ratio $\dot{\lambda}(\text{s}^{-1})$	Angular Frequency ω_1 (rad s ⁻¹)	Complex Modulus $E_{eq_1}^*$ (MPa)	R ² Value σ_1	Angular Frequency ω_2 (rad s ⁻¹)	Complex Modulus $E_{eq_2}^*$ (MPa)	R ² Value σ_2
0.025	0.03927	0.06613	0.9200	0.03927	0.06413	0.85662
	0.03927	0.07694	0.8843	0.03927	0.07568	0.89107
	0.03927	0.07726	0.8807	0.03927	0.07829	0.89665
	0.03927	0.07696	0.8736	0.03927	0.07709	0.88926
	0.03927	0.07418	0.8464	0.03927	0.07590	0.87668
0.050	0.07854	0.07312	0.8715	0.07854	0.07134	0.87599
	0.07854	0.08488	0.8906	0.07854	0.08618	0.91506
	0.07854	0.08689	0.8927	0.07854	0.08734	0.89729
	0.07854	0.08152	0.8757	0.07854	0.08483	0.90691
	0.07854	0.08307	0.8813	0.07854	0.08216	0.90942
0.075	0.1178	0.07388	0.8761	0.1178	0.07301	0.86716
	0.1178	0.08720	0.8931	0.1178	0.08677	0.90932
	0.1178	0.08684	0.8872	0.1178	0.08552	0.90273
	0.1178	0.09127	0.8871	0.1178	0.09204	0.91721
	0.1178	0.08775	0.8927	0.1178	0.08828	0.90604
0.100	0.1571	0.07420	0.8635	0.1571	0.07383	0.86794
	0.1571	0.09532	0.8535	0.1571	0.09878	0.85373
	0.1571	0.09619	0.8454	0.1571	0.09689	0.79042
	0.1571	0.08762	0.8748	0.1571	0.09191	0.88673
	0.1571	0.09572	0.9092	0.1571	0.09493	0.9002
0.200	0.3142	0.08885	0.8271	0.3142	0.08639	0.80797
	0.3142	0.1040	0.8473	0.3142	0.1068	0.83045
	0.3142	0.1071	0.8516	0.3142	0.1083	0.8441
	0.3142	0.1027	0.8686	0.3142	0.1062	0.84634
	0.3142	0.1084	0.8639	0.3142	0.1073	0.86454
0.300	0.4717	0.09590	0.8180	0.4717	0.09220	0.83475
	0.4717	0.1157	0.8641	0.4717	0.1127	0.86329
	0.4717	0.1181	0.8323	0.4717	0.1136	0.82168
	0.4717	0.1162	0.8334	0.4717	0.1164	0.84883
	0.4717	0.1118	0.8694	0.4717	0.1140	0.8433

Appendix B.6 - Biaxial Model Comparison to Experimental Data

VHB 4905 tape

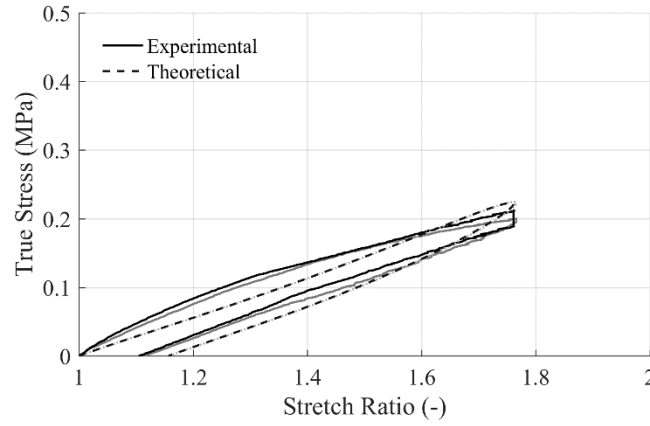


Figure B.13: Theoretical and experimental plots of biaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$

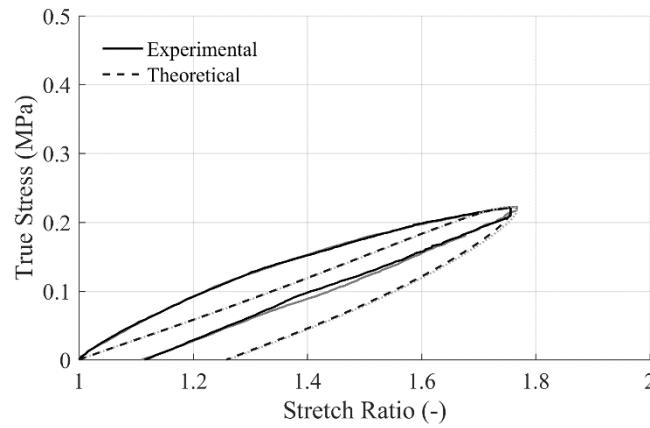


Figure B.14: Theoretical and experimental plots of biaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.050 \text{ s}^{-1}$

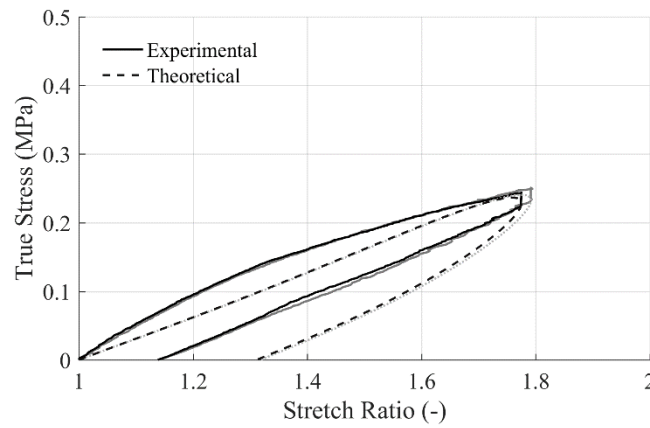


Figure B.15: Theoretical and experimental plots of biaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.075 \text{ s}^{-1}$

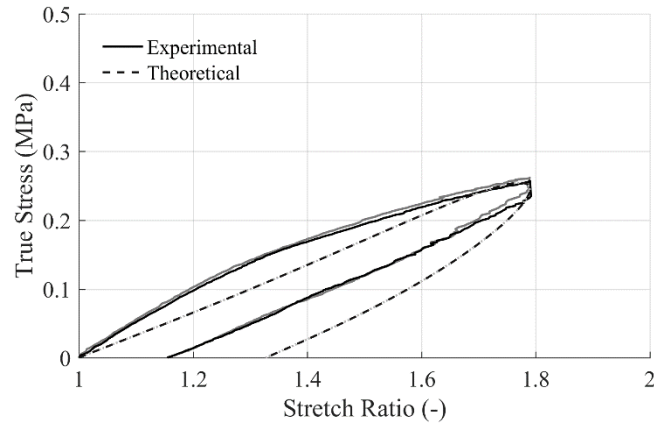


Figure B.16: Theoretical and experimental plots of biaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$

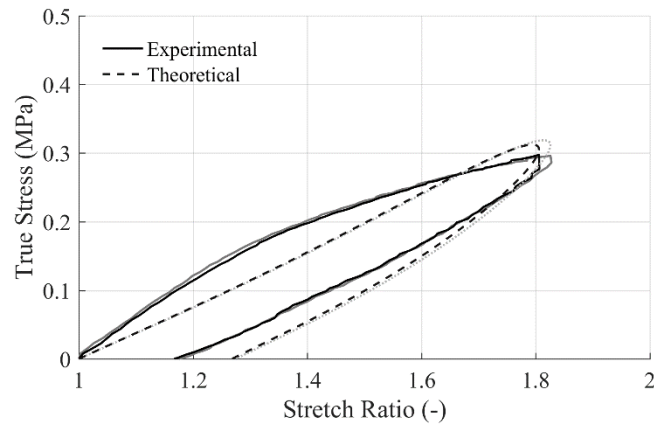


Figure B.17: Theoretical and experimental plots of biaxial tensile tests for VHB4905 tape at $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$

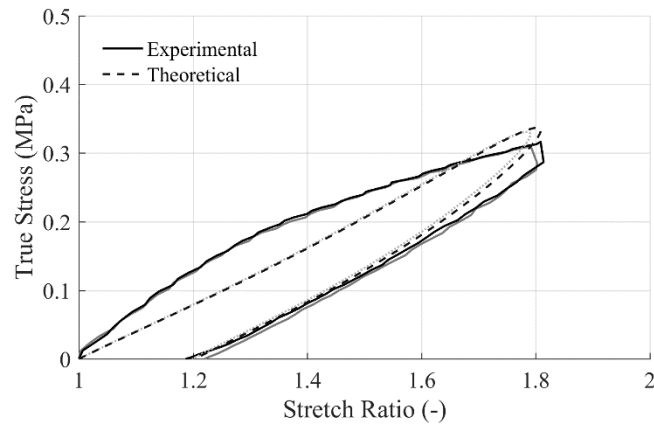


Figure B.18: Theoretical and experimental plots of biaxial tensile tests for VHB 4905 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$

VHB 4910 tape

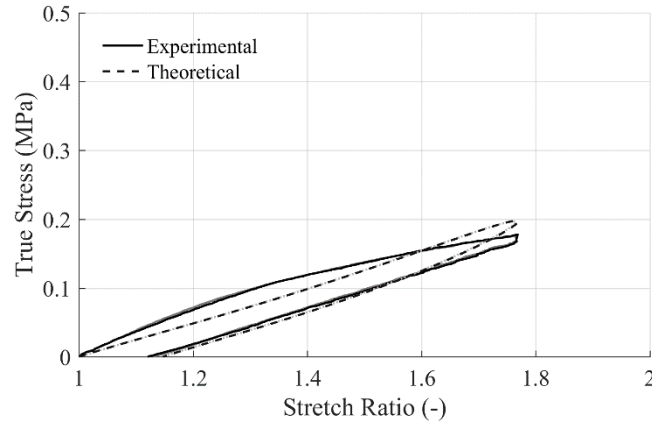


Figure B.19: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$

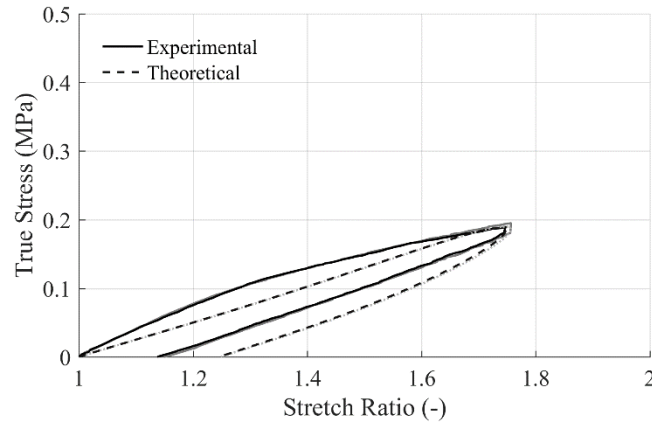


Figure B.20: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.050 \text{ s}^{-1}$

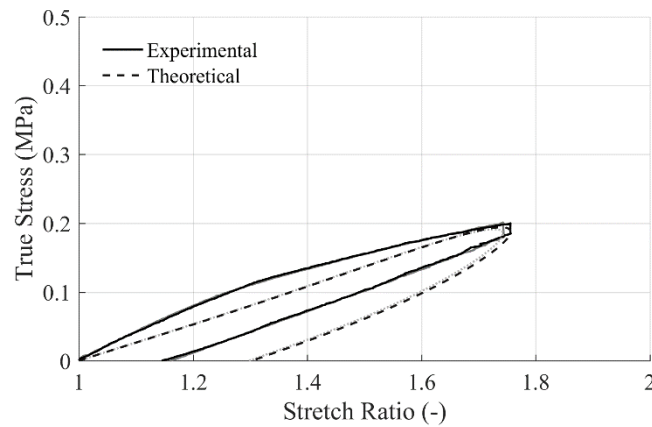


Figure B.21: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.075 \text{ s}^{-1}$

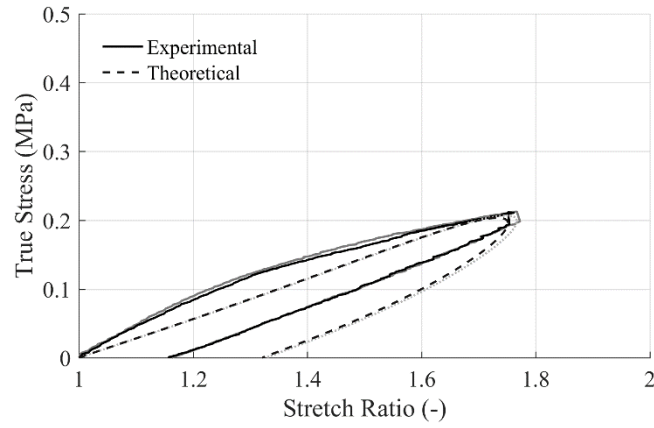


Figure B.22: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.100 \text{ s}^{-1}$

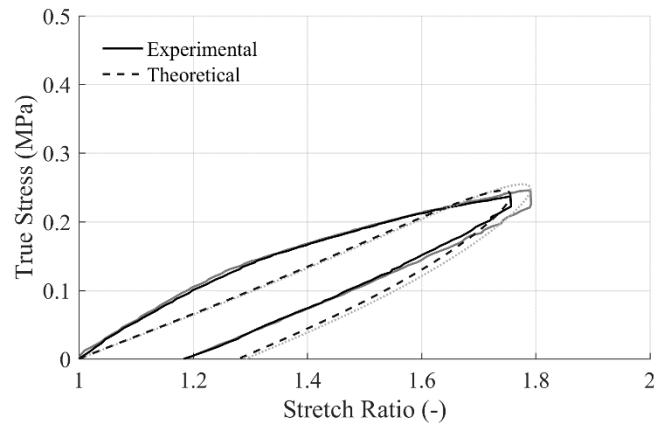


Figure B.23: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.200 \text{ s}^{-1}$

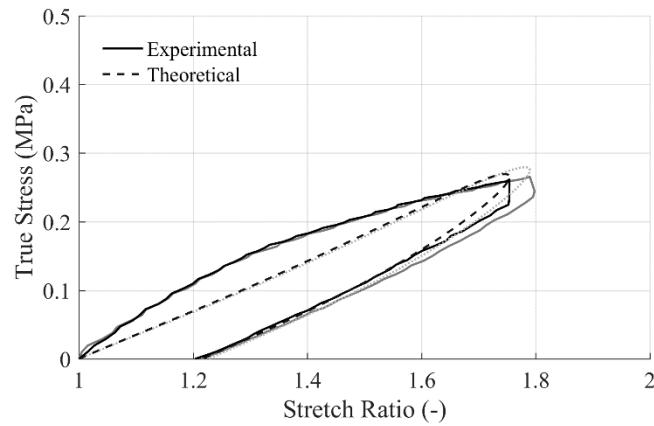


Figure B.24: Theoretical and experimental plots of biaxial tensile tests for VHB 4910 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$

VHB 4910 tape – non-equiaxial

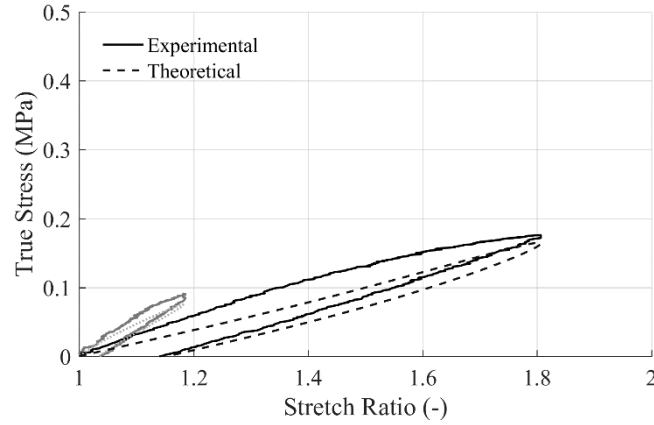


Figure B.25: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.25$

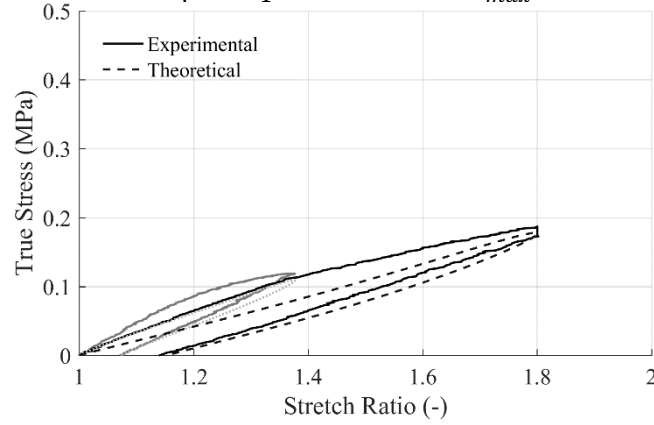


Figure B.26: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.50$

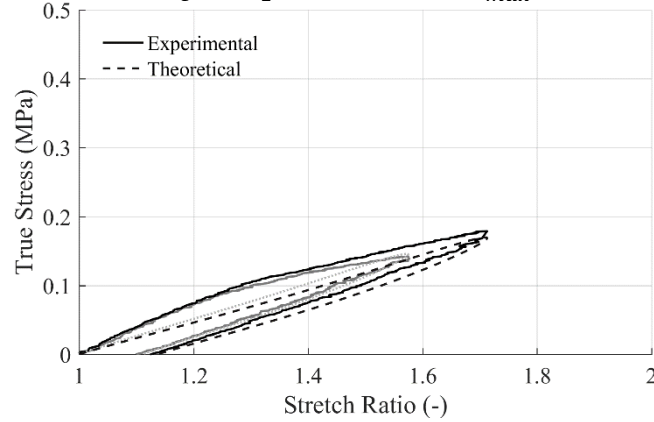


Figure B.27: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.025 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.75$

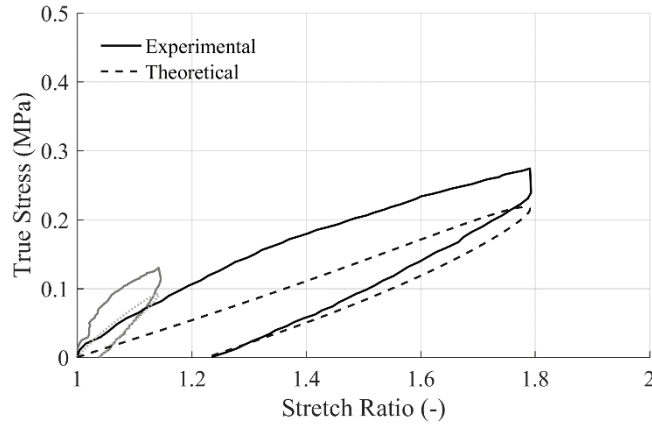


Figure B.28: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.25$

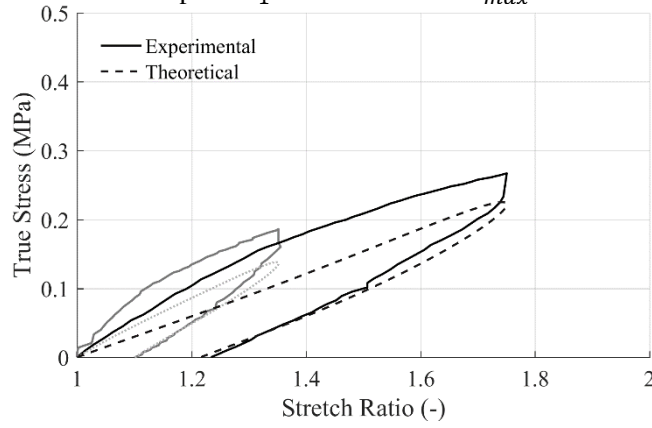


Figure B.29: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.50$

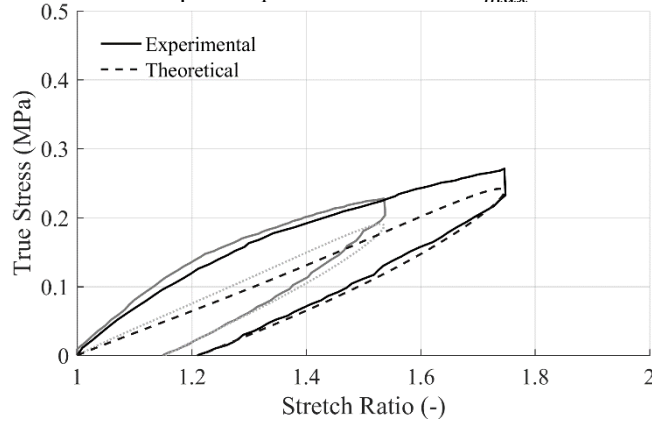
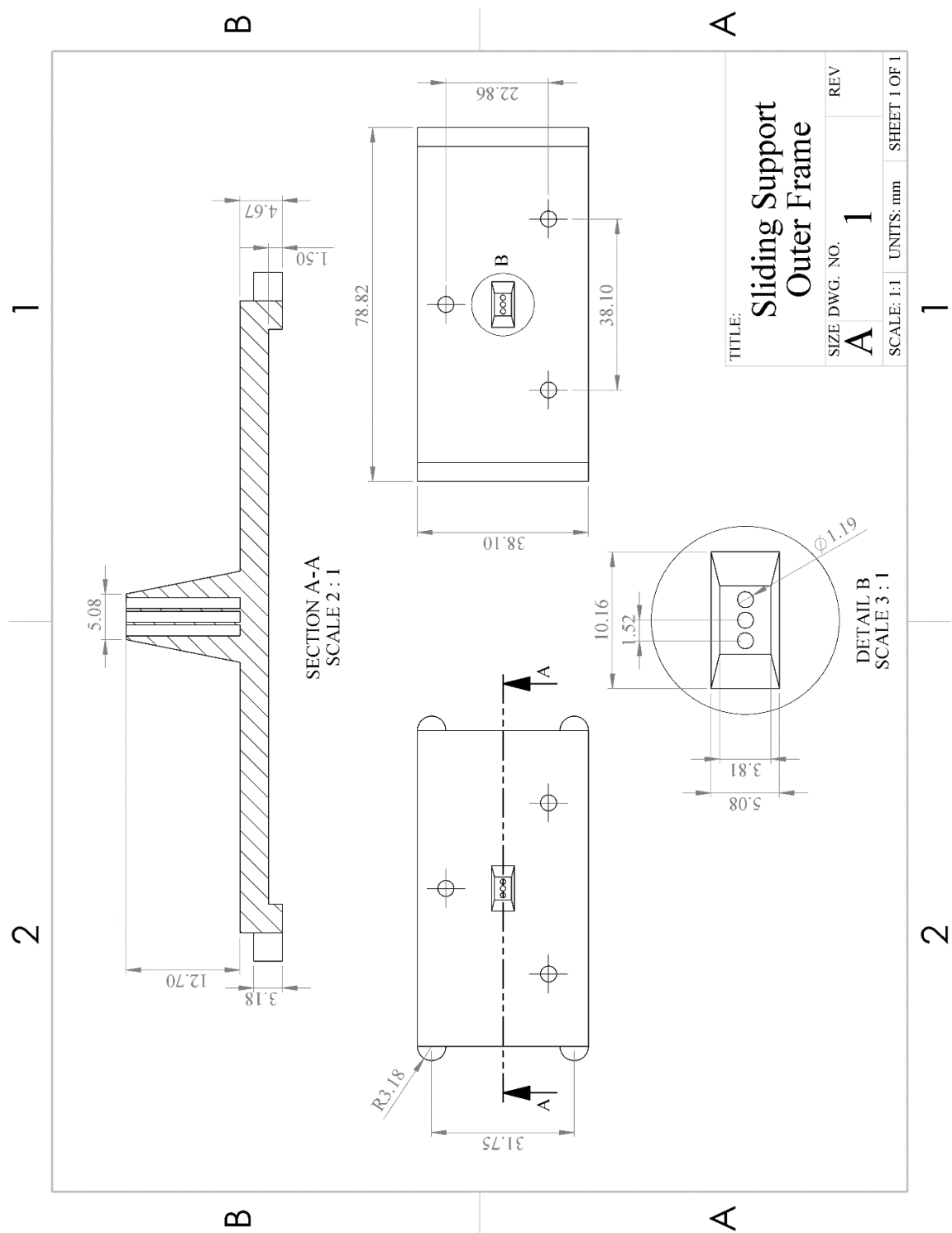


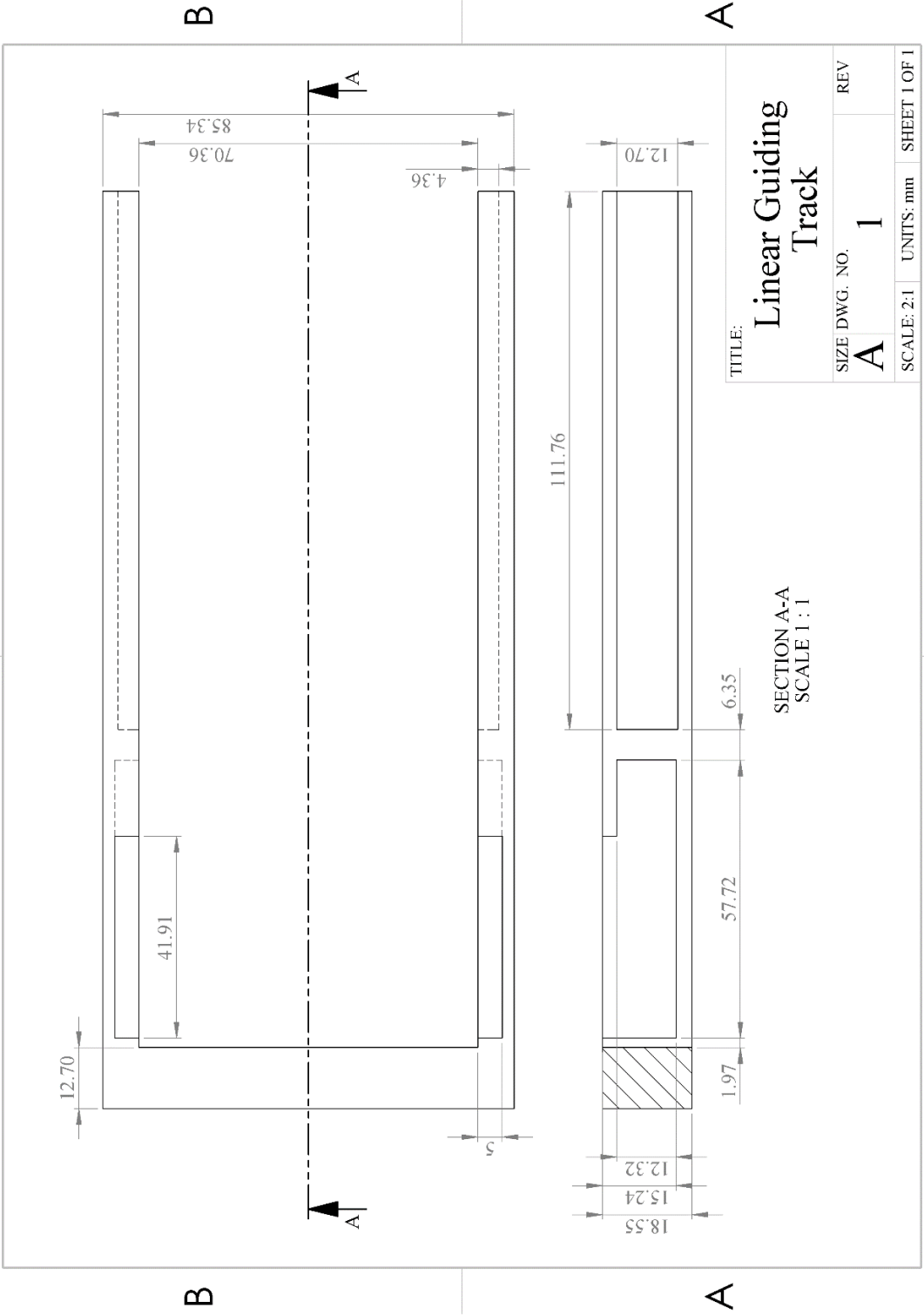
Figure B.30: Theoretical and experimental plots of biaxial tensile test for VHB 4910 tape at $\dot{\lambda}_1 = 0.300 \text{ s}^{-1}$ & $\lambda_{max} = 2 \times 1.75$

Appendix C

Appendix C.1 – Prototype Engineering Drawings



2 1



2 1

Appendix C.2– Prototype Assembly

The following section will illustrate the assembly process of the actuator prototype. In order to ensure a precise stretch ratio during application, a system of templates and guiding pins were used in order to apply the VHB tape to the acrylic plates. Similar to the steps used in Appendix A.6, a set of four laser-cut acrylic application plates were used. The plates were first wiped down with solvent wipes (70% isopropyl alcohol solution) to ensure proper bonding of the tape. The bottom two plates were then placed onto a sheet of ethylene-vinyl acetate foam (craft foam) for the application process. This was done as a precautionary measure, to ensure that the tape would not adhere to any surfaces other than the acrylic plates. For each pre-selected width stretch ratio, a template was etched on the foam surface, which reflects the initial dimensions required to achieve the desired lateral (λ_2) stretch ratio of the prototype. As can be seen in Figure C.1 (a), the plates are guided by nails that have been positioned along the inner perimeter of the templates. Once the plates have been properly aligned, four fixation pins were inserted into holes on the outer edges of both plates, and sunken into the board below, in order to maintain their position during tape application. A piece of VHB tape was then cut to a specific axial dimension, using the cutting mat and ruler method earlier illustrated in Figure A.1. The width of the sample was taken as to provide approximately 5 mm of bonding edges for either of the acrylic plates, in order to provide adequate adhesion during the stretching process. Due to the sample's large dimensions, a much greater force is required to achieve stretch ratios of up to $\lambda = 4$, which prevented the stretching method of Appendix A.6 from being used (where a thin clamping edge was used to elongate sample, and then left as part of the sample). The final DE film will therefore need to be cut down to size, once applied to the actuator assembly. This will be less of a concern than was previously described, since additional edge-reinforcements will be applied to the film, reducing the effects of any possible tears created during the cutting process.

The templates etched on the foam surface also included the delimitations of the tape sample's edges. These lines (seen through the tape sample in Figure C.1 (b)), along with electrical tape applied onto the acrylic plates, were used as guides to apply the elastomer directly on the centre of the plates. After having adhered the tape on the bottom plates (as seen in Figure C.1 (a)), the red polyethylene protective film was removed from the DE, exposing its adhesive backside. A second

set of acrylic plates were then lined up using the guiding pins, and pressed down onto the tape, sandwiching it between the two layers of acrylic (as seen in Figure C.1 (b)).

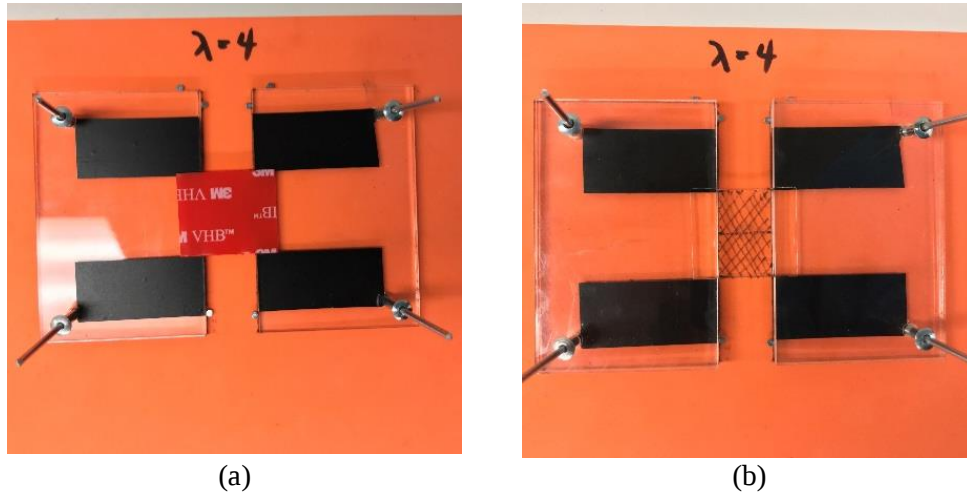


Figure C.1: VHB tape pre-stretching application
(a) application of film onto lower plates, and (b) application of the top plates onto the exposed backside of VHB tape

Once the sample was ready to be stretched, it was then brought over to a second template, which included guiding pins for both the application plates, as well as the prototype plates. After being laser cut to accurate size, the prototype plates' inner-edges were filed down to a fillet in order to minimize any risk of film tearing due to sharpness. Prior to film application, the plates were first wiped down with solvent wipes, to ensure proper adhesion. The lower plates were then placed on the board, following the guiding pins, and lined with a piece of VHB 4905 tape (as seen in Figure C.2 (a)). This was done to create a good bonding site for the DE film, and to minimize film slipping between the plates. VHB 4905 tape was selected for the liner application due to its thinner profile. This minimized the total width between the top and bottom plates for the slider-support. The VHB membrane was then stretched over the prototype plates, by aligning the application plates with the guiding pins, and lowering the stretched film onto the prototype plates (Figure C.2 (b)). A second layer of tape edge-liner was applied to the assembly, prior to applying the top prototype acrylic plates, for the same reasons as previously mentioned. In this step, however, a pair of 5-mm wide VHB 4905 tape side-edge supports (running along x-axis) were also added to the DE film (Figure C.2 (c)).

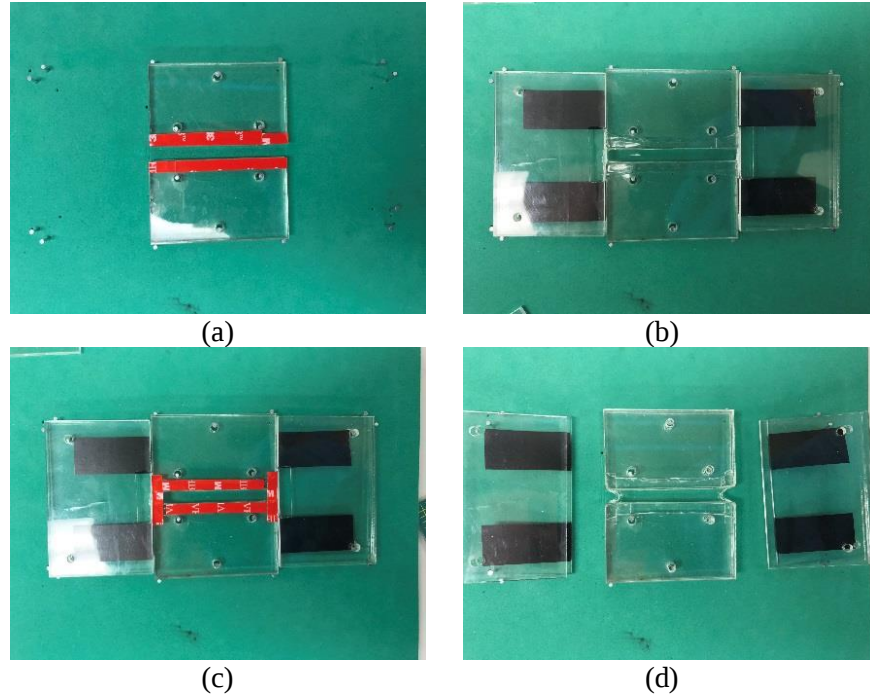


Figure C.2: VHB stretching application to prototype acrylic plates

(a) initial VHB 4950 liner strips on bottom plates, (b) application of VHB membrane onto plates, (c) application of VHB 4905 liner strips and side supports for membrane, and (d) final membrane once top plates have been applied and sides have been separated from application plates

The purpose of these side-edge supports is twofold. As previously mentioned, due to the large scale of the actuator, it was not possible to apply the tape in the same manner as Appendix A.6. This led to the film needing to be cut down to size once being stretched and applied to the actuator plates. During experimentation, this cutting process proved difficult and frequently left the actuator film with jagged, uneven edges (due to the tape's highly elastic and adhesive properties). These edge defects led to premature crack propagation during further stretching of the film along the axis of actuation (λ_1), and also seemed to increase the occurrence of dielectric breakdown during voltage application. The supports therefore firstly aided in minimizing these issues, by creating a more rigid edge on the film, halting possible crack propagation. Due to the free side-boundaries of the current prototype configuration, the film will also inevitably bow inwards as it is further stretched along the axis of actuation. This deformation will decrease the uniformity of the fixed width (λ_2) stretch ratio, which will affect the actuator's overall response during electro-mechanical coupling. The supports are therefore also assisting in maintaining a more consistent lateral stretch ratio, by resisting the inwards forces which otherwise make the tape deform unfavourably.

In order to ensure proper bonding between the side-supports and the DE film, the edge of a forceps was used to firmly press down onto the protective red film prior to its removal. Once both sides have been adhered properly, the protective films were then removed from the plate liners and edge supports, and the top prototype plates were pressed onto the assembly, following the guiding pins. The sides of the assembly were then carefully cut from the application plates, using a precision X-Acto blade, to complete the film application process (seen in Figure C.2 (d)).

Once the DE film was properly applied, the prototype plates were removed from the application pad and were then fitted with slider-support outer frames. These frames were placed on either side of the acrylic plates, lined up to their respective screw-holes, and attached using #6 steel machine screws and nuts. Wingnuts were used for all but two screws, in order to allow quick and tool-free initial tightening of the assembly. Regular hex nuts were used on the bottom two screws of the stationary (green) slider-support, since the wing nuts obstructed the application of the electrical tape and copper contact electrode that will be seen later in this section. Once all screws were properly fixed into the assembly, they were further tightened using a right-angle Robertson screwdriver (and nut driver for hex bolts). Careful care was taken not to overtighten the assembly, in order to prevent over-compressing the elastomer or deforming/cracking the end fixtures. The film-slider assembly was then ready to install into the linear guiding track, followed by electrode application.

To mount the slider-supports properly, the linear guide was first fixed into a bench vice, with open-side upwards. The mobile (grey) slider-support was then inserted into the end of the track, while the stationary (green) slider-support was held outside the track. The entire slider-support-membrane subassembly was then slid down the track until it reached its inner limit, and the stationary slider-support was then carefully stretched and inserted into its corresponding resting slot. Using a rubber band, the mobile end of the actuator was held at a pre-stretched configuration for electrode application (as seen in Figure C.3). Both sides of the stationary slider-support were first covered with electrical tape, in order to prevent any outside circuit interferences. A copper contact electrode was then applied to the support's surface (on top of the electrical tape), with a small contacting edge on the DE film. As can be seen in Figure C.3 (a), the edge of the copper tape was cut as in semi-circle prior to being adhered to the film. This was done in order to prevent any sharp edges of the foil from piercing through. The other edge of the copper contact-electrode

was then folded over onto itself and left to hang. This edge will be used as the clamping interface for the alligator-clip circuit connection. The contact electrodes were applied at an offset from one another (on either side of the film) to ensure that the DE would not be damaged from having mirrored foil contacts on its surfaces. Once both sides of the DE film have been outfitted with their contact electrodes, the membrane was then painted with the compliant carbon grease electrodes.

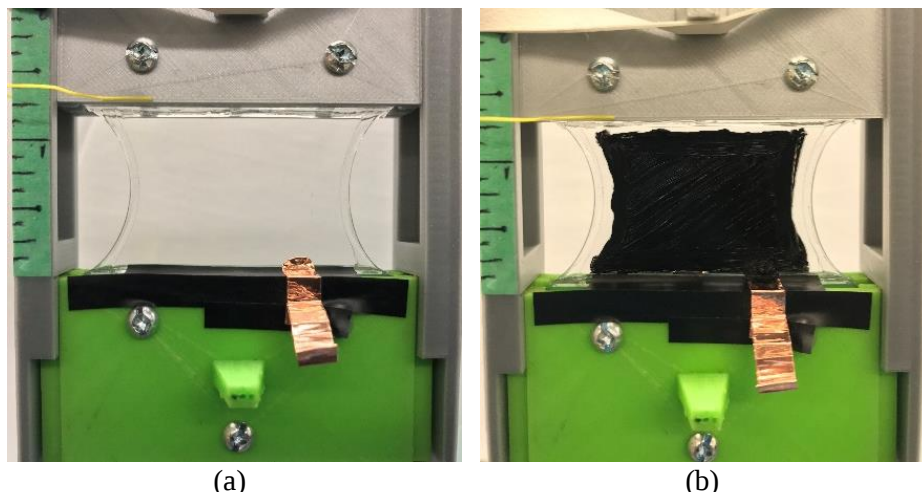


Figure C.3: VHB tape pre-stretching application
 (a) application of copper foil connection electrode on front side of membrane,
 and (b) membrane painted with compliant carbon grease electrode

The same 3:1 solution of carbon conductive grease and motor oil was used for the prototype's surface electrodes. As seen in Figure C.3 (b), an even coat was applied to the DE film using a fine-tipped paintbrush. Both sides were painted to be as symmetrical as possible, in order to provide an equal surface area during activation. An approximate edge of 10 mm (including the 5-mm edge-support liner) was left unpainted on either edge of the membrane, to provide an adequate safety factor for deformation. During the film's elongation, it's sides will bow inwards and start to thin, causing the electrodes to progressively approach the edge. It was observed that, without the unpainted edge, the electrodes would eventually get so close that a connection would be made between the two sides. This rendered the actuator ineffective and commonly led to a dielectric breakdown of the film. A generous coat of grease was also applied on and around the copper-film interface, in order to ensure proper connection between the circuit and the conductive grease. Once both surfaces of the membrane have been coated with their respective compliant electrode, the actuator assembly was ready to be fitted with the external springs and connected to the circuit.

As mentioned previously, music wires were selected to act as external springs on the prototype assembly. The wires were selected in 0.051 mm (0.020”), and 0.064 mm (0.025”) diameters for the experimental setup, as they both offered appropriate stiffness to resist the force of the DE film. Based on the desired initial axial (λ_1) stretch ratio, the music wires were cut down to various lengths. The prototype assembly and bench vice were brought over to the experimental setup and installed in their desired final position (either horizontal or vertical). The rubber band used to hold the mobile slider-support was then removed, and the springs were inserted into the prototype. Each spring was individually installed, by first inserting one extremity into the spring-cavity of the stationary slider-support. The DE membrane was then elongated by pulling back the mobile slider-support, and holding it in place. Finally, the spring was curved downwards, and inserted into the corresponding mobile slider’s spring-cavity. This process was repeated for all springs on either side of the prototype. Spring-combinations were positioned accordingly, to ensure stiffness would be centrally applied (e.g. if a four-spring configuration was to be used, the springs were placed in the outer most holes of the slider-supports). Once all springs have been installed into the assembly, the prototype was left to rest for 30 minutes, in order to allow the polymer to achieve its full stress-relaxed state. An example of a fully assembled prototype can be seen in Figure C.4.

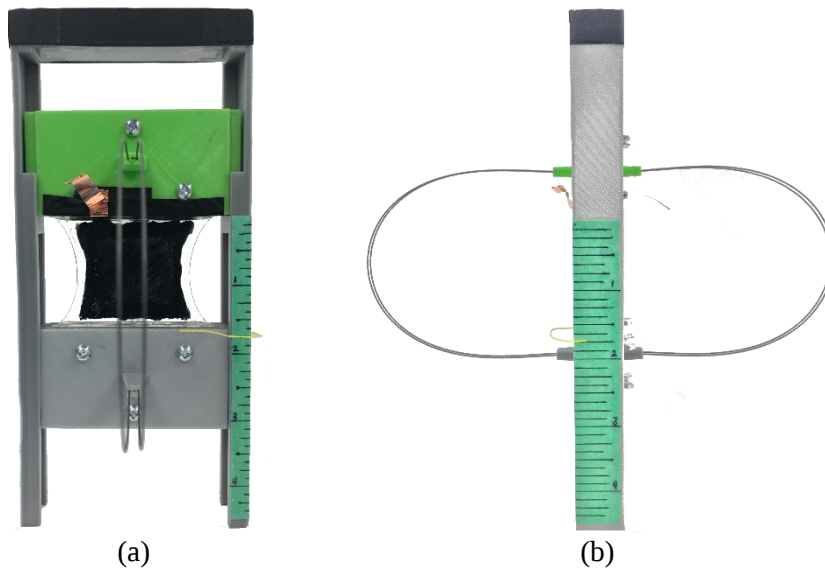


Figure C.4: Full prototype assembly
(a) front view, and (b) side view