3 Energy Storage in Natural Latex Bands

3.1 Natural Latex Characteristics

Primeline industries is the largest manufacturer of natural rubber products and states that natural latex is a plant extract that is vulcanised to form natural rubber. It can be converted to dry stock through mastication which allows it to be moulded or extruded, however masticated natural rubber has poorer qualities than non-masticated natural rubber. The best energy storage properties are gained through continuously dipped non-masticated natural rubber, which can be stretched to 750-900% of its original length before failure and is the material from which most speargun rubbers are manufactured [9]. The rings produced in continuously dipped natural rubber tube are visible in figure X below:

Figure 16 - A Continuously Dipped Natural Rubber Tube Cross-Section (image supplied by author)

More Content to be Added
More natural rubber properties Temperature sensitivity Fatigue performance (elongation comments) Marine Effects

This investigation will attempt to develop a function that calculates the energy stored in natural rubber tubing.

3.2 Experiment Outline

3.2.1 Sample Preparation

Figure 17 - Looped End of Rubber Sample

The rubber test samples were prepared by inserting a knotted loop of Dyneema approximately 20mm into each end. This was secured using a cinch knot, as is common rigging practice and depicted in figure X.

Figure 18 - Diagram of Unstretched Rubber Length Measurement

The unstretched length dimension was read from cinch knot to cinch knot, as the center portion of the band is the only part of the sample able to elastically deform.

Figure 19 - 27 Rubber Test Samples

There are 27 samples from 11 different manufacturers that vary from 275 to 391 mm in length and 14-20mm in diameter are depicted in figure X.

3.2.2 Variables

Inner diameter	Rubbers are marketed as micro, normal and large bore inner diameters which range from 1-3.5mm internal diameter. Micro bores contain more rubber and are thought to perform better but are harder to insert wishbone knots/beads. Larger inner diameters contain less rubber but are easier to rig.
Outer diameter	The principle dimension that influences the spring rate and energy storage capacity of the rubber.
Colour	Latex is naturally a translucent gum colour, so any other colour requires the addition of colouring agents. These impurities are likely to negatively affect the sample's mechanical performance. Colouring also prevents observation of the ring pattern indicative of continuous dipping – it is impossible to determine whether a coloured sample is naturally dipped or a masticated extrusion without consulting the manufacturer.
Unstretched Length	This variable is only important such that it determines the elongation percentage. Also, a greater length reduces the proportional error.

3.3 Experimental Procedure

One end of the rubber was anchored, the other was attached in-line to a crane scale per figure X below:

Figure 20 - Rubber Force Measurement Apparatus

A pulley system on the crane scale reduced the tension by a factor of 3, allowing a human to control the extension by hand.

This apparatus was laid next to a scale with the sample's specific elongation percentages of 0%, 50%, 100%, 150%, 200%, 250% and 280% marked. The sample was then elongated to these extensions, and the kilogram load recorded. No relaxation was allowed between measurements.

Once the rubber reached 250% elongation, it was held at that elongation for 30 minutes. 30 minutes does not represent a time of any proven statistical significance but facilitated the testing of the 27 rubbers within an achievable timeframe. This pause acknowledges that spearguns remain loaded when in use but won't be shot until a target is presented. It may take considerable time for a target to present and one may not present at all, yet the speargun remains loaded. The energy lost, if any, during this period is the subject of much debate in the spearfishing community.

Once 30 minutes have passed, the rubber was progressively relaxed and kilogram force readings taken at the same % elongation intervals.

3.4 Results & Key Themes

More Content to be Added
Internal Diameter patterns Colour patterns Force per mm^2 cross sectional area Energy per mm^2 cross sectional area

3.5 Data Manipulation

The force:% elongation data for each rubber must be converted to a form such that it can be applied to any speargun model.

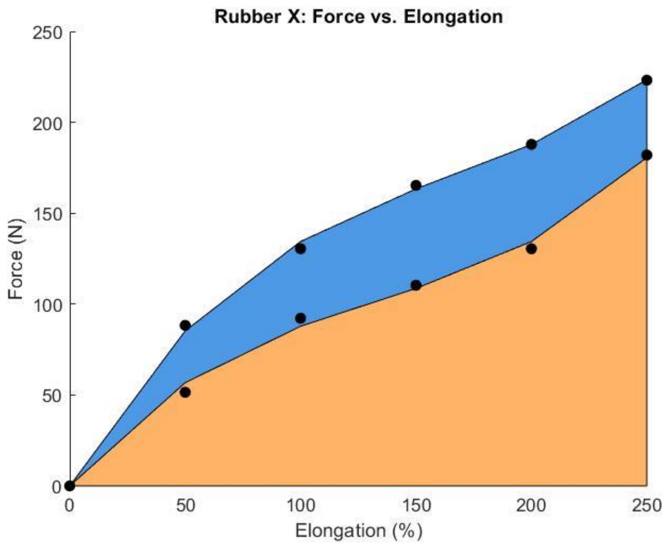


Figure 21 - Generic Force vs Elongation Graph

Figure X above represents some generic rubber data:

- The black dots are elongation (blue) & contraction (orange) data points.
- The black lines are 3rd order polynomial curve fits of these data points.
- The blue and orange areas combine to represent the energy required to stretch the sample.
- The orange area represents the constructive energy stored and then released by the sample.
- The blue area represents the unconstructive energy dissipated by the sample over 30 minutes.

Like the rubber data from which it is derived, the speargun model is assumed to dissipate energy over approximately 30 minutes before firing. The stretch data is used to determine loading forces, but the contract data is used to determine the energy released on firing.

Step 1) The diver must first state their maximum pull strength; this is the maximum force they can apply to load the speargun. The speargun's geometry will also specify the rubber's stretched length.

Known variables step 1: Max pull strength and max stretched length.

Step 2) The 3rd order polynomial curve fits of the stretch data (shown in table X below) are then solved (using the diver's maximum force) to determine the maximum % elongation (X represents % elongation and the result is force in Newtons).

Force given %E	X^3	X^2	X	C
Stretch	2.1012e-05	-0.01036	2.1706	0
Contract	2.0459e-05	-0.00820	1.4938	0

Table 2 - Example 3rd Order Polynomial Curve Fit

Thus, the model's maximum elongation percentage is determined.

Known variables step 2: Max pull strength and max stretched length, max percentage elongation.

Step 3) The models stretched length is divided by this maximum elongation % to give the unstretched band length. The minimum stretched length (only applicable to roller and inverted guns) is divided by the unstretched rubber length to give the minimum elongation percentage. This percentage is fed into the stretch polynomial in Table X to give the pretension force.

Known variables step 3: Max pull strength and pretension force, max stretched length, max & min percentage elongation and unstretched rubber length.

Step 4) The generic rubber data must now be related to the model through a *superimposition coefficient*.

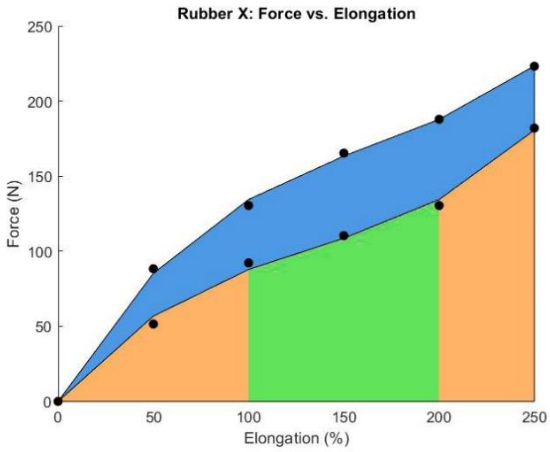
The area under the polynomials in Figure X can be evaluated using the definite integrals of Table X and the boundary condition:

F(0) = 0 (Force at 0 percent elongation is zero):

Area & %E	X^4	X^3	X^2	X	C
Stretch	5.2530e-06	-0.0035	1.0853	0	0
Contract	5.1148e-06	-0.0027	0.7469	0	0

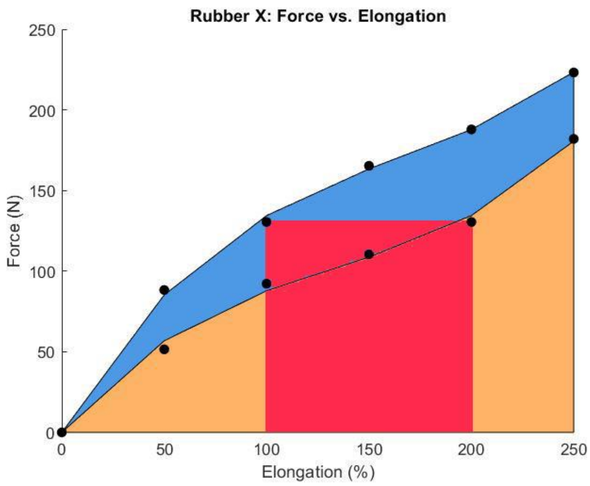
Table 3 - Example Integrated Polynomial Curve Fit

For example, the area between 100-200 percent elongation is depicted as green in Figure X:



Please note it doesn't yet equate to energy as energy is the integral of force with respect to distance, not % elongation.

The difference in elongation percentages (100%) is then multiplied by the force at the highest elongation percentage to give the red area in Figure X:



The superimposition coefficient can now be determined;

$$Sc = \frac{Green\ Area}{Red\ Area}$$

The Cp value is 0<Cp<1 and represents the proportion of energy released by the sample using just the force function and elongation percentages.

Known variables step 4: Max pull strength and pretension force, max stretched length, max & min percentage elongation, unstretched rubber length and superimposition coefficient

Step 5) Superimposition can then be used to give energy stored given the model's unstretched length, for example if the unstretched length was 0.1m, the Force-Distance graph would occur over the domain in Figure X below. The area under the curve represents the energy released as the data is now related to a distance and not % elongation.

$$Energy\ = Sc\ (\ F(Max\%)\ \times Travel)\ = \int_{Pretension\,\%}^{Max\ Elongation\,\%} Force\ .dx$$

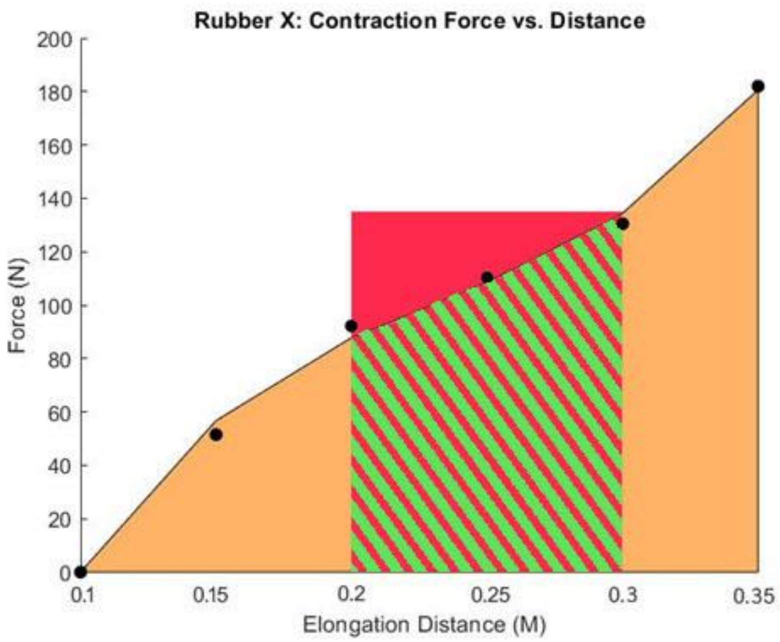


Figure 22 - Force vs Distance Graph

The Peak force (force function evaluation at maximum percentage elongation) multiplied by the distance travelled is represented by the red area (including the hashed area) in figure X; the red area would give the energy release in the model if the force was a constant.

The force is not constant; multiplying this nominal energy by the superimposition coefficient per Equation X accounts for changes in force due to changes in percentage elongation for that specific domain. This the actual energy released by the model:

$$\text{Green hashed area (energy released)} = Sc * \text{Red Area}$$

Collecting the force and elongation data of rubber samples has created a generic database of polynomials that can give all forces and energy stored within a model's geometry. These force vs elongation % and distance graphs are important for deriving the equations of motion in the next section.

3.5.1 Rubber Function Summary

The 27 samples were sorted by diameter and any outliers with odd properties were eliminated. A mean polynomial for each diameter was then developed; this included diameters 14, 16, 17, 18 and 19mm.

More Content to be Added
Database (curve fitted polynomials) Inputs: User max force, stretch length (speargun geometry) Outputs: - Min and max elongation % - Unstretched rubber length - Pretension force - Energy released