Tensile experiment based self-adaptive dynamic model for Tethered Space Net (TSN)

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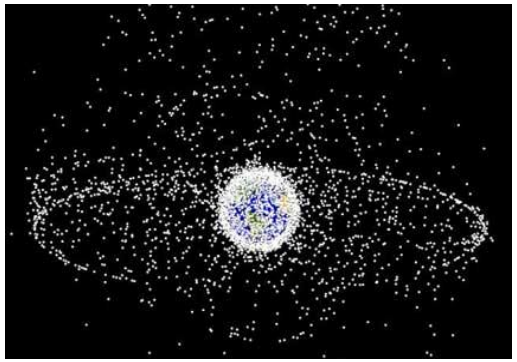
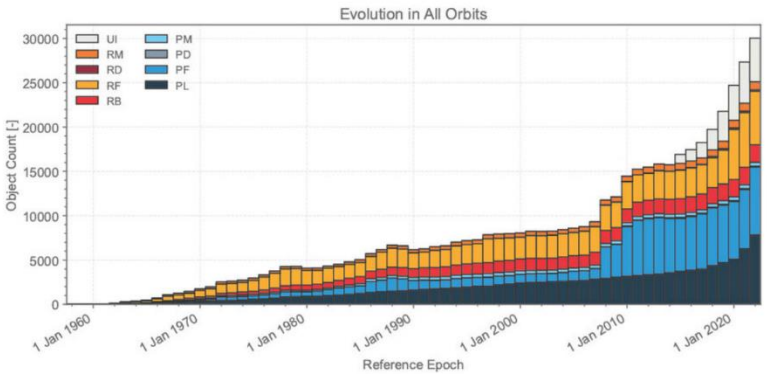
Catalogs

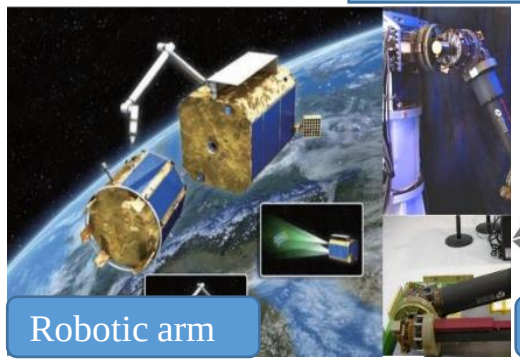


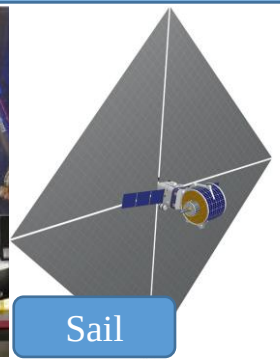


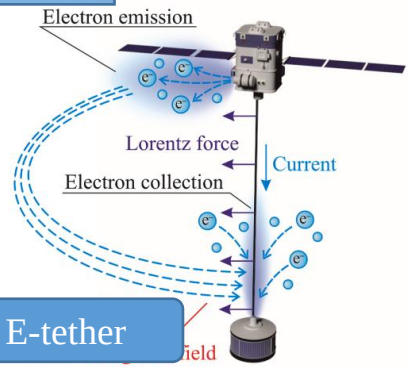
Up to December 2023 (from esa):

- debris' size >10cm, 36,500;
- debris' size 1~10cm, 1,000,000(one million);
- debris' size <1cm, 130 million.

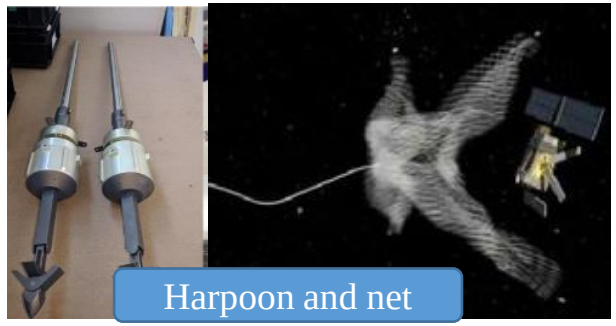
Active debris removal (ADR)

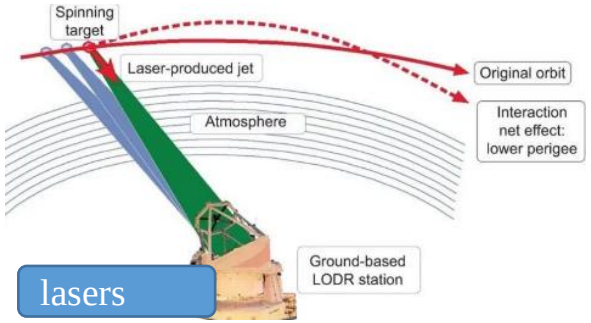

Robotic arm


Sail



E-tether


Harpoon and net

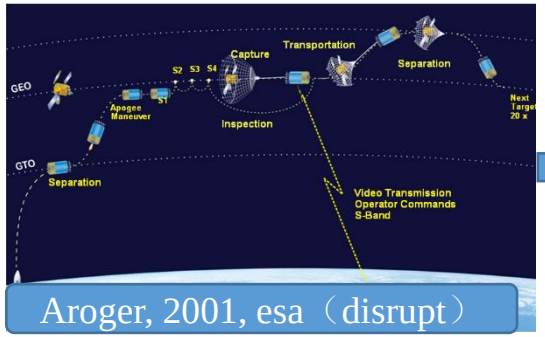


lasers

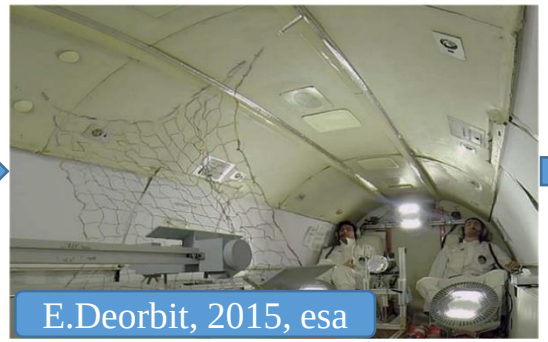
Tethered space net

Advantages:

- **Wide clearance range;**
- **High capture tolerance;**
- **Low impact risk on mother platform**

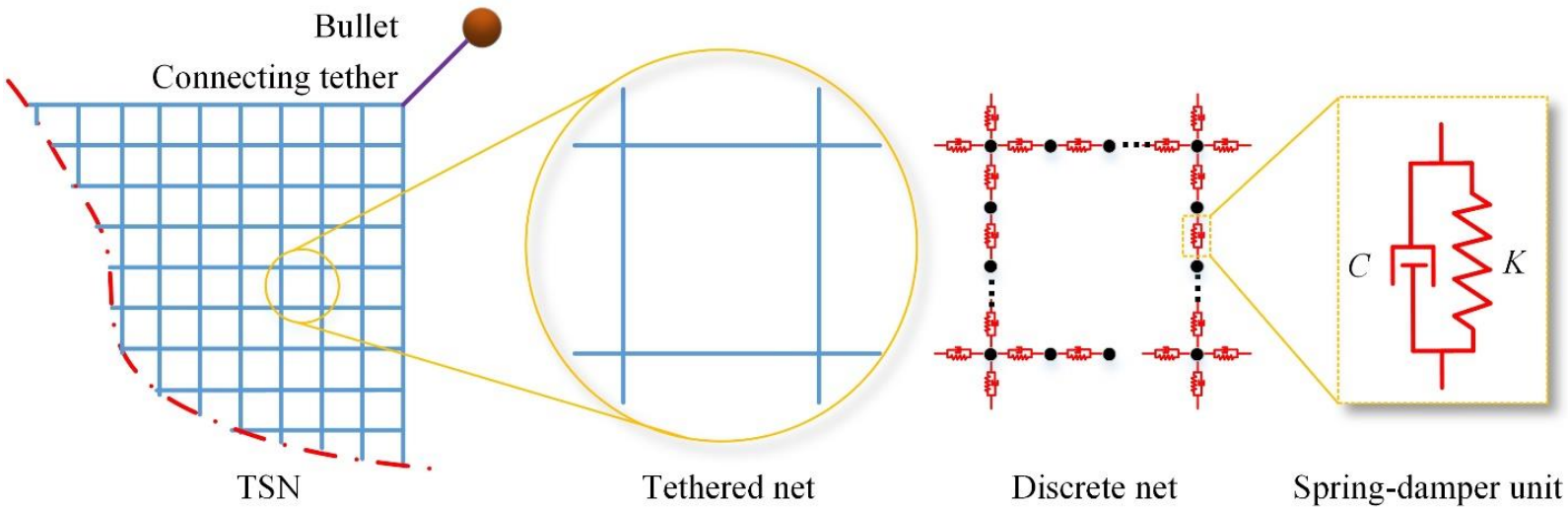


Aroger, 2001, esa（disrupt）


E.Deorbit, 2015, esa


Remove DEBRIS, 2018, Surry

Description



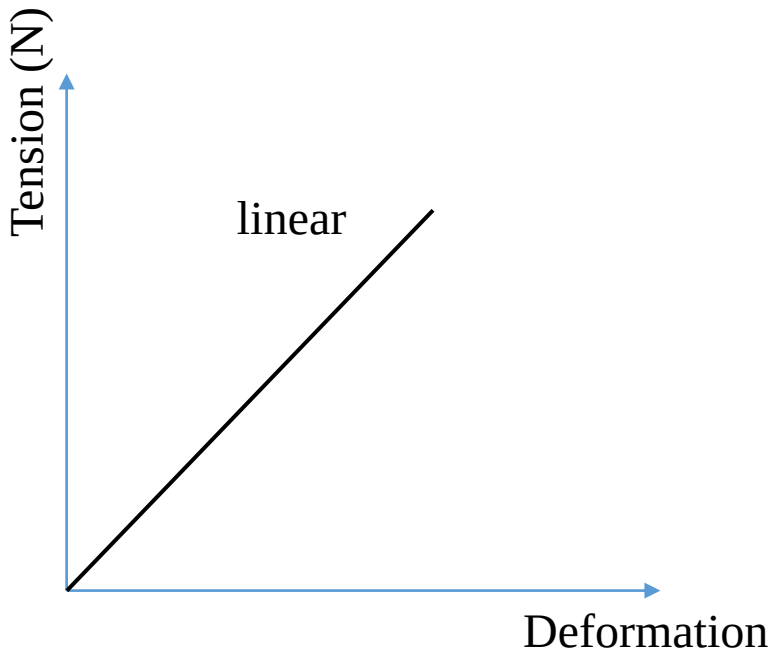
$$f_{ij} = \begin{cases} \wp_{ij}, & \wp_{ij} > 0 \\ 0, & \wp_{ij} \le 0 \end{cases}$$

$$\wp_{ij} = \begin{cases} C\dot{x}_{ij} + K(x_{ij} - l_0), & x_{ij} > l_0 \\ 0, & x_{ij} \le l_0 \end{cases}$$

$$\boldsymbol{m}\ddot{\boldsymbol{x}} = \begin{bmatrix} \boldsymbol{F}_1^{\mathrm{T}} & \boldsymbol{F}_2^{\mathrm{T}} & \cdots & \boldsymbol{F}_n^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} + \boldsymbol{F}^{\mathrm{ex}}$$

- *Simplified*
- *Linearity*

Problem



fiber

weave

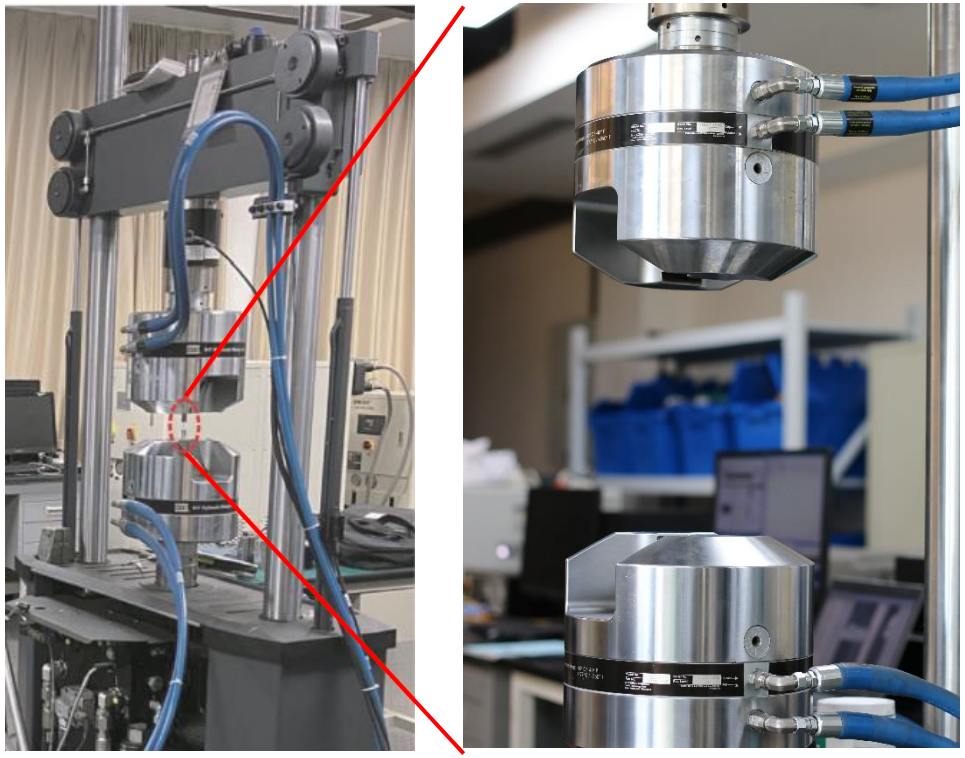
tether

Different thread number

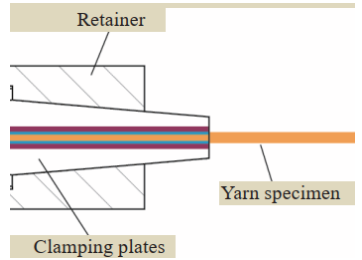
Different weaving method

- *Does the tensile properties of the braided tether still linear?*

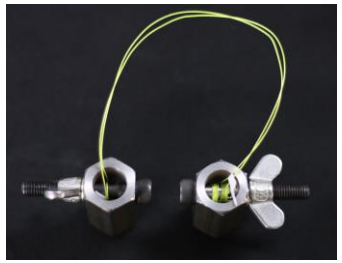
Solution

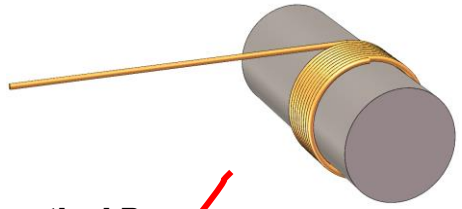


MTS810 tensile equipment



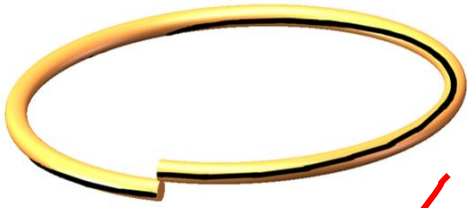
Clamper method A



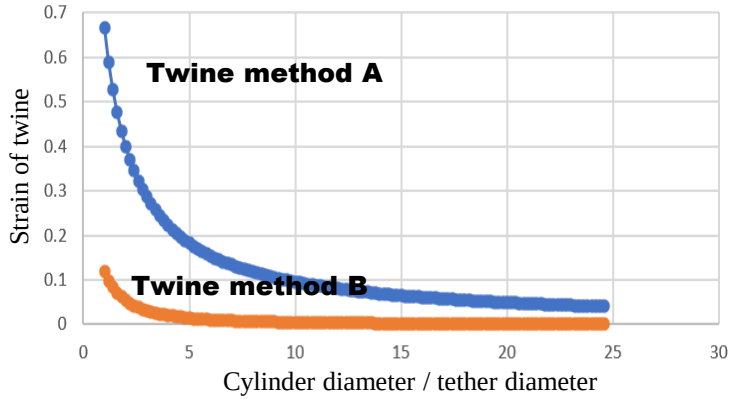


Clamper method B ✓

Twine method A



Twine method B ✓



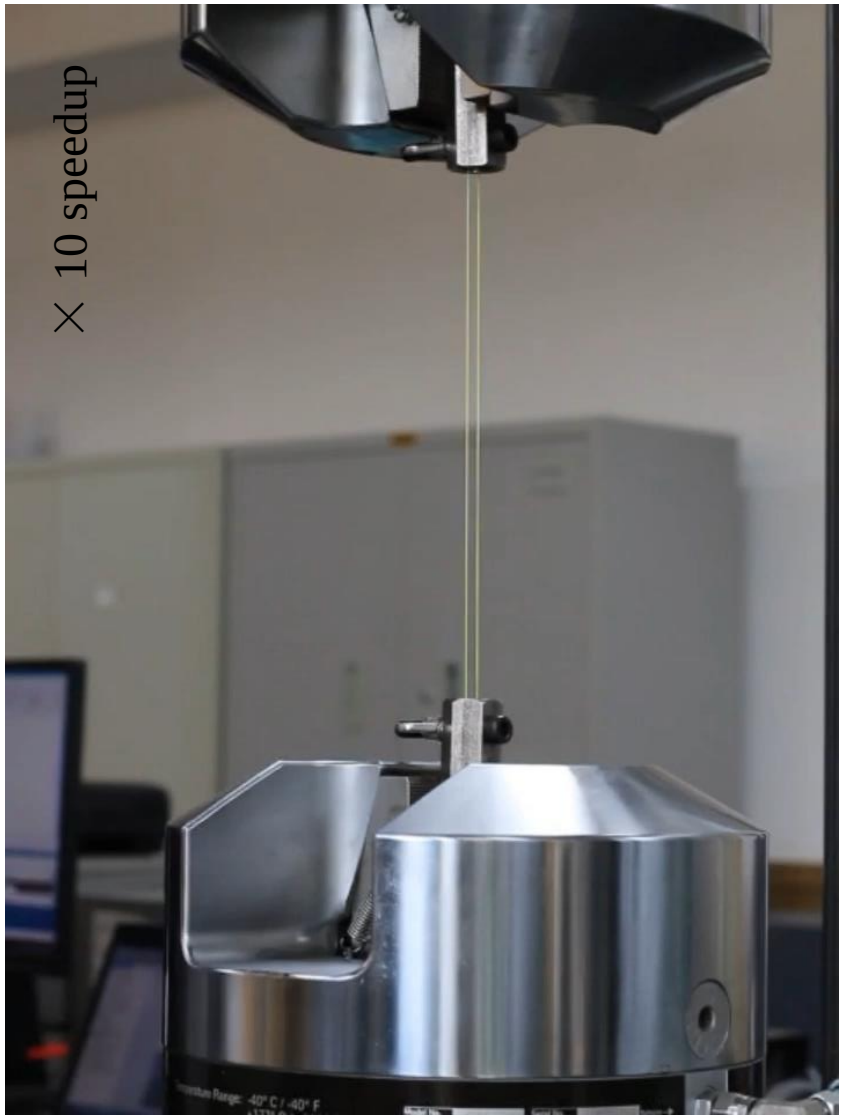
Test

- Eight-strand Dyneem tether
- 5 different size

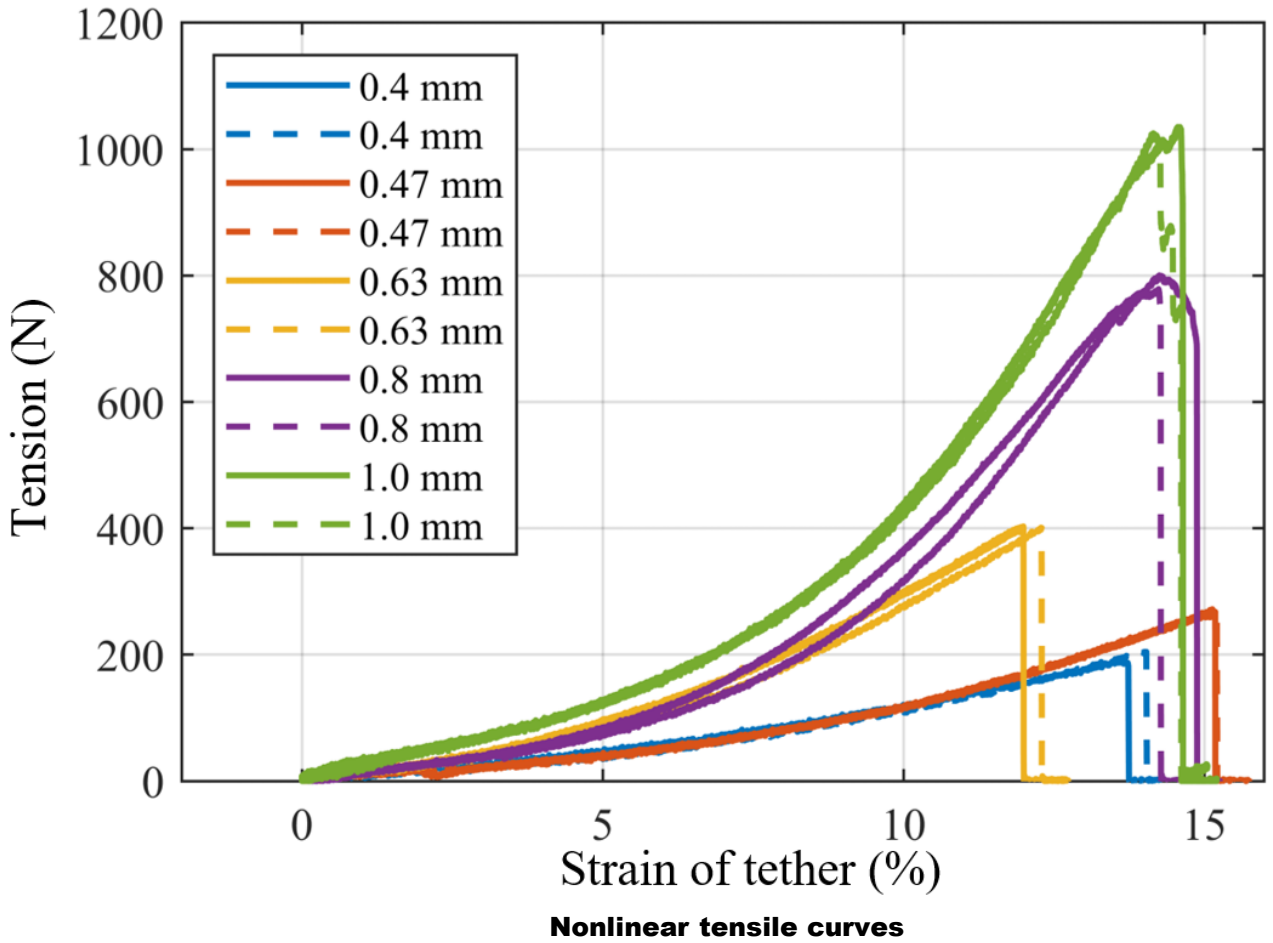
0.4mm, 0.47mm, 0.63mm,
0.8mm and 1.0mm

$$\varepsilon(t) = \frac{\|x_1 - x_2\|}{\|x_1|_{t=0} - x_2|_{t=0}\|} - 1$$

$$\sigma(t) = \frac{F_n}{2A_t}$$



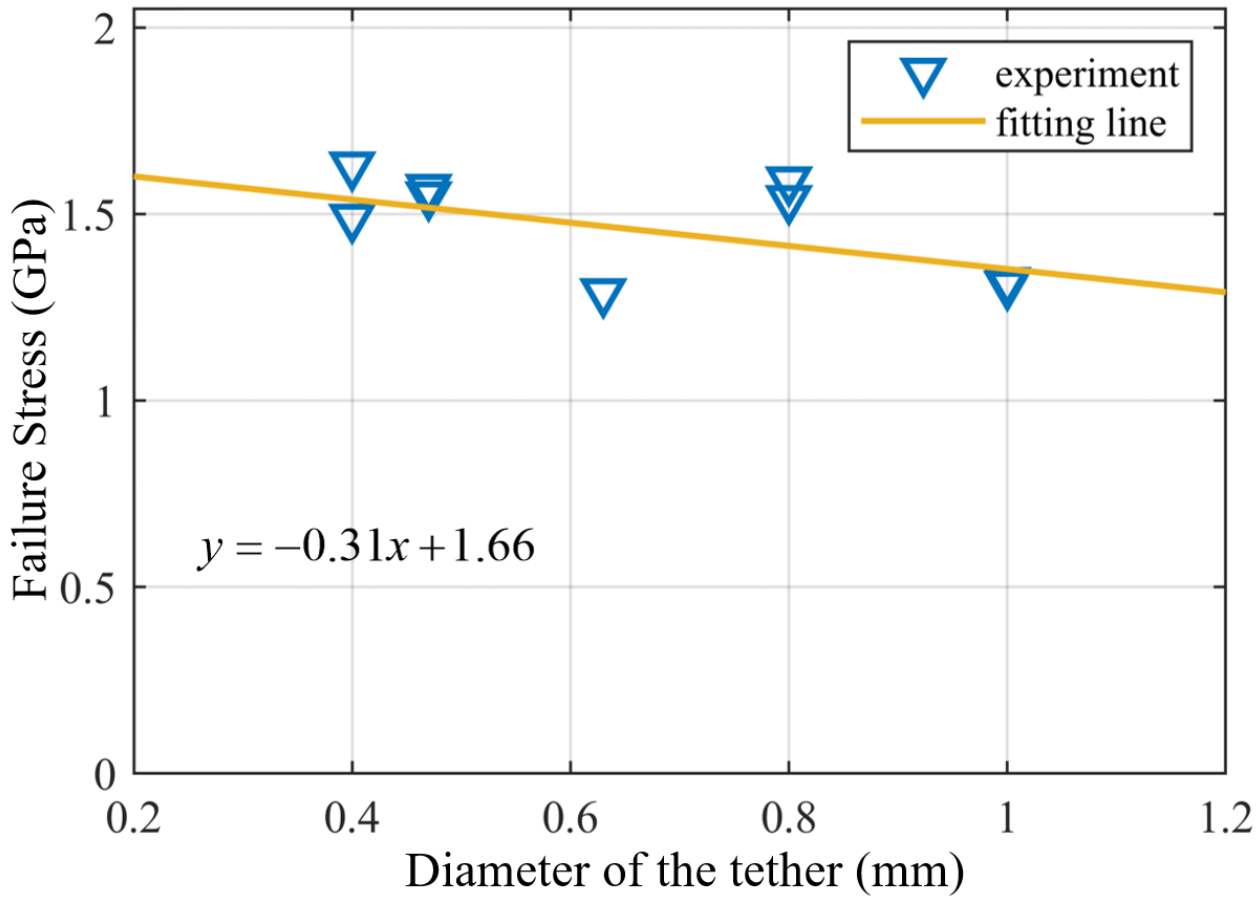
Test results



Nonlinear tensile curves

- *Strong Nonlinearity*
- *Failure tension increase with the diameter of the tether*
- *Failure strain is between 0.12~0.15 larger than the failure strain of the single fiber* (0.03~0.04)

Test results



- *Failure stress is around 1.5* GPa *smaller than the single fiber* (3.3~3.9 GPa)

Test results

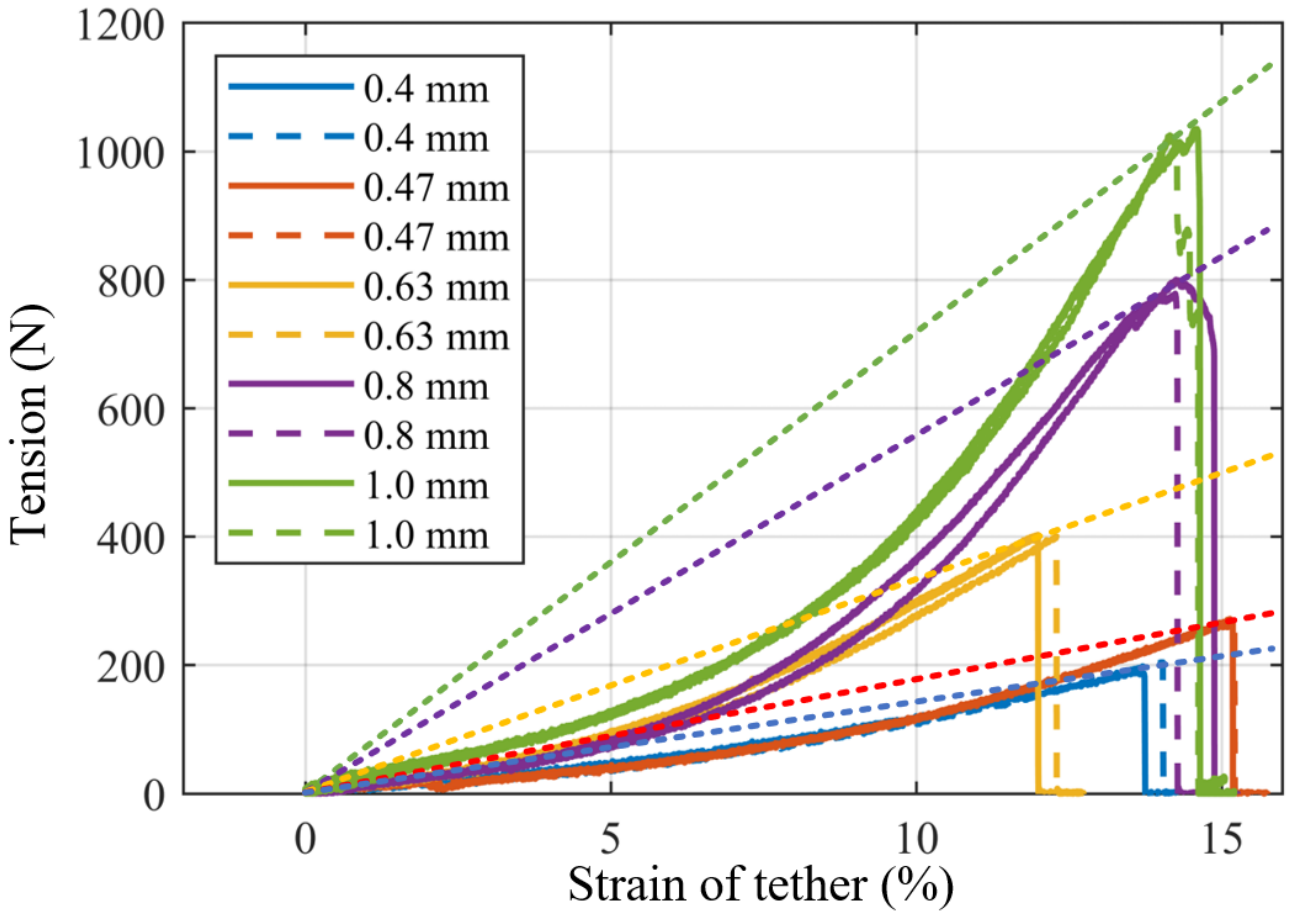
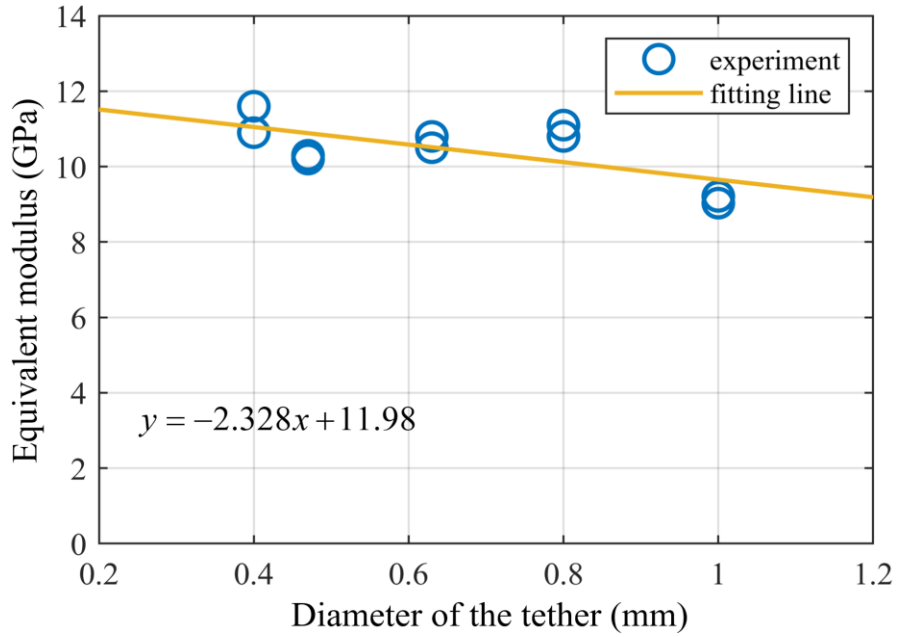
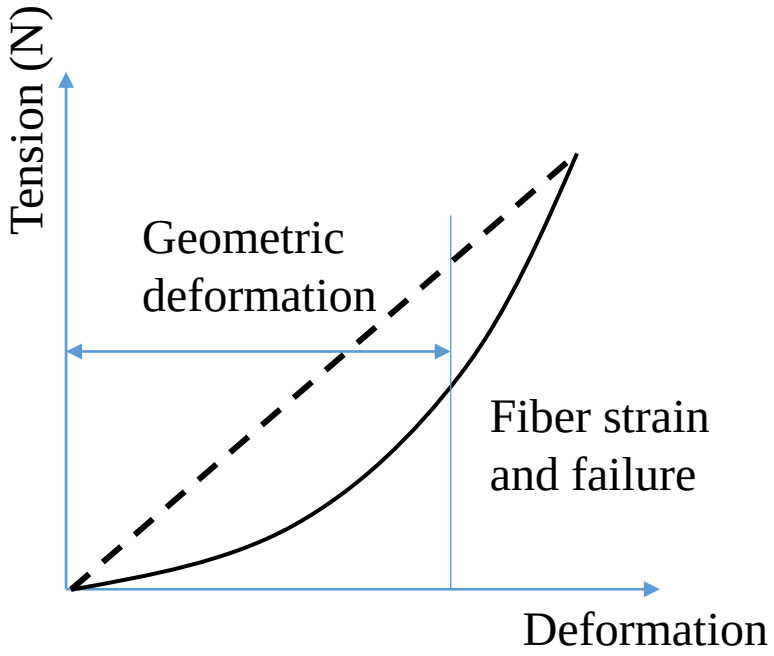


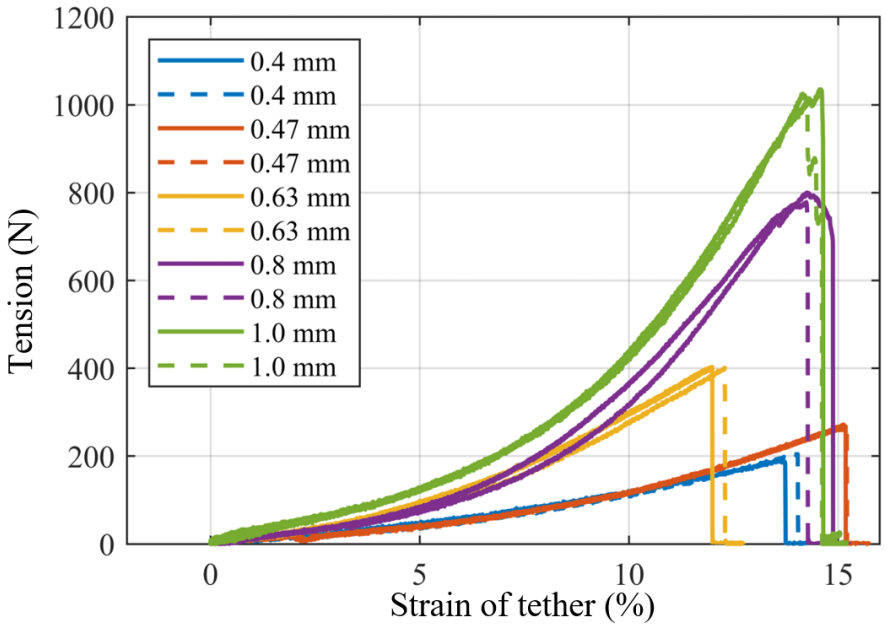
Figure out the average equivalent modulus



- *Equivalent modulus range from 9GPa ~12GPa, and decrease with the diameter*
- *Smaller than the modulus of fiber (around 80~100GPa)*

Explanation





The linear model may not accurate enough under a large deformation of the tether

Tensile process

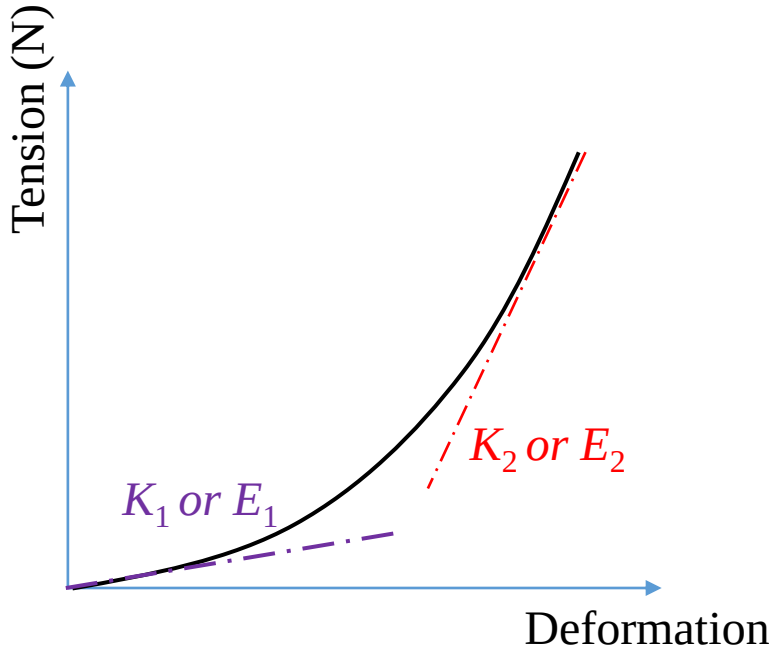
Gaps between fibers

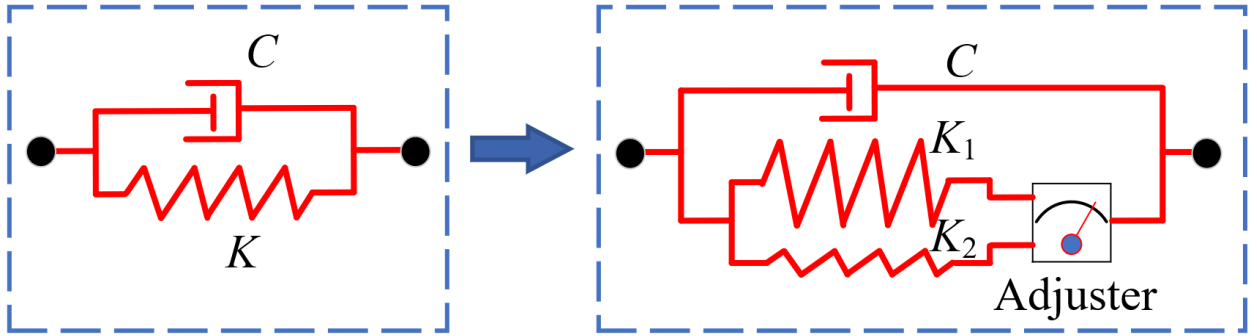
Weaving methods

- Geometric deformation
- Gap reduction
- Tensile, bending, compressed among fibers

- The strain of the tether > the real strain of fiber
- Tensile failure is **decreased** comparing to the single fiber
- Equivalent modulus of the tether is smaller than the single fiber

Improvement





Adaptive nonlinear spring-damper model

Linear model

$$f_{ij}=\begin{cases} C\dot{x}_{ij}+K(x_{ij}-l_0), & x_{ij}>l_0 \\ 0, & x_{ij}\le l_0 \cup f_{ij}\le 0 \end{cases}$$

Improved nonlinear model

$$\frac{\mathrm{d}f_{ij}}{\mathrm{d}(x_{ij}-l_0)}=\begin{cases} K_1\left(1-\dfrac{x_{ij}-l_0}{\bar{\varepsilon}_s l_0}\right)+K_2\dfrac{x_{ij}-l_0}{\bar{\varepsilon}_s l_0}, & l_0<x_{ij}<\bar{\varepsilon}_s l_0 \\ 0, & \text{else} \end{cases}$$

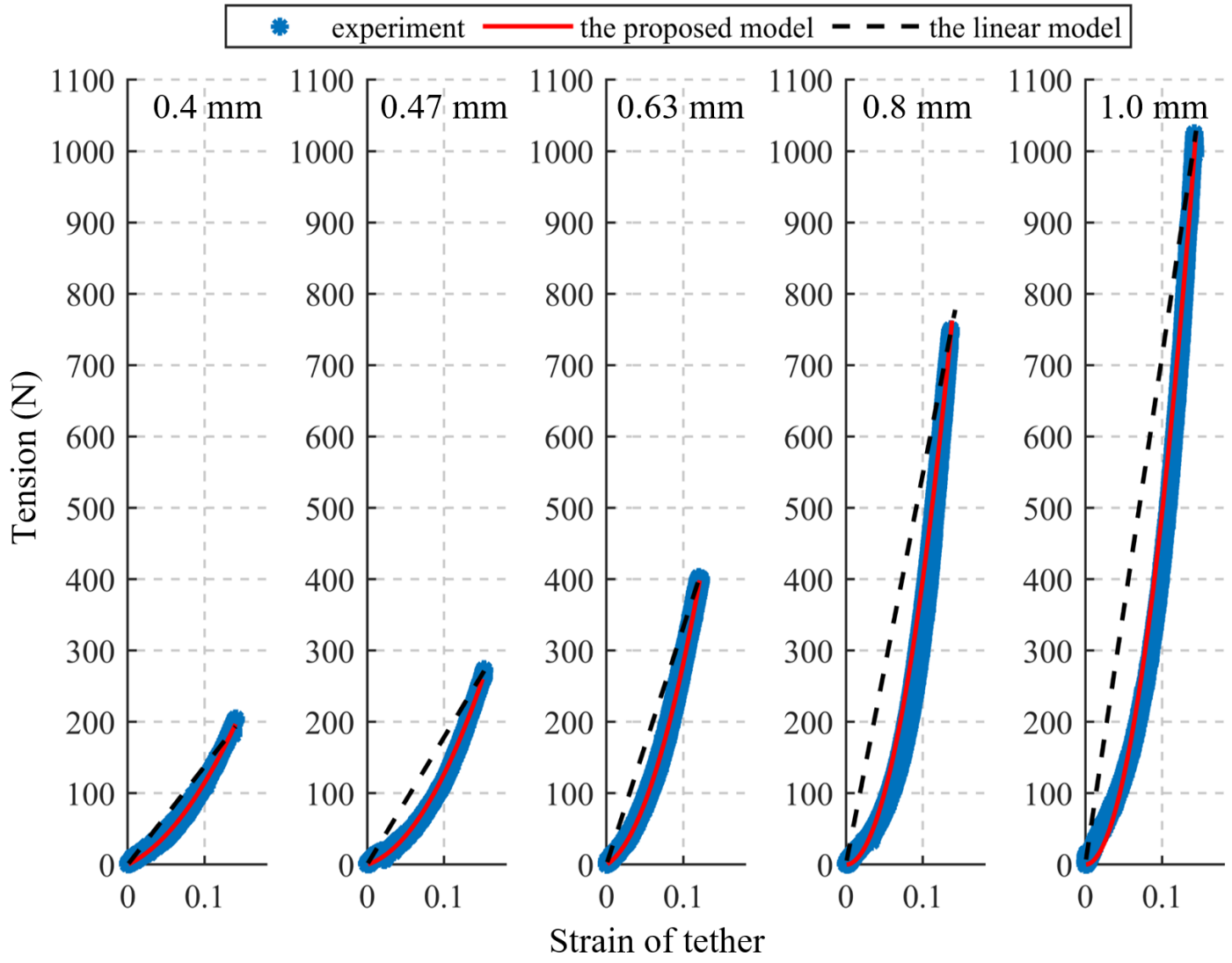
With the boundary conditions we get:

$$f_{ij}=\begin{cases} \dfrac{K_2-K_1}{2\bar{\varepsilon}_s l_0}(x_{ij}-l_0)^2+K_1(x_{ij}-l_0)+C\dot{x}_{ij}, & l_0<x_{ij}<\bar{\varepsilon}_s l_0 \\ 0, & x_{ij}\ge\bar{\varepsilon}_s l_0 \cup x_{ij}\le l_0 \cup f_{ij}\le 0 \end{cases}$$

$$\begin{cases} K_1=(1-\xi)\bar{K} \\ K_2=(1+\xi)\bar{K} \end{cases}$$

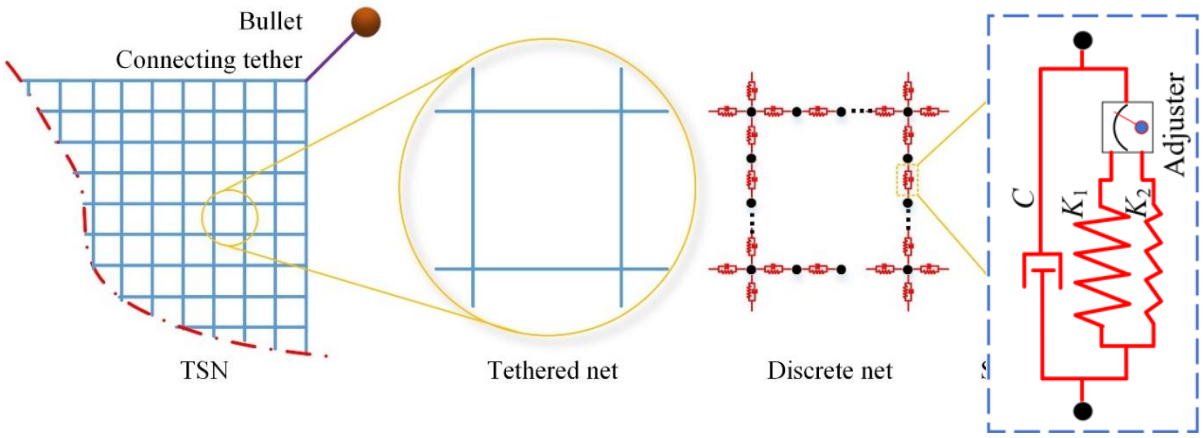
$$\bar{K}=\frac{\bar{E}A}{l_0}$$

Results



- *The proposed model and test data are basically consistent.*
- *It has a better performance on tethers whose diameter below 0.63 mm.*
- *Error that occur near zero increases with the tether's diameter, but it is still more accurate than the linearized model.*

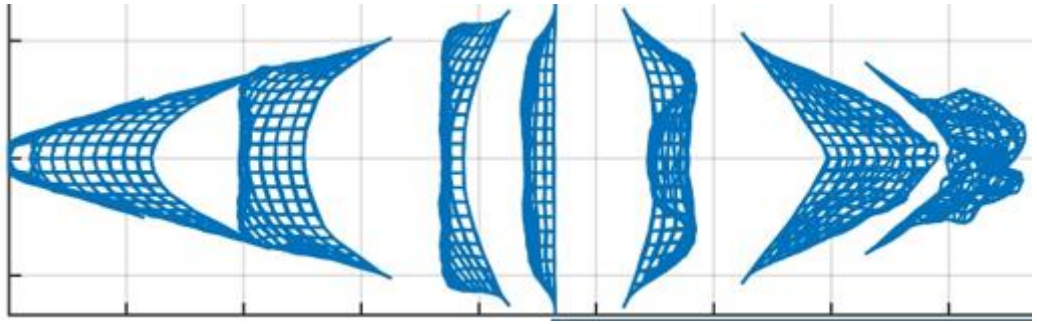
Back to the net

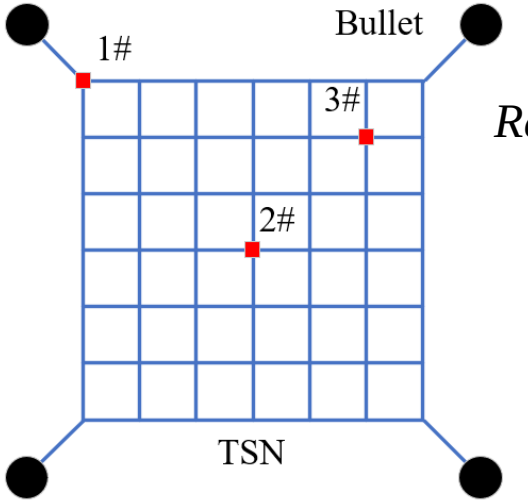


Simulation parameters

Parameters	values
Net size	5 m
Grid number	6
Launch angle	35 deg
Launch speed	2 m/s
Mass of bullet	350 g
Diameter of the tether	0.63 mm

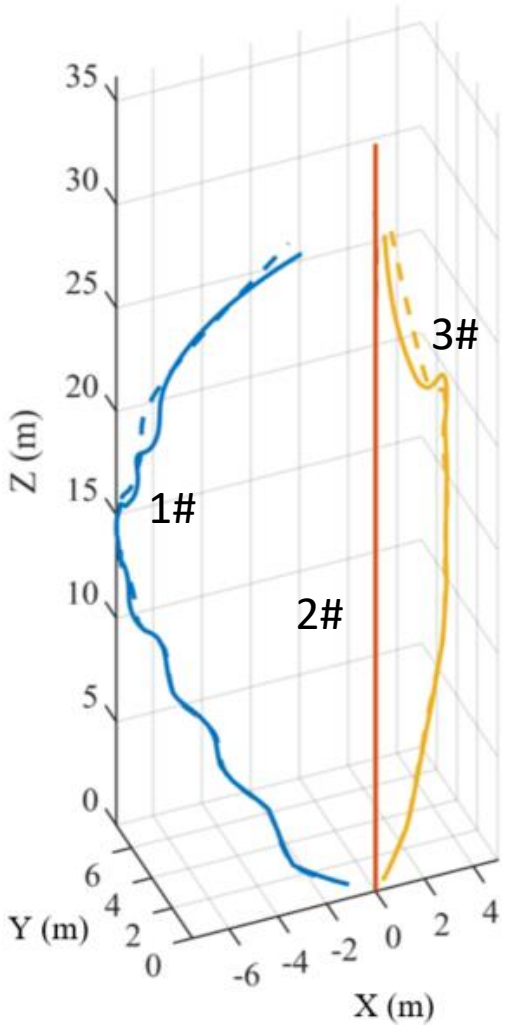
Adopted to study the deployment process



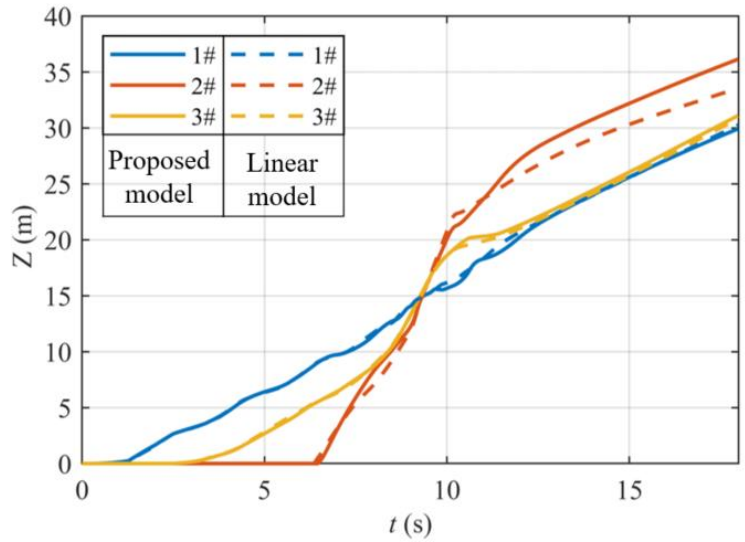


Record

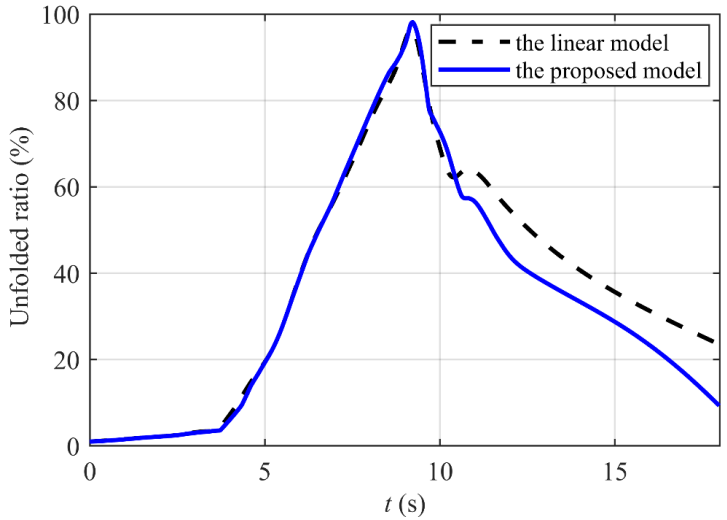
- The trajectory of the marker
- Deployment area



3D trajectory of the markers



Displacement of the marker with time



Unfolded ratio of the net

- The trajectory almost coincide at the beginning;
- After the full-deployment the trajectory has a significant difference
- In the initial stage of the deployment, the net is in a folded state and small mass, thus, the tension required to move the net is small and discontinuous. This makes it difficult to highlight the difference between the two models in the early stage of the deployment.
- After the full-deployment, the net is flat and most of the tether on the net is stretched by four heavy bullets. The visible difference between two modes arise.

The main conclusion this work are as follows:

- The nonlinear tensile properties of the tether is obtained by the tensile experiment.
- Study the mechanism of the nonlinear tension and improved the tether model with an adaptive nonlinear spring-damper model.
- The adaptive nonlinear tether model is more accurate to the tensile experiment results and it has a better performance on nonlinear characteristics of the tension of tether.
- In net deployment, the improved model has visible difference after the net is fully deployment.

Questions and Comments

Thanks for watching !

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