NUMERICAL ANALYSIS OF THE ARTIFICIAL MUSCLE MADE OF FISHING LINE

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1. Introduction

As stated in [1], artificial muscle are needed for diverse applications, ranging from humanoid robots, prosthetic limbs, and exoskeletons to comfort-adjusting clothing and miniature actuators for microfluidic "laboratories on a chip". Several materials are used for their elaboration having specific properties and features. One of them are low-cost high-strength polyethylene and nylon fibers, most of them used as fishing line. Twist is inserted into these polymer fibers to make them chiral, which enables them to function as torsional muscle. A tensile stroke is greatly amplified by inserting such a large amount of twist that some twist converted to fiber coiling. By completely coiling the fibers, tensile contractions exceeding the maximum in vivo stroke of human skeletal muscle were obtained. Immediately after coiling adjacent coils are in contact, limiting contraction during actuation, and must be separated by increasing load or reducing twist. When adjacent coils contact, due to insufficient applied load or excessive twist, the muscle-direction thermal expansion becomes positive. When adjacent coils do not contact due to applied load, the muscle-direction thermal expansion is negative and the muscle performs mechanical work [1].

In the papers [2-12], the several experimental measurements and numerical analysis are performed which extend the technological breakthroughs described in [1].

In the proposed paper, a short description of our device for elaboration of the artificial muscle made of fishing line is presented. The experimental measurement are done to specify the elasticity modulus of the untwisted and twisted fishing line, as well the spring constant of the coiled spring. The prestressing force in the twisted line and in the coiled spring is measured as well. The measured parameters input into the semi-analytical and finite element method model of the coiled spring for calculation of the spring elongation due to the applied mechanical load. Linear and non-linear elastostatic analysis is performed using the BEAM188 finite element [13]. The calculated results are compared with the experimentally measured elongation of the artificial muscle caused by additional mechanical load.

2. Elaboration of the artificial muscle

A device for the coiled spring elaboration is shown in Fig. 1. It consists of the supporting frame, the stepper engine, the controller and the note book with relevant software.

The device allows twisting of the fishing line to the state when the coiling begins, and subsequently, to creating the required number of turns of the coiled spring. The control unit allows control of the rotation speed and engine rotations number.

Fig.1:*The device for the artificial muscle elaboration.*

3. Measurement of the mechanical properties

InFig.2, the fishing line is depicted in its initial state: L_0= 500 mm is the length; d_0 = 0.635 mm is the diameter; E_0 = 3.8 GPa is the elasticity modulus; $\nu_0 = 0.39$ is the Poisson ratio and G_0 = 1.37 GPa is the shear modulus. After hanging weight $m = 0.56$ kg, twist is inserted into these polymer fibers by inserting n_t = 280 turns (Fig.2) to the state that some twist converted to fiber coiling.

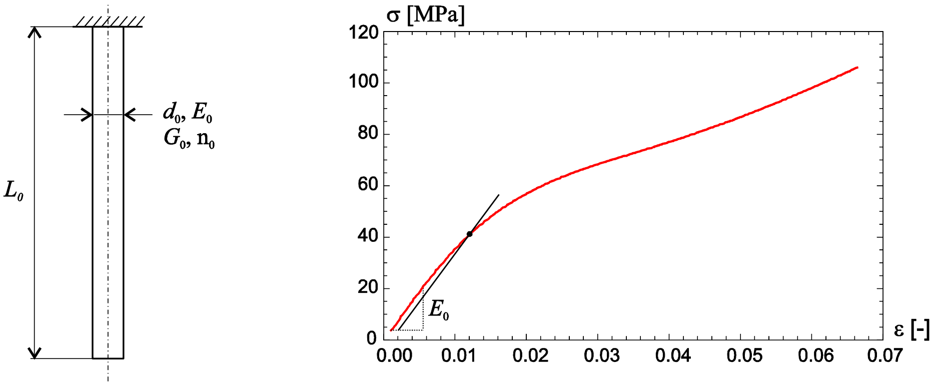

Fig.2: *To measurement of the material properties of the fishing line.*

In the Fig.3, L_t=440 mm, d_t = 0.687 mm, E_t = 2.7 GPa, G_t = 0.964 GPa and $\nu_t = 0.4$, is the length, the diameter, the elasticity modulus, the Poisson ratio and the shear modulus at this limit state, respectively. F_t = 5.5 N is the prestressing force at this limit state, which corresponds with the applied mass $m = 0.56$ kg and the gravity $g = 9.81\,\mathrm{ms}^{-2}$. The normal stress in the twisted line is $\sigma_t = \dfrac{F_t}{\pi d_t^2 / 4} = 14.8\,\mathrm{MPa}$. Comparing to the initial state, the material properties and the length of the line decrease and the diameter of the line increases.

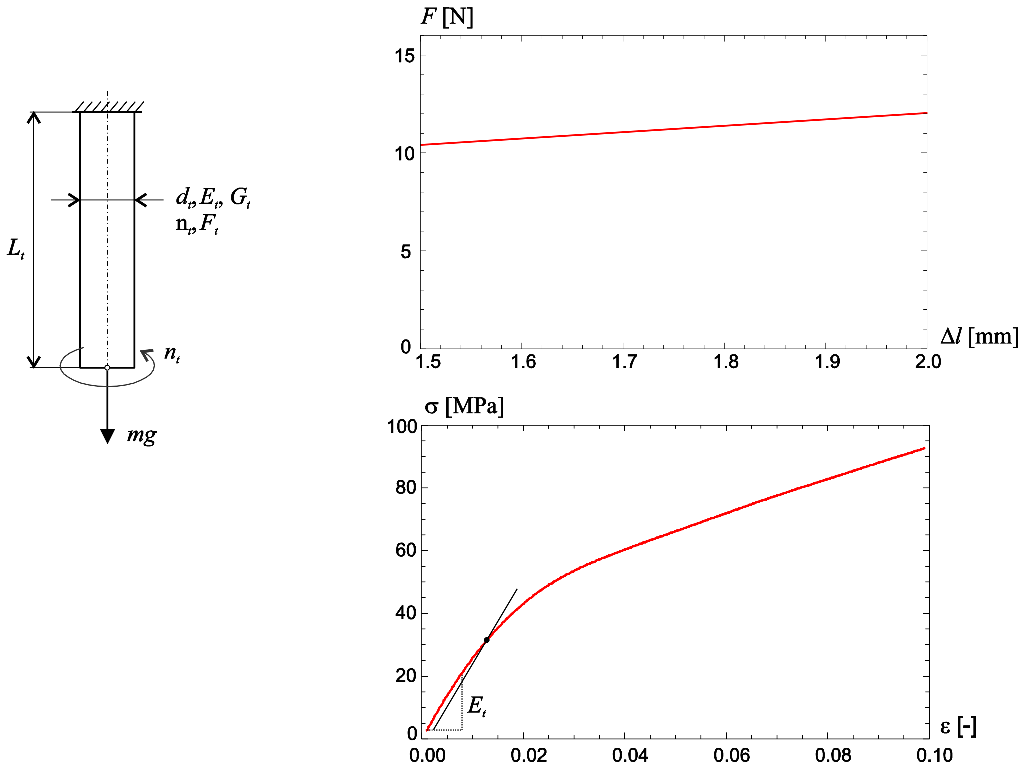

Fig.3:*To measurement of the material properties and prestress force of the twisted the fishing line.*

By inserting additional twist the coiled spring with n = 116 turns is obtained (Fig.4) with the length L_c = 79.7 mm and the mean radius R_c = 0.7175 mm (see also Fig.5). The prestressing force is $F_c = F_t$ = 5.5 N and the spring constant is k_c = 2000 N/m. After removing of the mass m, the spring is partially unwound to a steady state in which the prestress force decreases to F_c = 1.3 N and the spring constant is k_c = 103 N/m. In that state, the energy in the actuator is much lower, but the future handling of it is user friendlier. Changing of the material properties and the diameter of the twisted line after coiling is negligible. The above measured values are the mean values from the 5 times repeated measurements.

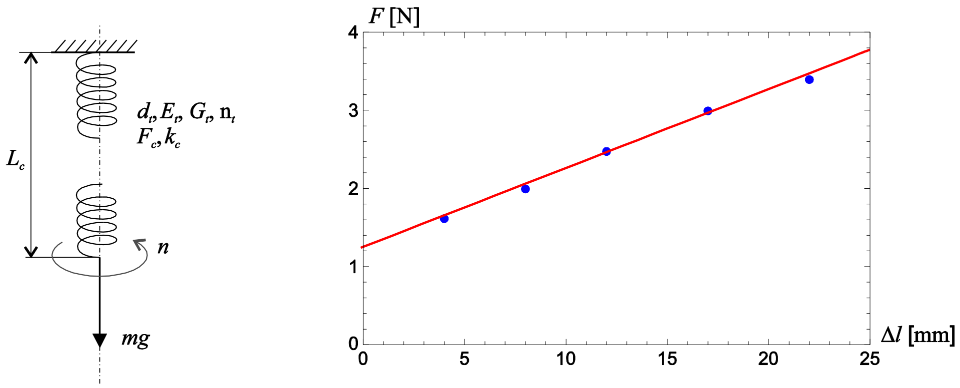

Fig.4:*To measurement of the spring constant and prestress force of the coiling spring.*

4. Modelling and numerical simulation of the artificial muscle

Fig. 5shows the coiled spring loaded by vertical load $F = mg$, m is the mass of the applied load and g is the gravity. Further, $L_c = nd_t$ is the coiled sprig length, n is the number of turns, d_t is the diameter of the twisted fiber and R_c is the mean radius of the coiled spring. The adjacent coils contact that means the pitch of the spring is equal to the diameter of the twisted fiber d_t. An elongation ΔL_c of the pre-stressed spring is expressed as:

$$\Delta L_c = \frac{4R_c^3 n\left(F - F_c\right)}{G_t r_t} \qquad (1)$$

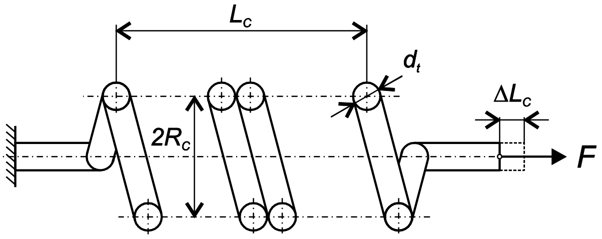

Fig. 5:*Computational model of the coiled spring.*

In (1), G_t is the shear modulus of the twisted fiber and F_c is the prestressing force in the coiled spring. Both parameters are obtained by the measurements presented in chapter 3.

For the coiled spring(see Fig.1 and Table 1), the FEM model is created (Fig 6). Elastostatic linear and nonlinear analysis is performed using 31500 number of BEAM188 finite element [13](there is insignificant difference arose between both the approaches).

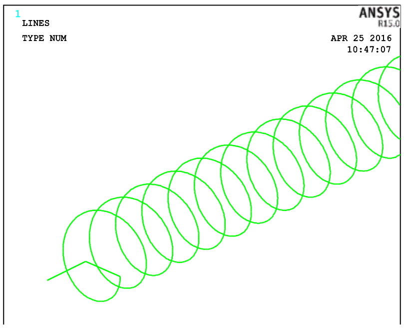

Fig. 6: FEM model of the muscle.

A dependence of thecoiled spring elongation on the applied vertical load is shown in Fig. 7.

Tab. 1.*Results of the numerical analysis and measurement.*

	m [kg]	*F*[N]	Δ*l*[mm]		
			Expression (1)	*Measurement*	*FEM*
1	0.13	1.3	0	0	0
2	0.15	1.47	2.2	3	2.4
3	0.20	1.96	8.4	8	9.5
4	0.25	2.45	14.6	13	16.5
5	0.30	2.94	20.9	19	23.4
6	0.35	3.43	27.1	25	30.21
7	0.40	3.92	33.4	-	37.0
8	0.45	4.41	39.6	-	43.6

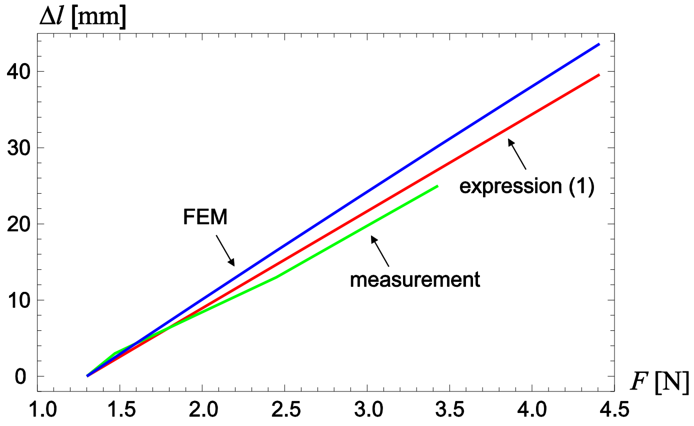

Fig. 7: Elongation of the coil.

As shown in Fig.7, a good agreement of the calculated and measured results is obtained.

5. Conclusion

In the proposed paper, the experimental measurement are done to specify the mechanical properties of the untwisted and twisted fishing line, as well the spring constant of the coiled spring (as an artificial muscle). The prestressing force in the twisted line and in the coiled spring is measured as well. Linear and non-linear elastostatic analysis is performed using the BEAM188 finite element [13]. An analytical approach is also used for the calculation of the elastic elongation of the artificial muscle. The calculated results are compared with the experimentally measured elongation of the artificial muscle caused by additional mechanical load. A good agreement of the measured and calculated results is obtained. In the further work, a thermal-elastic analysis of the artificial muscle will be done and experimental verification of the obtained results will be accomplished.

Acknowledgement

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