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Deformational Behavior and Strength of Catheter Reinforced with Braids (Visco-elastic Response under Multi-axial Loading for Tension and Torsion)

Y. Kato and Y. Yamamura

Summary

The purpose of this study is to investigate the deformational behavior and strength of the catheter which is made from the soft nylon resin and is reinforced with thin stainless wires called braid. When we image the usage conditions of catheter in the actual surgical operation, it is expected that the multi-axial loading for tension, torsion and the bending are applied and deformations occurring in the catheter become very complicated.

As the first step of this study to reveal these phenomena, the combined loadings for tension and torsion are chosen as the subject of this study and we carry out these experiments and investigate the visco-elastic response influenced by the existence of braids. Especially, although the direction of the principal axis of stress rotates in the space with changing the ratio of tension and torsion variously, we examine how the relation between the direction of the principal axis of stress and the direction of braid in the catheter influence the visco-elastic behavior.

Introduction

Generally, soft characteristic is required as the materials of catheter so as not to damage the urethra and the vascular wall etc. during insertion of the catheter. On the other hand, as for the catheters used in the surgical operation such as the myocardial infarction and the cerebral infarction, the relatively long catheters are often used, and it is necessary to make the tip of the catheter arrive at a target region by remote manipulation smoothly, then the superior operationality is required. Therefore, not only a soft characteristic but also the responsiveness and enough rigidity are necessary as the properties of material of the catheter. As the usage of the catheter spreads as mentioned above, various catheters according to the request of user have been developed. However, evaluations of the quality for the catheters depend on sensation and experience of doctors who actually uses those catheters, and the details of the studies on the mechanical properties of a material and the deformational behaviors of catheters are hardly revealed. Hence we take note of this theme, and the catheter composed from different kind of materials which is made from the soft nylon resin and is reinforced with thin stainless steel wires called braid is chosen as the subject of this study, and we will reveal the mechanical property of this catheter in this paper.

In our previous study, we ever have made clear the effect on reinforcement of braids and the visco-elastic property of catheter by investigating the stress response under the uni-axial tension, and the analytical model concerning an elastic modulus was suggested by considering the internal pressure which is caused by the difference of the Poisson's ratio between stainless steel wire and nylon matrix, moreover the validity of this model has been confirmed by comparing with the experimental results of uni-axial tensile tests. However, when we image the actual surgical operation, it is expected that the multi-axial loading for tension, torsion and the bending are applied in the catheter, and deformations produced in the catheter become very complicated.

As the preliminary step to reveal these phenomena, the visco-elastic responses under the combined loadings for tension and torsion are investigated in this paper. Especially, performing experiments of stress relaxation under proportional loading by changing the ratio of the tension and the torsion variously, we investigate the stress response under the step strain, and we elucidate how the relative angle between the direction of the principal axis of stress and the direction of braid influences the visco-elastic property. Moreover, the analytical model under the combined loading of tension and torsion are proposed and the results of numerical calculation are compared with the experimental results.

Configuration of Catheter Reinforced with Braids and the Deformation

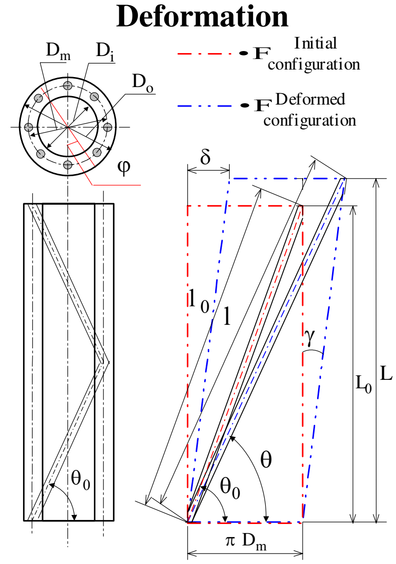


Figure 1: Configuration of catheter reinforced with braids

The relation between initial undeformed configuration and deformed configuration of the catheter under applying the combined loading of tension and torsion is illustrated schematically in Figure 1. As mentioned in the introduction, the catheter treated in this paper is composed of the matrix made from soft nylon resin (outside diameter D_o, inside diameter D_i, mean diameter D_m and one pitch length L_o) and braids, i.e. thin stainless steel wires (diameter d_b, one pitch length $\ell_o$and angle of braidθ_o). These braids consist of 16 wires, and 8 wires within them are woven in the clockwise direction and the remains are anti-clockwise direction. In this figure, the configuration of the catheter per one pitch, i.e. the axial advance per one revolution, is illustrated by taking note of a single wire. When we image the deformed state of the catheter, the matrix is stretched from L_o to L in the longitudinal direction and simultaneously the matrix is twisted by φu Then a braid also changes its length and direction, and the initial length of the braid ℓ_o turns into the current length ℓ and the initial angle of braid $\theta_o$also turns intoθ. Here, extensional strains for the matrix and the braid are expressed as follows.

$$\varepsilon = ln(L/L_o), \quad \varepsilon_b = ln(\ell/\ell_o) \tag{1}$$

Moreover, the relation between the extensional strain of the matrix and the extensional strain of braid can be derived as equation (2) in consideration of geometrical relations.

$$\varepsilon_b = ln\left(\frac{L\,sin\theta_o}{L_o sin\theta}\right) = \varepsilon + ln\left(\frac{sin\theta_o}{sin\theta}\right) \tag{2}$$

Thus these strains are dependent on each other. On the other hand, the shearing strain is represented as

$$\gamma = \frac{\delta}{L_0} = \frac{\varphi}{L_0}\frac{D_m}{2} \tag{3}$$

In the experiments, three types of different test pieces were adopted, and. these inside and outside diameters and the ratio of total area to the matrix area, i.e., $\alpha = A_m/A$, are indicated in the Table 1. Further, the gauge length of all test pieces is the same and it is 190 [mm].

Table 1: Configuration of catheter and ratio of total area to matrix area

Type of test peace	Outsides diameter Do [mm]	Inside diameter Di [mm]	Ratio of matrix-area α [-]
Contain braid No.1	1.37	1.07	0.921
Contain braid No.2	1.67	1.14	0.938
Contain braid No.3	2.01	1.40	0.962

Experimental Conditions

The multi-axial loading test machine used in the experiments is shown in Figure 2. This test machine has a system that can apply the tension and torsion at the same time by combining the torsional test machine with the tensile test machine. The experiments of the stress relaxation are performed under the step strain. Namely, the tension and the torsion are applied at the same time with the constant speed and after that the displacements generated by these loads are fixed simultaneously and are held constant until 3000 [sec.]. Here, the tension speed and the torsion speed for each direction of the principal axis of stress are indicated in Table 2.

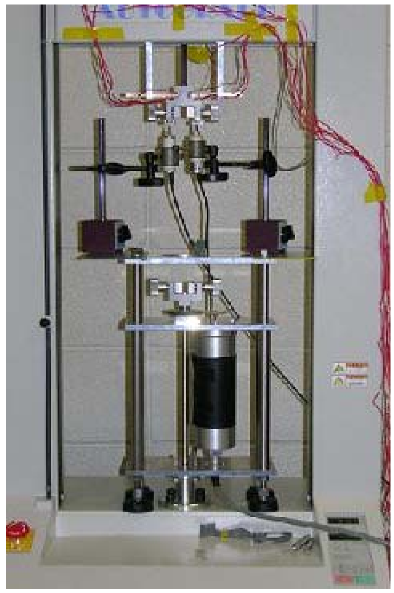


Figure 2: The multi-axial loading test machine

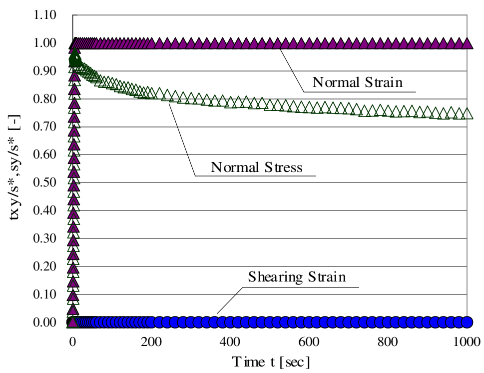
Table 2: Tension speed and torsion speed for each direction of principal axis

The direction of principal axes [deg.]	45.0	61.0	75.2	90.0
Tension speed [mm/sec.]	0	3.0	7.0	5.0
Rotational speed for torsion [r.p.m.]	1.0	1.0	1.0	0

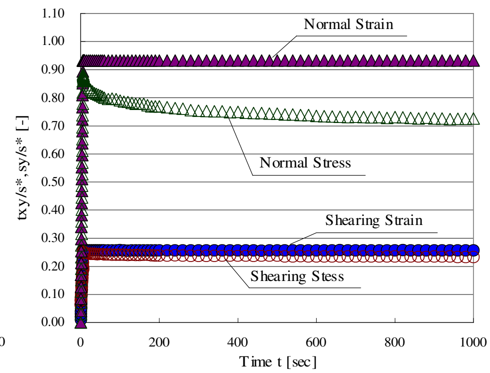
Experimental Results

The experimental results of stress relaxation for each principal axis are indicated from Figure 3(a) to Figure 3(d), where, these figures are the results of the specimen No.1 and are described until 1000 [sec.] when the stress approaches the certain constant value, and the angles of braid in these figures are the same, i.e.θ_o = 45[deg.].

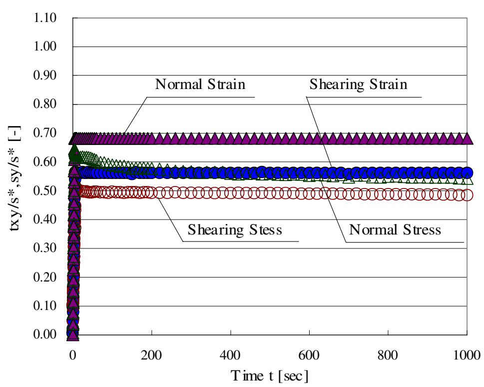
Figure 3(a) shows the experimental results of uni-axial tension, i.e., the direction of the principal axis of stress is 90[deg.]. Here, triangular plots in this figure signify the normal stress and it gradually decreases and approaches the constant value with the passage of time. Figure 3(b) and (c) show the experiment results of 75.2[deg.] and 61[deg.] respectively, which are obtained by applying the tension and the torsion simultaneously. Figure 3(d) is the experimental results of uni-axial torsion, i.e. the direction of the principal axis of stress is 45[deg.]. In order to compare these results under the same condition, the stress and strain in each figure are represented as the non-dimensional value by dividing the stress and strain with each principal value (σ^*).



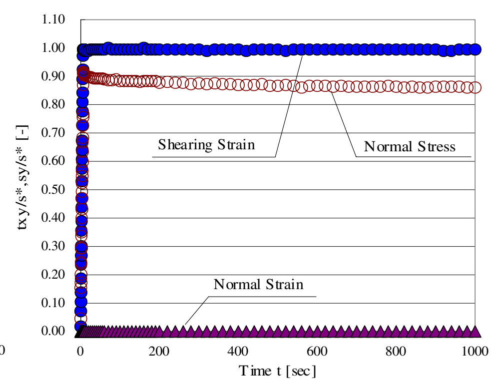
(a) Principal axis 90[deg.]



(b) Principal axis 75.2[deg.]



(c) Principal axis 61.0[deg.]

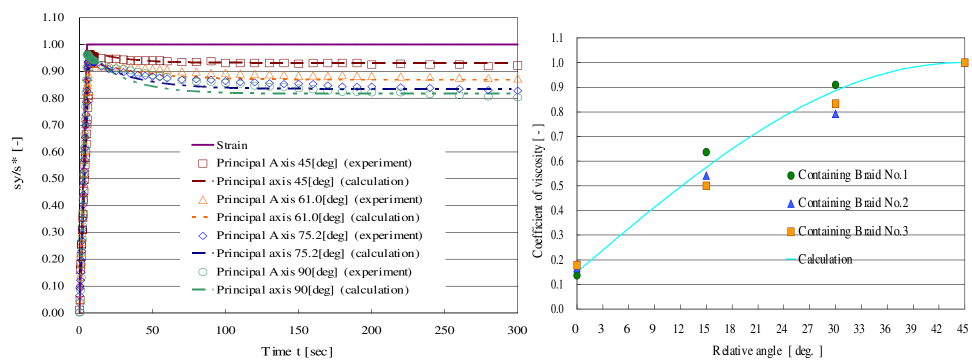


(d) Principal axis 45[deg.]

Figure 3: Stress relaxations for each principal axis (Braid angle; 45[deg.])

The decreasing tendency of stress in the uni-axial tension (90[deg.]) appears larger than in the uni-axial torsion (45[deg.]). Hence, the phenomenon of the stress relaxation arises in the uni-axial tension more than uni-axial torsion (see Figure 3 (a) and (d)). It can be explained that since the direction of braid and the principal axis of stress for torsion coincide with each other, the effect of braid that reduces the viscosity of catheter occurs largest in this direction. In the case of multi-axial loading state shown in Figure 3(b) and (c), we cannot clearly estimate the effect of braid that reduces the viscosity of catheter by only separately investigating the phenomenon of each stress relaxation of the normal stress and the shearing stress. Then we calculate the principal stress$\sigma_2$from those two stress components, and examine the phenomenon of stress relaxation on the principal axis. Hence, by performing such normalization, we can compare the experimental results from 90[deg.] to 45[deg.] under the same condition.

Figure 4(a) shows the experimental results on each principal axis obtained after performing such normalization. Since phenomena of the stress relaxation reduce in the order of 90,75.2,61.0 and 45 [deg.], it is clear that the effect of braid that reduces the viscosity of catheter more appear when the relative angle between the direction of the principal axis of stress and the direction of braid is smaller. Figure 4(b) shows the relation between the coefficient of viscosity, i.e. Newtonian viscosity, and the relative angle.



(a) Stress relaxations on each principal axis (b) Coefficient of viscosity

Figure 4: Relation of stress relaxation and principal axes (Braid angle; 45[deg.])

Moreover, the analytical model under the combined loading of tension and torsion are proposed in consideration of the relation in Figure 4(b). In Figure 4(a), these numerical results are compared with the experimental results, and we can confirm from this figure that the analytical results agree well with experimental values.

Concluding Remarks

Performing experiments of stress relaxation under proportional loading by changing the ratio of the tension and torsion variously, the effects of the braid which reduces the viscosity of the catheter were revealed by investigating the stress relaxation in the various direction of the principal axis of stress. As a result, it could be confirmed that not only the volume ratio of the material but also the angle of the braid is related to the visco-elastic property of catheter.

References

1. Aleksey D.Droxdov, (1996): *Finite Elasticity and Viscoelasticity*, World Scientific