Effect of Diameter Ratio on Loop Strength of Nylon Guts and Stainless Steel Filaments

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Abstract

The loop strength of nylon guts and soft stainless steel filaments was measured and the relation between it and the load-elongation curve in simple tensile test was investigated. The results obtained are as follows:

1. The loop strength of samples used increases with increasing the diameter ratio. The degree of increase is dependent upon the tensile breaking strain of samples.
2. The following experimental equations were obtained for nylon guts:

$$\Delta e = \varepsilon e_{mo} \dots (a), \quad e_{mo} = 1 / (1 + \varepsilon_r \gamma_{do}) \dots (b)$$

where Δe is the decrease of strain which is defined as the difference between the tensile breaking strain and its tensile strain at the breaking point in the loop test, e_{mo} is geometric bending strain calculated from the micrographs of the hooked part, γ_{do} is diameter ratio, and ε and ε_r are constants independent of the diameter ratio. Therefore, the loop strength for a given diameter ratio can be estimated from both the above equations and their load-elongation curves obtained by simple tensile tests.

1. Introduction

In the previous paper^[1], it was pointed out that:

- 1) The loop strength of nylon, polyester, and soft stainless steel fibers decreases with decreasing the tensile breaking strain.
- 2) It is estimated by scanning-electron-microscopic observation of the rupture surface that the rupture of a nylon filament in the loop test begins at the outer side of the bending part.
- 3) If it is assumed that the rupture of a filament in the loop test takes place at the region where the sum of the bending strain e_m and the tensile strain e_f has just reached the breaking strain e_B obtained in the simple tensile test of the filament, the decrease of breaking strain (defined as the difference between the breaking strain e_B in the tensile test and the tensile strain e_{fb} at the breaking point in the loop test) should be nearly equal to the bending strain e_m ($e_{fb} \ll 1$).
- (4) This bending strain e_m decreases with decreasing e_B , and the experimental equation $\Delta e = e_m = B e_B$ is obtained. where B is 0.56 for nylon 6 and 0.95 for stainless steel filaments respectively.
- 5) Above results being approved, the loop strength can be estimated from the simple tensile load-elongation curve, since on this curve the load at the point where strain is equal to $(e_B - \Delta e)$ should be one half of the loop strength.

However, the measurement of this bending strain e_m by photo-elasticity was so difficult that the validity of the above assumption in 3) could not be ascertained.

In this report, firstly, the shape of the broken end and its position are surveyed microscopically to examine the propriety of the above assumption on the rupture condition in the loop test. Secondly, the loop strength of a sample hooked on other single filament of different thicknesses is measured to clarify the effect of the bending strain e_m induced by bending. On the other hand, geometrical bending strain e_{mo} at different diameter ratios (the ratio of the diameter of a filament to that of the specified sample) is calculated from photographs of the bending part just before broken. Then, the relationship between e_{mo} and $e_m (= \Delta e)$ is investigated, and finally it is discussed whether the loop strength at different diameter ratios could be estimated from the simple tensile load-elongation curves.

Moreover, two filaments having about the same thickness but different breaking strain e_B are hooked to investigate whether there were a rule concerning which filament of them is broken in the loop test.

2. Definition of Terms

Loop strength ratio: Ratio of one half of the loop strength to the simple tensile breaking strength.

Sample: Weaker filament which is subjected to the loop test, and arranged so that this filament may always break and the other filament or filaments hooked on may always remain unbroken.

Diameter ratio: Ratio of diameter D_{02} of a filament to diameter D_{01} of the sample.

Decrease of strain: Difference between the breaking strain in the simple tensile test and the tensile strain e_{fb} at the broken point in the loop test.

N gut: Nylon gut

SS filament (or SS): Soft stainless steel filament

HS filament (or HS): Hard steel filament for a fishing line.

3. Experimental Method

3.1 Effect of diameter ratios

A. Filaments

Commercial N guts, SS filaments, and HS filaments were used, the diameter of which are shown in Table 1 (a). Other properties are tabulated in Table 1 (b).

B. Combination of two filaments hooked mutually

Combination of filaments tested, and their diameter ratios are shown in Table 2.

Diameters of samples used in IB and IIB are larger than those in IA and IIA, respectively, so that the loop test may be performed at the diameter ratio smaller than unity.

Table 1. Samples used

(a) Diameters

Samples	Diameters (mm)
N (nylon) gut	0.129, 0.171, 0.290, 0.370
SS (Soft stainless steel) filament	0.025, 0.030, 0.040, 0.050, 0.10, 0.20
HS (hard steel) filament	0.102, 0.130, 0.171, 0.194, 0.250

(b) Notation, diameters and tensile properties

	Notation	Diameter (mm)	Breaking strength (kg/mm ²)	Breaking strain (%)
N gut	N 06	0.129	76.2	28.5
	N 1	0.171	82.4	29.7
SS filament	S 2	0.025	85.2	29.4
	S 2'	0.024	92.8	9.9
	S 20	0.20	76.4	42.0

Table 2. Combination of filaments hooked and their diameter ratios

Notation	Combination	Samples	Diameter ratio
IA	N gut-N gut	N06	1.00, 1.33, 2.25, 2.87
IB	N gut-HS	N1	0.60, 0.76, 1.00, 1.14, 1.46
IIA	SS-SS	S2	1.00, 1.20, 1.60, 2.00, 4.00
II A'	SS-SS	S2'	
II B	SS-HS	S20	0.65, 0.86, 0.97, 1.25

Table 3. Tensile properties of filaments having different tensile breaking strain

Sample	Notation	Tensile properties		
		Breaking Load (g)	Strength (kg/mm ²)	Strain (%)
20d Nylon	N (46)	122.3	61.2	46.0
	N (24)	137.1	77.5	24.6
20d polyester	E (24)	102.2	63.0	24.5
	E (15)	103.6	67.9	15.5
N gut (N1)	N1 (G)	1830	79.7	27.4
	N1 (C)	1600	69.7	32.0

C. Simple tensile tests and loop tests

Tensilon made by Toyo Measuring Instrument Co. was used to measure the simple tensile strength and the loop strength. The load-elongation curves were obtained at 20°C and 65% RH at the strain rate of 100%/min. The distance between the upper and lower chucks was 100 mm.

3.2 Loop tests between two filaments which have about the same thicknesses but different tensile breaking strains.

Samples having different breaking strains were made by drawing commercial polyester and nylon filaments and N guts in a water bath at 70°C. The tensile breaking strengths and strains of these samples are shown in Table 3.

4. Results and Discussion

4.1 Effect of diameter ratios

A. Change of loop strengths with diameter ratios

The loop strength ratios obtained are plotted in Fig. 1 against the logarithmic diameter ratio.

In general, the loop strength ratio increases with increasing the diameter ratio. The loop strength ratio in the combination of SS filament-SS filament (IIA) rapidly increases to nearly 100% at the diameter ratio of 1.6. On the other hand, the loop strength ratio in the combination of N gut-N gut (IA) does not increase so largely, and is 81% at the diameter ratio of 3.

The loop strength ratio of N gut in the combination of N gut-HS filament (IB) is much larger than that in the combination of N gut-N gut at the same diameter ratio. Thus, the loop strength ratio versus diameter ratio curve for N gut-HS filament (IB) shifts to the left side. The loop strength ratio of SS filament in the case of SS-HS is larger at the diameter ratio of unity than that in the case of SS-SS, but nearly the same in both cases at larger diameter ratios. From these results, it is found that the loop strength ratio is remarkably affected both by the nature of the filament hooked on and the diameter ratio.

Moreover, the loop strength ratio of S2' (made by drawing SS filament S2 by 20% to give 9.9% tensile breaking strain which is lower than that of the original sample S2) is about 10% smaller than that of S2, as expected from the result in the previous paper^[1].

B. Shapes and positions of broken ends

It is unquestionable that the filament rupture in loop test usually takes place at the bending part. However, it serves as a good reference for investigating the breaking mechanism to ask at what position the rupture takes place. Therefore, the bending part was divided into four parts, A, B, C, and D, as shown in Fig. 2 (a), and the distribution of the rupture position was surveyed. The results are tabulated in Table 4.

For 20 d nylon used in the previous study^[1], those samples having tensile breaking strain of 41.3% break almost at A or B, and the frequency is about the same. However those having smaller breaking strain break almost at A.

For N gut-N gut, the samples N06 having the breaking strain of 28.5% break almost at A when the diameter ratio is unity. As the diameter ratio increases, however, the frequency of B increases. When the diameter ratio is 2.87, the frequency of B is very large, and that of C reaches to one-third.

Although this result may be caused by friction at the inside of the bending part, yet the lateral compression at the inner side seems to play an important part in this case, because the sample is wrapped by the opposite thick filament as shown in Fig. 3.

For N gut-HS filament, almost the same results are obtained as those for N gut-N gut. At the diameter ratio of 1.13, however, a few specimens break at D. As the diameter ratio increases, the frequency of D seems to increase.

Fig. 1 Loop strength ratio versus diameter ratio

○: N gut-N gut (IA); ×: SS-SS (IIA) ⊖: N gut-HS (IB); *: SS-HS (IIB) *: SS-SS (IIA')

(a) Broken positions

(b) Broken shapes

Fig. 2 Classification of broken shapes and broken positions

Fig. 3 Bending parts of a N gut(No6) just before broken in case of N gut-N gut

So, the breaking mechanism assumed in this study may be inappropriate to explain the rupture at such a large diameter ratio.

For SS filament-HS filament, the rupture always takes place at A, at the diameter ratio of 0.86 but does not take place at A and mostly at C at the diameter ratio of 1.25. So, it is found that the distribution of rupture position is charac-

teristic for SS filament-HS filament, and the breaking mechanism of SS filament may be a little different from that of N gut.

When the loop strength ratio is above 90% and the scatter of tensile breaking strength is larger, some specimens of nylon or polyester filaments break near the chuck or at a straight portion (not shown in Table 4). On the contrary, SS filaments break at the bending part, even if their loop strength ratio is above 90%.

From these results, it is found that the assumption in the previous paper^[1] for the breaking mechanism in the loop test is appropriate for the study in this paper.

The shapes of breaking ends in the loop test are grouped into three types, X, Y, and Z as shown in Fig. 2 (b), and their proportions are shown in Table 4. There were no obvious correlations among them.

C. Observation of bending parts

Fig. 3 shows micrographs of samples N06 just before broken. Fig. 3 (b) was taken when the samples were rotated around the axis of stretching by 90° from those in Fig. 3 (a).

The bending part of this sample N06 is wrapped in and compressed at both sides by the thicker filament. This is the reason why many samples break at B or C as mentioned above.

When N1 is hooked on HS filament of different thicknesses, the cross-section of the bending part is flattened especially at a larger diameter ratio (see Fig. 4). Young's modulus of steel is in the order of 10^4 kg/mm² which is much larger than that of N gut ($3-4 \times 10^2$ kg/mm²), and the moment of inertia

Table 4. Shapes of broken ends and their positions

Sample	Diameter ratio	Broken position (%)				Shape of broken end (%)			
		A	B	C	D	X	Y	Z	
N 06 (Ngut-Ngut IA)	1.00	88.9	11.1	0	0	63.0	33.3	3.7	
	1.33	51.7	48.3	0	0	58.6	27.6	13.8	
	2.87	7.1	60.7	32.1	0	67.9	17.9	14.3	
N 1 (Ngut-HS IB)	0.76	92.3	7.7	0	0	76.9	5.1	18.0	
	1.00	94.6	5.4	0	0	83.8	5.4	10.8	
	1.13	55.3	38.3	4.3	2.1	74.5	8.5	17.0	
	1.46	38.8	42.9	10.2	8.1	71.4	10.2	18.4	
S 20 (SS-HS II B)	0.86	100.0	0	0	0				
	0.97	40.0	52.5	7.5	0				
	1.25	0	12.5	87.5	0				
Breaking strain(%)									
20d nylon	41.3	1.00	48.1	51.9	0	0	75.0	17.9	11.2
	33.0	1.00	79.3	20.7	0	0	55.2	34.5	10.4
	24.2	1.00	74.3	20.0	5.7	0	48.5	51.4	0
	21.5	1.00	89.2	8.1	2.7	0	43.2	56.8	0
20d nylon	41.3	normal					82.4	5.9	11.8
	33.0	tensile					66.7	25.9	7.4
	24.2	test					78.1	15.5	6.3
	21.5						58.3	41.7	0

Fig. 4 Bending parts of a N gut(N1) just before broken in the combination of N gut-HS; Diameter of HS filament: (a) 0.102, (b) 0.194, (c) 0.250

Fig. 5 Schematic diagram of the bending part in a loop test

of a circular-section is proportional to the fourth power of its diameter. Therefore, the flexural rigidity of HS filament rapidly increases with increasing the diameter. As a result, the curvature of the bending part of the thick HS filament is small, and so the cross-section of N gut is considerably flattened (the ratio of the major axis to the minor axis is about 3 for the sample in Fig. 4 (c)).

A schematic diagram of the bending part in a loop test is shown in Fig. 5. In this figure, the sample is drawn parallel with the sheet (different from its position in Fig. 4).

As mentioned in the previous paper^[1], it is difficult to decide the position of the neutral axis in the bending part. Therefore, the following equation is assumed:

$$\rho_n = (R_1 + R_2)/2 = D_1/2 + R_2 \dots \dots \dots (1)$$

where ρ_n is the radius of curvature of the sample's neutral axis in the bending part. The geometrical bending strain e_{mo} at outside of the bending part is defined as

$$e_{mo} = D_1/2\rho_n = 1/(1 + \gamma_d) \dots \dots \dots (2)$$

$$\gamma_d = 2R_2/D_1 \dots \dots \dots (2)$$

Figs. 3 and 4 were enlarged to measure R_1 , R_2 , and D_1 . ρ_n and e_{mo} calculated from eqs. (1) and (2) are plotted in Fig. 6. ρ_n for N gut-HS filament is smaller than that for N gut-N gut. This may be because:

Fig. 6 Geometric bending strain, radius of curvature of neutral axis, and diameter ratio; $\odot$: N gut-N gut, $\ominus$: N gut-HS

Fig. 7 D_1 -versus diameter ratio; $\odot$: N gut-N gut, $\ominus$: N gut-HS

- (1) R_2 of HS filament is nearly equal to the radius of the straight part. But R_2 of N gut is larger than the radius of the straight part, owing to the distortion of the bending part;
- (2) The cross-section of the sample in the case of N gut-HS filament is flattened to decrease D_1 .

As the diameter ratio increases, D_1 increases in the case of N gut-N gut, but decreases in the case of N gut-HS filament to show smaller values than that in the former case (Fig. 7). Thus, the calculated e_{mo} in Fig. 6 is about the same in both cases.

Let define ϵ_r with the following equation:

$$\gamma_d = \epsilon_r \gamma_{do} \dots \dots \dots (3)$$

Then, we obtain from eq (2):

$$e_{mo} = 1/(1 + \epsilon_r \gamma_{do}) \dots \dots \dots (4)$$

This ϵ_r is a coefficient depending upon the degree of cross-sectional distortion of the bending part. Broken lines in Fig. 6 are calculated values of e_{mo} for three ϵ_r values 1, 1.3 and 1.5. Although the loop strength ratio for N gut-N gut is smaller than that for N gut-HS filament, the values

Fig. 8 Decrease of strain Δe versus diameter ratio: $\odot$: N gut-N gut(IA), $\ominus$: N gut-HS(IB), $\times$: SS-SS (IIA) $\ast$: SS-HS (II B)

Fig. 9 Decrease of strain Δe versus geometric bending strain e_{m0}
 $\odot$: N gut-N gut, $\ominus$: N gut-HS

of e_{m0} in both cases are the same at the diameter ratio of unity. This may be caused by the following reasons: (1) In the case of N gut-N gut, the specified sample is wrapped in and compressed at both sides by the other filament. (2) In the case of N gut-HS filament, the neutral bending axis of N gut may be shifted towards the outside owing to the large cross-sectional distortion of N gut as shown in Fig. 4. As a result, the bending strain e_m is much decreased in comparison with the case of N gut-N gut.

D. Decrease of strain

The decrease of strain, Δe , defined above was obtained from the simple tensile load-elongation curve by the same method as in the previous paper^[1], and is plotted in Fig. 8 against the diameter ratio on a log-log scale.

As the diameter ratio increases, Δe for SS filament-SS filament rapidly decreases, and the loop strength ratio increases to nearly 100%. For N gut-N gut, however, Δe decreases more gradually with increasing the diameter ratio, and the loop strength ratio does not increase so much. Δe for N gut-HS filament is smaller than that for N gut-N gut, and the loop strength ratio for the former is larger than that for the latter. Δe for SS filament-HS filament is larger than Δe for SS filament-SS filament, since the tensile breaking strain of the former sample is larger than that of the latter (refer to the previous paper).

The relation between Δe and e_{m0} for N gut-N gut and N gut-HS filament is approximately linear as shown in Fig. 9, and can be expressed by:

$$\Delta e = \varepsilon e_{m0} \dots \dots \dots (5)$$

where ε is a constant, and is 0.394 for N gut-N gut and 0.234 for N gut-HS filament. From these results, it is found that the geometric bending strain e_{m0} is an important factor of Δe or α . Moreover, it is reasonable to assume that e_{m0} decreases at a constant rate ε in case of N gut-N gut or N gut-HS filament, and the real bending strain e_m becomes εe_{m0} . From this assumption, the effect of the diameter ratio on the loop strength is quantitatively accounted for.

If the load f in the simple extension of N gut is a function of the tensile strain e , and represented by

$$f = F(e), \dots \dots \dots (6)$$

the loop strength f_L and the loop strength ratio α of N gut are expressed as follows:

$$f_L = 2F(e_B - \Delta e) \dots \dots \dots (7)$$

$$\alpha = f_L / 2f_B = F(e_B - \Delta e) / F(e_B) \dots \dots \dots (8)$$

$$\Delta e = \varepsilon e_{m0} = \varepsilon / (1 + \varepsilon r \gamma_{d0}) \dots \dots \dots (9)$$

On the other hand, as found from the results in Fig. 8, the following experimental equation holds for all the samples used:

Table 5. Values of c and n in eq. (10)

Notation	Samples	Combination	C	n
I A	N 06	N gut-N gut	0.147	0.434
I B	N 1	N gut-HS	0.095	0.693
II A	S 2	SS-SS	0.200	0.153
II B	S 20	SS-HS	0.262	0.647

Fig. 10 Loop strength ratio versus numbers of filaments hooked on; $\odot$: N gut (N1), $\times$: SS filament (S2) $\triangle$: Polyester E(24), $\triangle$: Polyester E(14)

$$\Delta e = C \gamma_{do}^{-n} \dots \dots \dots (10)$$

where C and n are constants shown in Table 5.

Although the physical meaning of C and n is ambiguous, the loop strength for different diameter ratios can be obtained from eq. (7) or the simple tensile load-elongation curve by using Δe calculated from eq. (10). C represents Δe at the diameter ratio of unity, and takes a large value for large breaking strain e_B and/or ε in eq. (5)

E. Loop strength when hooked on numbers of filaments

Fig. 10 shows the loop strength ratio hooked on a bundle composed of numbers of filaments in place of a single filament. The characteristics are summarized in Table 3, excepting the sample E(14) which was made by drawing the sample E(24).

The loop strength ratio increases with increasing the number of other filaments, especially with the change from 1 to 2.

Micrographs of the bending part of N gut just before broken are shown in Fig. 11. e_{mo} calculated from them is plotted with dot in Fig. 9. Almost the same relation is obtained, between Δe and e_{mo} as that for N gut-N gut (IA), because the cross-section of bundled filaments is so distorted that the sample hooked on the bundle is smoothly bent as shown in Fig. 11.

Fig. 12 shows the simple tensile load-elongation curves of various samples which are normalized in order that their breaking load and elongation may be unity. The loop strength ratio of the sample N1 at the diameter ratio of unity is equal to the load value at the elongation of 0.44 ($=1 - \Delta e/e_B$) on this normalized curve, because $\Delta e/e_B$ obtained for N1 in the previous paper^[1] is 0.56, which is equal to the decrease of the normalized strain. If it is assumed that $\Delta e/e_B$

Fig. 11 Bending parts of a N gut hooked on numbers of N guts and stretched until just before broken

Fig. 12 Normalized load-elongation curves of various samples

for polyester samples is about the same as that for nylon gut N1, the loop strength ratio of E(14) and E(24) must be larger than that of N1, and that of E(24) larger than that of E(14), as found from Fig. 12. Furthermore, as the diameter ratio increases, Δe decreases so that the point $(1 - \Delta e/e_B)$ on the normalized load-elongation curve shifts to the right, and thus the loop strength ratio must increase along the curve in Fig. 12. Actually, each loop strength ratio of samples in Fig. 10 increases with increasing diameter ratio, as estimated from Fig. 12.

4.2 Loop test of various samples

Results of the loop test of various samples are tabulated in Table 6. In this case two filaments hooked each other have about the same thickness but different breaking strains (See Table 3). Table 6 represents the proportion that the sample in the left column is broken with the filaments shown in the upper column. Sample E(15) having the smallest breaking strain is always broken at a large percentage not less than 80%. Although there are cases where two filaments hooked each other break at the same time, these specimens are excluded from the percentage calculation. Sample N1 (G) is always broken with sample N1 (C) which has larger breaking strain than N1 (G), though the breaking strength of N1 (G) is larger than that N1 (C). This sample N1 (C) is sold as a gut having better quality and larger loop strength ratio than

Table 6. Proportion of broken samples in the loop test

Samples observed		Opposite filaments			
		N (46)	N (24)	E (24)	E (15)
Nylon	N (46)	—	7	10	0
Nylon	N (24)	93	—	44	10
Polylster	E (24)	90	56	—	20
polylster	E (15)	100	90	80	—

Samples		Opposite filaments		
		N1 (C)	N1 (G)	N1 (C')
N gut	N1 (C)	—	0	35
N gut	N1 (G)	100	—	57
N gut	N1 (C')*	65	43	—

* N1 (C') was made by drawing N1 (C) to let it have about the same breaking strain of 26.0% as that of N1 (G).

N1 (G). However, N1 (C') which is prepared by drawing N1 (C) to give about the same breaking strain as N1 (G) is broken at a large percentage (43%) with N1 (G). It is concluded from these results that the sample of smaller breaking strain is broken at larger percentage in this experiment. Although the loop test between polyester and nylon filaments should be carried out to insist this conclusion, such samples as having the same thickness could not be prepared.

On the other hand, the sample heat-treated above 160°C for nylon or above 200°C for polyester has a tendency to have smaller loop strength ratio than the untreated sample. Hence, it must be borne in mind that the loop strength is affected by heat-treatment besides its tensile breaking strain. Among samples shrunk to different lengths by heat-treatment, however, the larger their breaking strain is, the larger their loop strength ratio is.

5. Summary

A. The loop strength of N guts and SS filaments was measured, and the relationship between the diameter ratio and the geometrical bending strain, decrease of strain, were investigated.

1. The loop strength of samples used increases with increas-

ing the diameter ratio. The degree of increase is dependent upon the simple tensile breaking strain of samples.

2. The loop strength is affected by the shape of distorted cross-section and the curvature of bending part of the opposite filament hooked on.

3. The following experimental equations were obtained for sample N1:

$$\Delta e = \varepsilon e_{mo} \dots\dots(5); \quad e_{mo} = 1/(1 + \varepsilon_r \gamma_{do}) \dots\dots(4)$$

ε is 0.394 for N gut and 0.234, for N gut-HS filament, and is independent of diameter ratio.

So, e_{mo} is an important factor for the loop strength. The loop strength f_L for a given diameter ratio can be estimated from both the above equations and their load-elongation curves of simple tensile test.

4. The following assumption proposed in the previous paper is concluded to be appropriate: a fiber in loop test begins to rupture at the region where the sum of bending and tensile strains has just reached the tensile breaking strain of the fiber.

B. In the loop test between two different filaments, which have about the same thicknesses but different tensile breaking strains, the specimen having the smaller tensile breaking strain is apt to be broken. This is because the loop strength of the samples used in this experiment decreases with decreasing the tensile breaking strain.

C. When a single gut of N1 is hooked on the bundle composed of different numbers of N1, it is bent smoothly along the surface of the bundle. Therefore the relation between e_{mo} and Δe in this case is nearly the same as that when hooked on a single N gut of different thicknesses.

Furthermore, the loop strength ratios of polyester and SS filaments, each of which is hooked on its bundle, also increases with increasing the numbers of other hooked filaments, as estimated from their load-elongation curves.

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