Effect of Surface Damage on Tensile and Fatigue Properties of Nylon Fishing Line

Journal of Tokyo University of Fisheries, Vol. 88, pp. 39-46, 2002

Effect of Surface Damage on Tensile and Fatigue Properties of Nylon Fishing Line

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(Received August 31, 2001)

Abstract: The effect of notch damage on the tensile strength and fatigue life of branch line used in tuna longline were investigated both in dry and wet condition. A razor blade was used for making an artificial notch on the surface of nylon monofilament lines at various depths.

The result of tensile testing indicated that the tensile strength of notched nylon monofilaments was rapidly decreased with increasing of notch depth. The relationship between the tensile strength and the notch depth can be described by the following equation.

$$BS = 100\ \{1 - (ND/100)^{\alpha}\}$$

where BS is tensile strength (%) of a notched fishing line, ND is notch depth (%) and α is constant.

Fatigue tests were carried out under cyclic loading method. From experimental results, relationship between notch depth and fatigue life of the fishing line can be expressed by the following linear equation.

$$ND = m - n \log N$$

where N is number of cycles to failure (fatigue life), m and n are constants.

By using these relations, fatigue life curves can be described mathematically by the following equation.

$$S/T_0\ (\%) = (100\text{-}6.8 \log N)\ \{1\text{-}(ND/100)^{\alpha}\}$$

where S is imposed load (kgf), T_0 is initial tensile strength (kgf), (100-6.8 log N) is obtained from the relationship between S/T_0 (%) and N of un-notched samples. The result shows good coincidence between the fatigue life curves and observation fatigue data.

Key words: *Nylon monofilament, Notch, Fatigue life, Cyclic loading, Tuna longline*

Introduction

Nylon monofilament is widely used for fishing gears such as tuna longline, gill net and sport fishing. It offers the advantage of relatively invisible in the water so that the higher catch could be respected. It was reported that the catch efficiency for tuna longline was approximately 6.7 times higher by using nylon monofilament as compared with multifilament (cremona) branch line.[1)]

In recent year, wire and multifilament in sport fishing and tuna longline fishing gear have been replaced by nylon monofilament.[2)] However, fishing line is exposed to a number of complex physical effects such as contact with hauling rollers, sharp edges and other equipments on the vessel. Once a fishing line has damaged, it can be easily broken and reduced in durability. For these reasons, it is usually replaced with the new one after another within a short period of use.[2)]

The fatigue properties and durability of tuna branch line were investigated by Kanehiro *et al.*[3-5)] However, there is little information about the effect of surface damage on the mechanical properties of fishing line. In this study, the effect of surface damage on tensile strength and fatigue property of nylon monofilament used for tuna longline were investigated.

Materials and Methods

Nylon monofilament No.150 (diameter 2.05mm, use in the branch line of tuna longline) and No.60 (diameter 1.28mm) were examined. The specimen was prepared from a 70 cm length of nylon monofilament with an eye on both ends. These eyes were fastened with aluminum tubes and set to cylindrical (diameter 50mm) chucks as shown in Fig.1. The notches were made with a razor blade to different depths on the surface at the center of specimens. In case of the wet condition, the notched samples were immersed into distilled water for a week in order to have a steady of the water content in the nylon monofilaments. A Tensilon (UTM-10T, Toyo Baldwin Co. Ltd.) tensile testing machine was used for these experiments. The tensile tests were carried out under tension speed of 100 mm/min. All of the tests had been conducted at room temperature (20°C) and 65% relative

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humidity. The notch depth of samples cut by the razor blade was measured from the fracture photographs of the samples. The notch depth ND (%) was represented by the ratio of notch depth (mm) and diameter (mm) of filament. In tensile testing, ten test pieces were used.

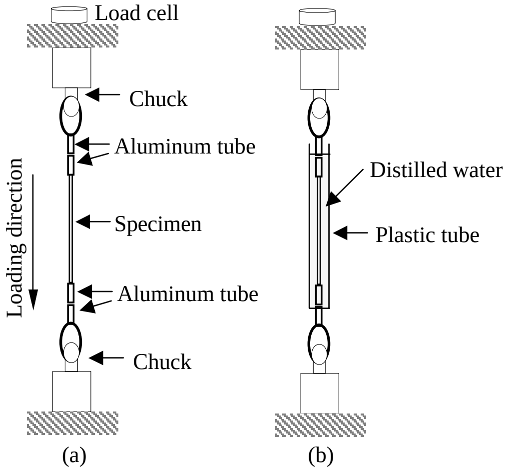

Figure 1. Scheme of tensile and fatigue experiments. A specimen set on the chucks. (a) dry condition. (b) wet condition.

The fatigue test was carried out with the cyclic loading method using a Shinko TCM-1000S testing machine. Samples were pulled cyclically from zero to a maximum load (S, kgf) at a cyclic speed of 500 mm/min. The fatigue load (S/T_0, %) was varied within 10-95% of the breaking strength (T_0, kgf) of virgin samples. The number of cycle to fatigue failure (fatigue life, N) was measured within the cycle range of $1\text{-}10^4$. Data regarding broken at the aluminum tube were excluded. In case of the fatigue test for the wet condition, samples were covered by plastic tube filling with distilled water during testing (Fig.1b). In fatigue testing, ten test pieces were used.

Results and Discussion

Effect of the notch damage on tensile strength

Values of average and standard deviation on tensile strength of un-notched nylon monofilaments used in this study are shown in Table 1. The tensile strength for the wet samples of both No.150 and No.60 are about 10% lower than for the dry ones. The loss in the tensile strength of nylon monofilaments when they are immersed to water is a well-known fact.[6] Fig.2 shows the water absorption (%) of the nylon monofilament (No.150) after immersion in water (20°C). It was shown that the water absorption of nylon monofilament reached at equilibrium state (about 5%) in 10-14 days. In this experiment, the water absorption (%) of tested lines after a week immersion in water (20°C) was about 4.5% near to the equilibrium amount.

Table1. Mechanical property of nylon monofilament specimens in initial condition

Samples		Diameter (mm)		Tensile strength T_0 (kgf)	
No.150	Dry	2.05	(0.05)	218.4	(2.0)
	Wet	2.05	(0.07)	193.0	(4.3)
No.60	Dry	1.28	(0.03)	81.0	(2.7)
	Wet	1.28	(0.04)	69.6	(0.8)

Values in blankets indicate standard deviation.
Ten test pieces for each sample were used.

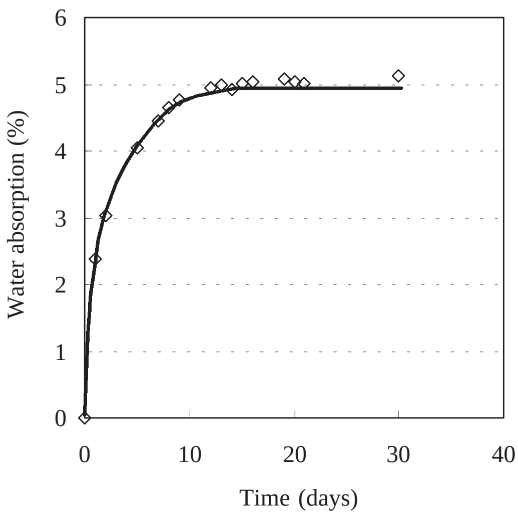

Figure 2. Changes in water absorption of nylon monofilament. Water absorption (%) = $((W_t\text{-}W_0)/W_0) \times 100$. Where W_0 is the initial weight (g) of tested sample and W_t is weight (g) after immersion, t (days).

Fig.3 shows a failure surface of a notched sample, in which various areas of the surface are observed. As the stress on the notched filament was increased, slow ductile cleaving (Area B) occurred across a straight front from the leading edge of the notch. Then the stress reached a certain value, the filament failed brittle fracture (Area C).

Relationship between tensile strength (T, kgf) and the notch depth (ND, %) is shown in Fig.4. The result indicated that the tensile strength of notched samples rapidly decreased with increasing of notch depth. Between nylon monofilament No.150 and No.60, the

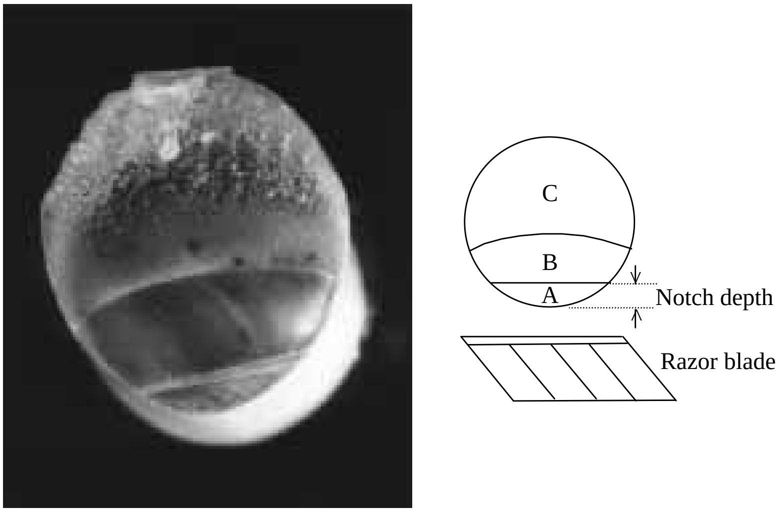

Figure 3. Failure surface of a notched sample (A: Razor notch, B: Area of ductile fracture, C: Area of brittle fracture). ND (%) = (Notch depth (mm)/ Diameter (mm)) × 100.

decreasing in the tensile strength of No.150 was steeper than that of No.60. When comparing between dry and wet tensile strength of the same diameter and notch depth samples, it appeared that the tensile strength of wet notched samples were similar to dry samples. In case of un-notched wet samples, it could be considered that the loss in breaking strength occurred after absorbing water due to the weakening of attractive force among neighboring molecules. For notched wet samples, it can be suggested that the surface damage has more significant effect on the loss in breaking strength of nylon monofilament than that of weakening after absorbing water.

Fig.5 shows the relationship between notched depth, ND (%) and retained breaking strength, BS (%) where BS=(T/T_0) × 100. The significant effect of surface damage on the tensile strength can be clearly seen from Fig. 5. The tensile strength of nylon monofilaments (No.150 and No.60) decreased about 30-50% within only 10% of notch depth. BS (%) of wet samples was about 5% higher than that of dry samples for both No.150 and No.60 because of the difference in initial strength (T_0) between dry and wet samples.

We try to derive a mathematical model that describes on the decreases in the tensile strength of nylon monofilaments by the notch damage. Fig.6 shows the observed data and the calculation curves represented by the following equation for the BS-ND relation.

$$BS = 100\,[1-(ND/100)^{\alpha}] \qquad (1)$$

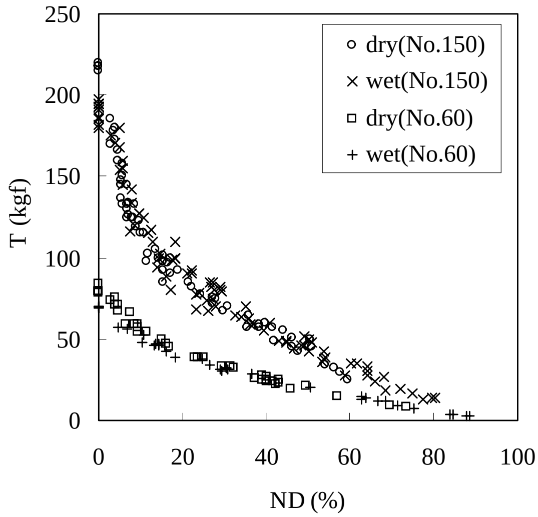

Figure 4. Relationship between tensile strength (kgf) and notch depth (%) of dry and wet nylon monofilament (No.150 and No.60).

where BS is tensile strength (%) of notched nylon monofilament, ND is notch depth (%) and α is constant. In Fig.6, BS-ND observed data for No.150 nylon monofilament and calculated curves for some different α values by the equation (1) are shown. The value of α of good fit for No.150 nylon monofilament was 0.30.

The BS-ND data in Fig.6 was in good agreement with the calculated curve by equation (1). But, examining Fig.6

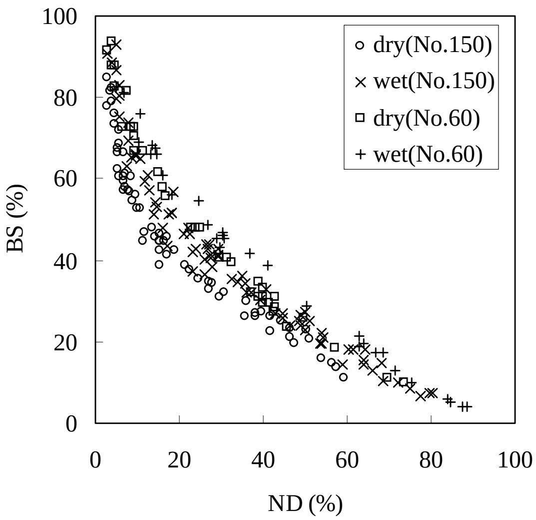

Figure 5. Relationship between retained breaking strength (%) and notch depth (%) of dry and wet nylon monofilament (No.150 and No.60).

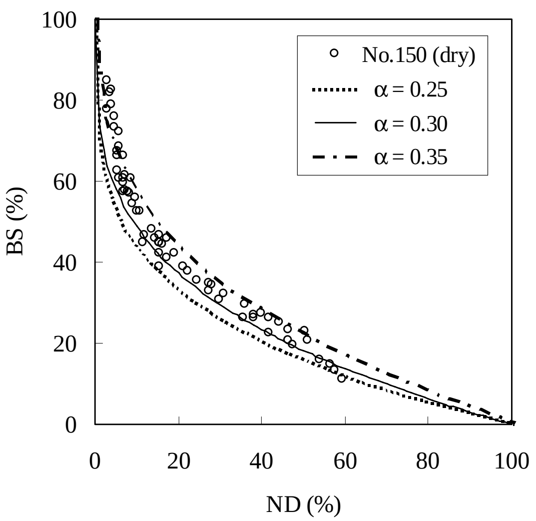

Figure 6. Calculation curves for some different α values by the equation (1) with observed data of No.150 nylon monofilament.

in detail, BS values near ND=0 appear not to be good agreement and not passed through 100%. This suggests that the internal-micro defects already exist in the virgin un-notched nylon monofilaments. It can be considered that the ideal nylon monofilament having no defects has higher initial strength than that of usual un-notched nylon monofilament. Assuming that the un-notched nylon monofilament has such inherent internal crack corresponding to the notch depth, ND_0 in the fiber structure, actual notch depth (ND′) of notched sample with notch depth (ND) was represented as follows:

$$ND' = ND + ND_0 \qquad (2)$$

The existence of the inherent notch depth in nylon monofilament was also reported in another studies.[7,8] Fig.7 shows BS-ND′ relation considering equation (2). In Fig.7, solid and dotted curves show BS-ND calculated curve by equation (1) and BS-ND′ calculated curve for α = 0.29 and 0.30, respectively. From Fig.7, it is clearly seen that BS-ND′ calculated curve was good agreement with the observed data for No.150 nylon monofilament. In the same way, the smooth curve of good fit for all four specimens (dry and wet for both No.150 and No.60 monofilament) is calculated. The value of α for each samples estimated are shown in Fig.8. From these results, it was shown that BS-ND relation of notched nylon monofilament could be described accurately by the equation (1). It can also be seen in Fig.8 that the estimated value of ND_0 was about 2.5% for both No.150 and No.60 samples. The constants α for good fit to experimental data were 0.29 (dry) and 0.35 (wet) for No.150 samples, 0.41 (dry) and 0.47 (wet) for No.60 samples.

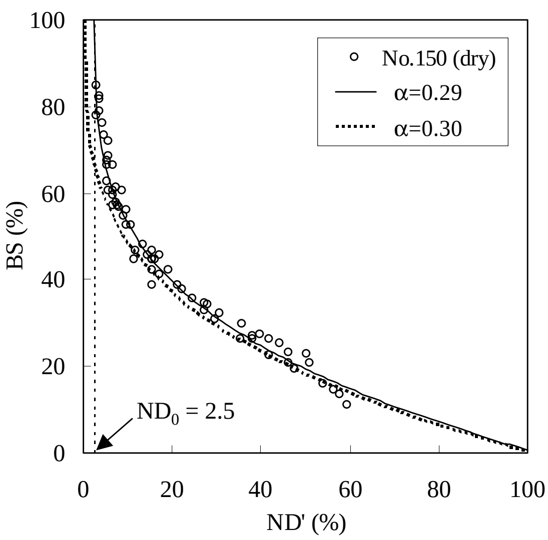

Figure 7. Calculation curves for relationship between breaking strength and notch depth with observed data of No.150 nylon monofilament.
$BS = 100\,\{1-(ND'/100)^{\alpha}\}$. Where $ND' = ND + ND_0$.

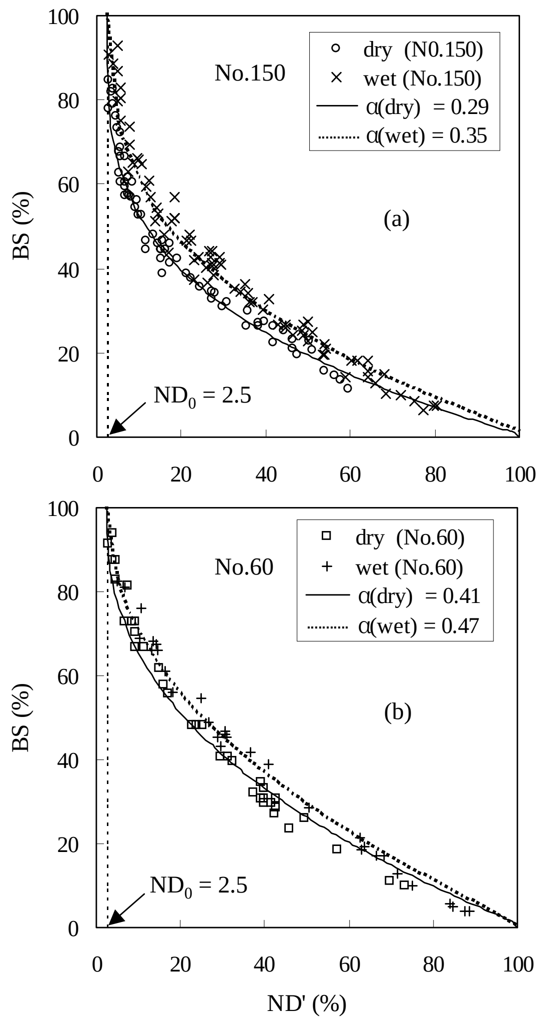

Figure 8. Calculation curves for relationship between breaking strength (%) and notch depth (%) of four specimens (dry and wet for both No.150 and No.60 nylon monofilament).

Fatigue life of un-notched nylon monofilament

The result of the fatigue test for dry un-notched nylon monofilament (No.150) is shown in Fig.9. An arrow indicated the specimen that did not break within 10^4 cycles of the testing. From the result, a linear relationship between imposed load (S/T_0, %) and logarithm of number of cycles to failure (N) was observed.

From this result, the relationship between imposed load and fatigue life of nylon monofilament defined by the regression line in Fig.9 can be expressed by following equation.

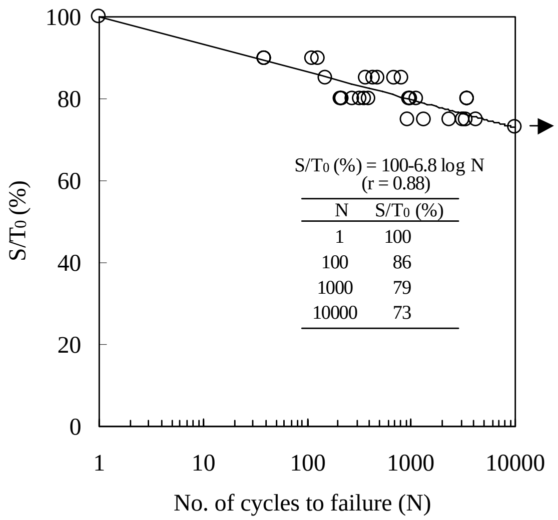

Figure 9. Relationship between imposed load (S/T_0) and number of cycles to failure of un-notched filament (S/T_0 (%) = *a* - *b* log N; *a* = 100, *b* = 6.8). r: coefficient of correlation. An arrow indicated the specimen that did not break within 10^4 cycles of the testing.

$$S/T_0\ (\%) = a - b \log N \qquad (3)$$

where S is imposed load (kgf), T_0 is dry tensile strength (kgf), N is number of cycles to failure, *a* and *b* are constants (100 and 6.8, respectively) from the data. From this equation, the fatigue life of the nylon monofilament at various imposed load can be estimated.

Fatigue life of notched nylon monofilament

The result of the fatigue test for notched nylon monofilament is shown in Fig.10 with the relationship between ND and N under different imposed load conditions. Values (%) in Fig.10 represent imposed load (S/T_0, %) conditions in the fatigue testing.

The result indicates that fatigue life of notched nylon monofilaments decreased with increasing of notch depth under the same imposed load. The result shows the linear relationship between notch depth and logarithm of number of cycles to failure at any imposed load conditions. Comparison of fatigue life between notched and un-notched samples (referred to Fig.9) under the same condition at imposed load of 70%, the notched samples (ND<10%) failed within few cycles while the occurrence of failure can not be observed within 10^4 cycles of testing for un-notched samples. It is clearly seen from these results that the effect of notch was very significant on the decreasing in fatigue life of monofilament. Comparing fatigue life between dry and

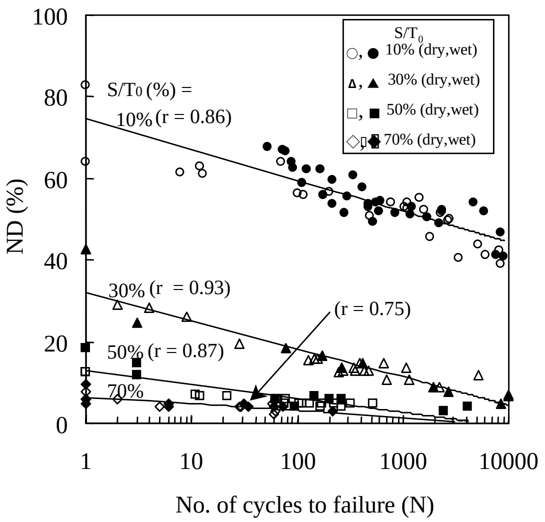

Figure 10. Relationship between notch depth (%) and number of cycles to failure for dry and wet nylon monofilament (No.150).
ND = *m* - *n* log N.

Table 2. The constants of *m* and *n* in the equation (4) for notched filaments by imposed load

Imposed load S/T_0 (%)	*m*	*n*	*r*
10	74.64	7.56	0.86
30	31.98	6.88	0.93
50	12.95	3.43	0.87
70	6.43	1.63	0.75

r : coefficient of correlation.

wet samples, the result shows that there is no significant difference.

In Fig.10, the relationship between notch depth and number of cycles to failure can be expressed by the following least square equation.

$$ND\ (\%) = m - n \log N \qquad (4)$$

where *m* and *n* are constants and these values for each imposed load are given in Table 2.

Fatigue life estimation

The objective of estimation on fatigue life of notched nylon monofilament is to develop a mathematical model, which is effective for forecasting its durability (available life) under practical use. As mentioned before there was no significant difference between dry and wet both in tensile (%) and fatigue life, so that the estimation on fatigue life of dry notched nylon monofilament will be given as an example in this paper.

Fig.11 shows BS-ND observed data (opened circles) from the tensile test and BS-ND values (solid circles) at N=1 from the fatigue relation of Fig.10, including the calculation curve by equation (1), α=0.29. In Fig.11, the solid circles represent the extrapolated ND values at N=1 for different S/T_0 (=10, 30, 50 and 70%) in Fig.10. It can be seen that both data of the estimated data from the fatigue relation (●) and tensile data (○) appear to have good agreement with the calculation curve by equation (1). Therefore, it can be suggested that the described model of equation (1) can be used for estimating the fatigue life curve of notched and un-notched nylon monofilaments.

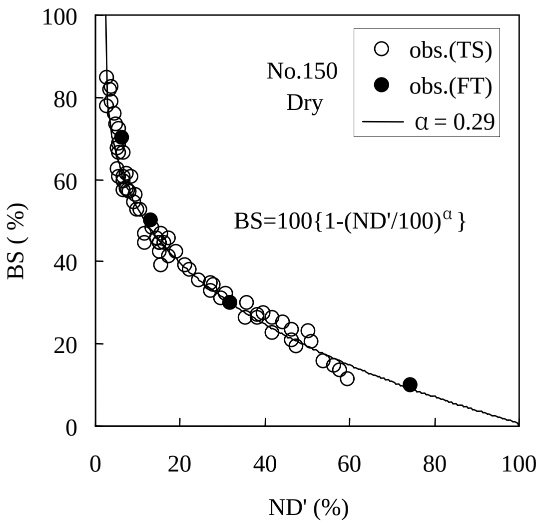

Figure 11. Fatigue life curve for fatigue data. ○ : tensile observed data referred to Fig. 8(a), ● : the value of ND(%) and S/T_0 (%) were calculated from equation (4), ND values at constant imposed load (10, 30, 50 and 70%) were estimated by extrapolating at N = 1.

In case of un-notched samples, the relationship between S/T_0 (%) and N can be expressed by equation (3) as mentioned before. For notched samples, the term of notch effect that cause the decreasing in fatigue life should be added to the equation (3). The S/T_0 - N relation for notched nylon can be expressed by the following equation.

$$S/T_0\ (\%) = (a - b \log N)\ \{1-(ND/100)^{\alpha}\} \qquad (5)$$

where the first term, *a* - *b* log N, means relationship between S/T_0 (%) and N of un-notched samples and the second term, $1-(ND/100)^{\alpha}$, means factor of notch effect.

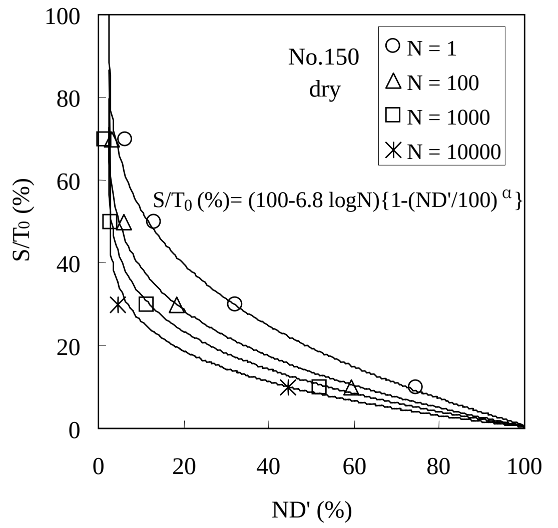

Figure 12. Fatigue life curves calculated from equation (5).

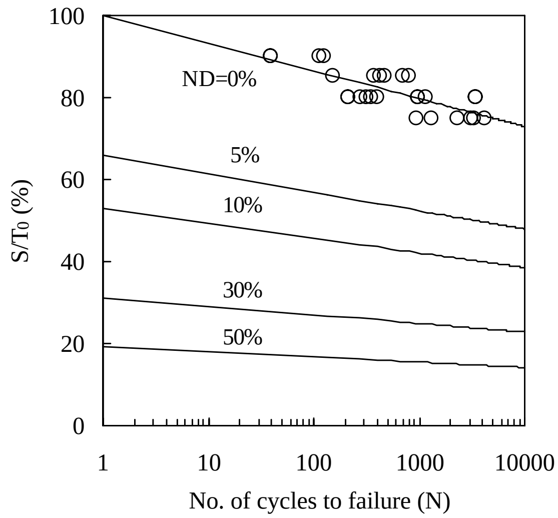

Figure 12. Relationship between imposed load and number of cycles to failure of notched nylon monofilament. S/T_0 (%) = (100 - 6.8 log N) {1-(ND/100)$^{\alpha}$}, α = 0.29. Solid lines at various notch depth were calculated at constant α = 0.29.

Fig. 12 shows S/T_0 - ND relations for notched samples at various loading cycles. The plots show S/T_0 - ND data at N=1, 100, 1000 and 10^4 calculated from equation (4). Solid lines show good fitting curve at each loading cycle. For the good fit on the observation fatigue data, α is equal to 0.29, 0.23, 0.20 and 0.17 for each fatigue life curve. The result in Fig. 12 shows an accordance of the forecast on the fatigue life curves with the calculated values by equation (5).

Fig. 13 shows the calculated relationship between imposed load and number of cycles to failure for nylon monofilament at various notch depths from equation (5). The fatigue life curves can be estimated by using this mathematical model with the relationship of BS, ND and N.

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ナイロンテグスの疲労寿命に対する表面傷（ノッチ）の影響

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マグロ延縄漁業に使用されるナイロンテグスの強度特性と疲労寿命に対する表面傷（ノッチ）の影響を乾・湿の両条件下で調べた。ノッチの深さと破断強度の関係では，破断強度（BS, %）とノッチ深さ（ND）の関係は次式で表わされ，ノッチが深くなるにつれて破断強度は急激に減少していく関係が得られた。

$$BS = 100\ \{1-(ND/100)^{\alpha}\}$$

疲労試験では，ノッチにより破断回数（疲労寿命）の著しい低下が認められ，疲労寿命において，ノッチ深さ（ND）と破断回数の関係は次式で表わせた（m , n は定数)。

$$ND = m - n \log N$$

これらを総合して，ナイロンテグスのノッチの深さ（ND）と応力（S/T_0）および疲労寿命（N）の関係は次式で表わせるものと考えられた。

$$S/T_0\ (\%) = (100 - 6.8 \log N)\ \{1-(ND/100)^{\alpha}\}$$

ここで，　第1項(100 - 6.8 log N) はノッチの無い（ND=0）テグスの疲労直線を表わし，第2項　$1-(ND/100)^{\alpha}$　はノッチによる影響を表わす。

キーワード: ナイロンモノフィラメント，ノッチ，疲労寿命，繰り返し荷重，マグロ延縄