Analysis of Compressional and Tensile Properties of Silk Weaves

ANALYSIS OF COMPRESSIONAL AND TENSILE PROPERTIES OF SILK WEAVES

Mitsuo MATSUDAIRA

ABSTRACT

Silk weave shows deformable and stretchable properties in compressional and tensile properties especially in the small load (strain) region. The reason of these properties is analyzed by inspecting fiber shapes and yarn mechanical properties. Silk fibroin fiber has a small crimp, although the most part of the crimp is removed by the process of making raw silk yarn, it recovers again by the process of sericine removement. Silk yarns shows very deformable in lateral compressional property and very stretchable in tensile property because of the fiber crimp and the weave crimp of yarn. These characteristics bring about soft and deformable features in tensile and compressional properties. Random and irregular shapes of the fiber crimp make the fiber assembly bulky and being high FUKURAMI.

1. Introduction

It is generally said that silk weaves have soft and good handle. In the investigation of mechanical properties and fabric handle of silk weaves, it was shown that one of the mechanical property characterizing silk weaves appears in compressional and tensile properties, especially in a small pressure or tensile force region and silk weaves show very deformable and stretchable in the force region[1). As the result, silk weaves show high FUKURAMI (fullness and softness)[1).

Compressional and tensile properties of weave are considered to have relation with tensile and lateral compressional properties of yarn in the weave. The yarn property is also related to fiber property, especially in small strain region such as before Hookean region. In this paper, the cause of the weave deformability and extensibility in small force region of compressional and tensile properties is studied by inspecting crimp of silk fiber and mechanical properties of silk yarns.

2. Experiment

2-1 Measurement of Crimp of Silk Fibroin Fiber

The load-extension behaviour of a single fiber is observed at a constant rate of extension (40%/min). There are two initial lengths defined here. One is the initial length of the crimped fiber, which is denoted by 1_r and defined as the distance between the clamps when the crimped

昭和 62 年 9 月 16 日受理

fiber is held under a very small initial tension of 2.0×10^{-5} N per a silk fibroin fiber (this value is equal to 245 kPa when cross-section of the fiber is considered to be triangle), which is the minimum tension detectable on the load-extension curve. The other initial length, denoted by l_0 is the fiber length along the fiber axis when all crimp is removed. This initial length is estimated by the intersection of the extension line along the Hookean slope of the load-extension curve and the horizontal axis[2]. The stretch ratio of the crimped fiber λ is defined in relation to l_0 such that:

$$\lambda = (\text{distance between two clamps})/l_0 \quad \cdots\cdots (1)$$

The initial stretch ratio λ_r is defined as:

$$\lambda_r = l_r/l_0 \quad \cdots\cdots (2)$$

Crimp shrinkage of a single fiber ε_r is defined as[3]:

$$\varepsilon_r = (1-\lambda_r)\times100(\%) \quad \cdots\cdots (3)$$

Silk fibers are sampled out from three major stages in the processing of sericine removement, that is, the cocoon fiber which is pulled out from cocoon, the raw silk fiber which is gummed together from eight cocoon fibers and the fibroin fiber which is the final fiber after sericine is removed. The crimp shrinkage of these silk fibers are measured and also wave length and radius of the fiber crimp are inspected.

2-2 Measurement of Lateral Compressional Property of Yarn

Lateral compressional properties of silk yarns sampled out from silk weaves are measured by Wire Method[4] as follows. A steel wire of 0.5 mm diameter is fixed on a horizontal base, and a yarn is hung on the wire with tension F_y as shown in Fig. 1. The angle between the yarn and the horizontal level is 0.523 rad which is approximately equal to the averaged yarn intersecting angle in various weaves. The compressive force between the yarn and the steel wire is given as follows.

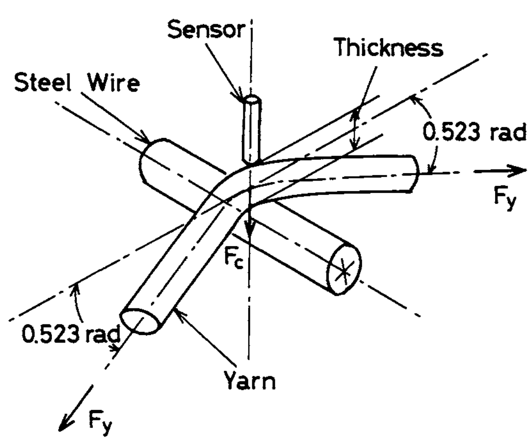

Fig. 1 Principle of the Wire Method.

$$F_c = 2F_y \sin 0.523 \quad \cdots\cdots (4)$$

The yarn thickness in the cross-over point is measured by a LDT(Linear Differential Transducer) having a needle sensor contacting at the top of the yarn surface with a small compressional force of 100 mg, and is recorded as a function of yarn tension F_y, or contacting force F_c.

Silk yarns examined here are sampled from silk filament weaves called "Habutae"[1] which is a most typical silk weave for women's thin dress and having plain weave structure. Polyester yarns are samped from polyester weaves having the same structure as the silk weaves and measured their properties for comparison. So-called "silk-like" polyester weaves[5,6] which are made to simulate silk weaves are also used to inspect lateral compressional properties of the yarns. Compressional properties of these three weave groups measured by KESF system[7] and plotted in the relation of logarithms of pressure versus thickness strain are shown in Fig. 2[1]. Silk weave shows most deformable property and polyester weave is undeformable. Tensile properties of these three weave groups showed almost the similar tendency as the compressional properties[1].

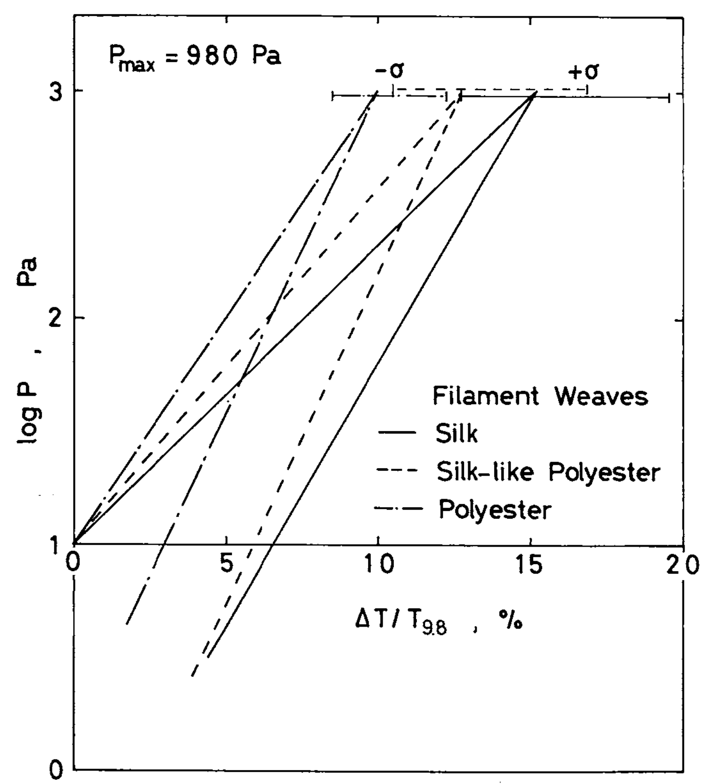

Fig. 2 Compressional properties of silk, polyester and silk-like polyester filament weaves mesured by KESF system. Each curve shows the averaged compressional property of the weave group.

2-3 Measurement of Tensile Property of Yarn

Tensile properties of silk, polyester and silk-like polyester yarns sampled out from each three weave groups mentioned above are inspected using load-extension curves. As the yarns sampled from weaves have weave crimp, the weave crimp is eliminated as follows. The initial length of yarn, denoted by L_0, is the yarn length when all weave crimp is removed and the length is estimated by the intersection of the extension line along the Hookean slope of the load-extension curve and the horizontal axis as the case of fiber crimp. The stretch ratio of the yarn Λ is defined in relation to L_0 such that:

$$\Lambda = (\textit{distance between two clamps})/L_0 \quad \cdots\cdots(5)$$

The strain of the yarn of which weave crimp is eliminated is defined as:

$$E = (\Lambda - 1) \times 100\ (\%) \quad \cdots\cdots(6)$$

The load at the initial length is considered to be used to stretch only weave crimp and the load is also eliminated as shown in Fig. 3. Therefore, new load-extension (strain) curve can be obtained in this way. Justification of this method has been confirmed by comparing with the yarn of which weave crimp is removed completely by exposure to hot (373 K) steam.

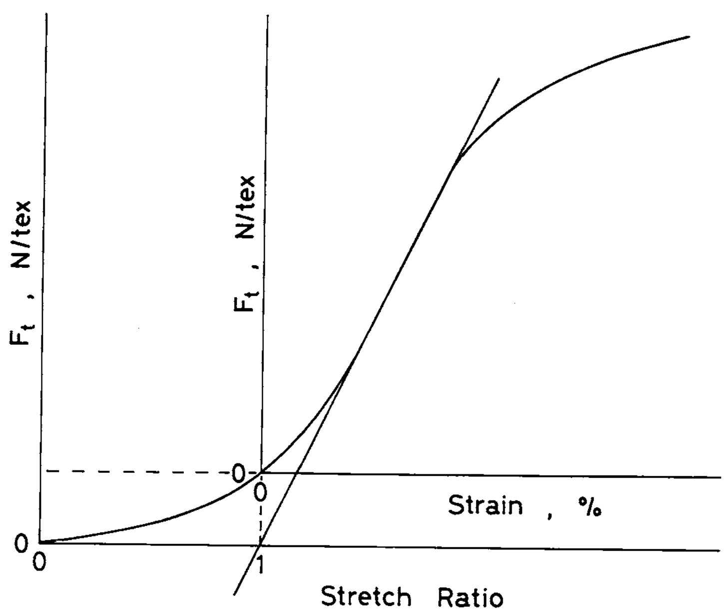

Fig. 3 A load-stretch ratio curve of a yarn having weave crimp and the method of eliminating the weave crimp to obtain a load-strain curve of straight yarn.

Tensile properties of yarns having weave crimp are also inspected because the yarns which have large influence on weave compressional property is under crimped state in weave and the tensile strain connected with fabric handle is considered to be very small. Silk weaves have "effective gap"[8] at the cross-over points of warp and weft yarns and only weave crimp may be stretched at the initial region of weave extension or compression. Therefore, tensile properties of yarns having weave crimp is also important for analyzing compressional and tensile properties of weave.

All the measurements were carried out at 60±5 % relative humidity and 293±2 K temperature conditions.

3. Results

3-1 Crimp of Silk Fibroin Fiber

The crimp shrinkage of silk fibers sampled from three stages are shown in Fig. 4. The circle point is an average value of 20 measurements of samples and a standard deviation is also shown by the vertical line. The result of the cocoon fiber of which sericine is removed is shown for reference. It is shown that the crimp shrinkage decreases remarkably by the process from the cocoon fiber to the raw silk fiber. However, it increases a little by the process from the raw silk fiber to the silk fibroin fiber, that is, sericine removing process. The sericine-removed cocoon fiber shows almost the same crimp shrinkage as the silk fibroin fiber.

The wave length and the radius of fiber crimp were inspected by two-dimensional observation putting a fiber between two glass plates. The results are shown in Table 1 including wool

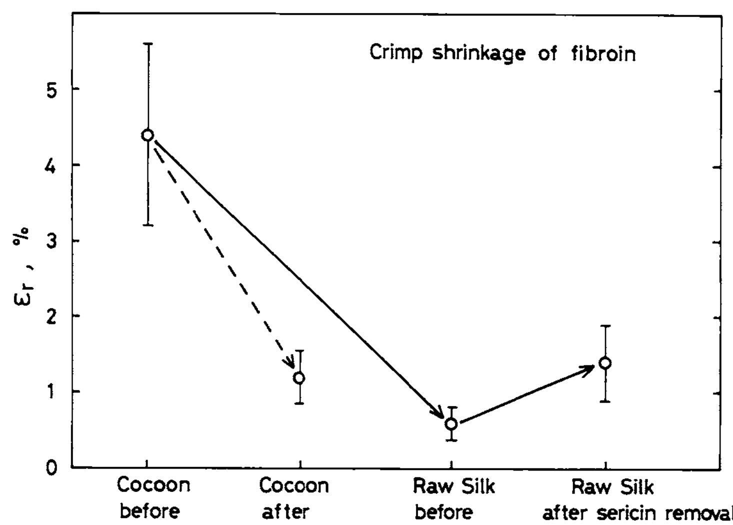

Fig. 4 Change of crimp shrinkage by the process of making the raw silk and sericine removement.

Table 1 Crimp of Silk Fibers*

	Crimp Shrinkage (%)	Wave Length (mm)	Radius (mm)
Cocoon Fiber	4.4	0.5−3.0	0.05−0.5
Raw Silk Fiber	0.6	1.0−5.0	0.05−0.2
Silk Fibroin Fiber	1.4	0.5−3.0	0.05−0.3
Wool Fiber	5.2	0.5−2.0	0.10−1.0

*These fibers were measured at 295 K, 64 % RH conditions.

fiber. Although the wave length of the silk fibroin fiber is as same as that of the cocoon fiber, the radius is a little smaller. Therefore, the decrease of crimp shrinkage is caused by the decrease of the crimp radius. The crimp radius of silk fiber is much smaller than that of wool fiber.

3-2 Lateral Compressional Property of Yarn

The results of lateral compressional properties of silk, polyester and silk-like polyester yarns sampled from each three weave groups are shown in Fig. 5 as compressive force versus

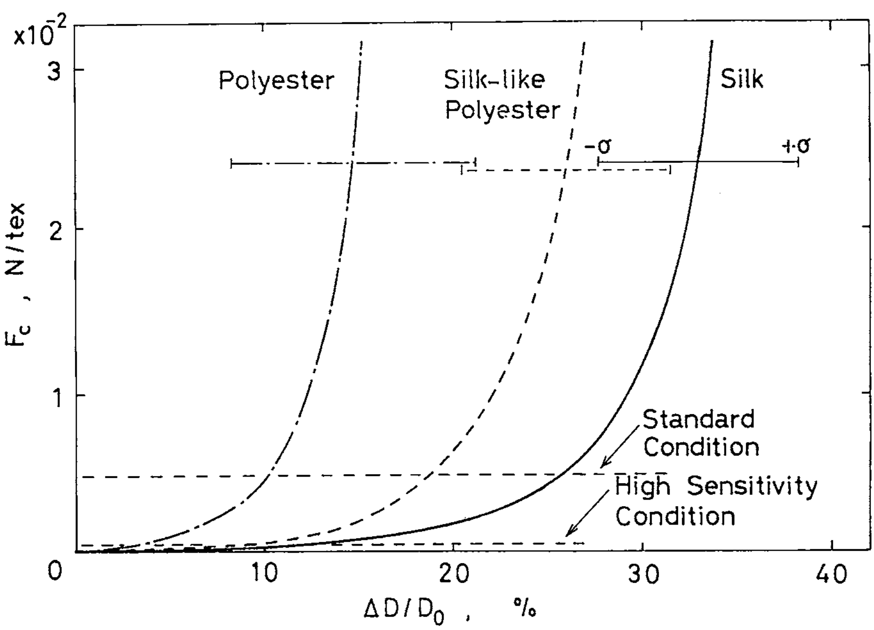

Fig. 5 Lateral compressional properties of silk, polyester and silk-like polyester yarns sampled from each three weave groups shown by the relation between the compressive force versus strain of yarn diameter.

strain of yarn diameter. The each curve shows the averaged one of warp and weft yarns sampled from five weaves in each group. A standard deviation of each group is also shown in horizontal line at 0.024 N/tex. The maximum tensile force of weave measured by KESF system[7] is shown by horizontal broken line for standard[9] and high sensitivity conditions[10]. It is clear that silk yarns are most deformable and polyester yarns change their diameters very little. The order of deformability is just as same as that of weave thickness strain as shown in Fig. 2.

3-3 Tensile Property of Yarn

The results of tensile properties of silk, polyester and silk-like polyester yarns sampled out from each three weave groups are shown in Fig. 6. Weave crimp is eliminated in these curves as the method mentioned before (2-3). The each curve shows the averaged one of warp and

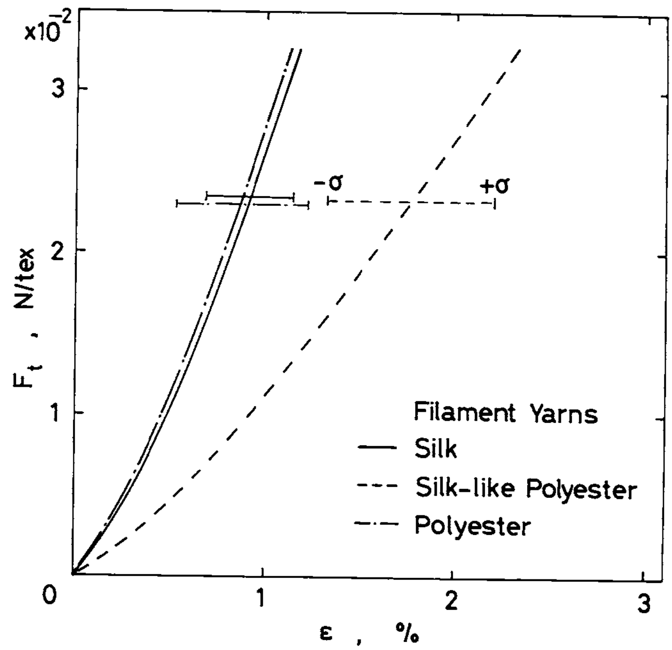

Fig. 6 Tensile properties of silk, polyester and silk-like polyester yarns of which weave crimp is eliminated.

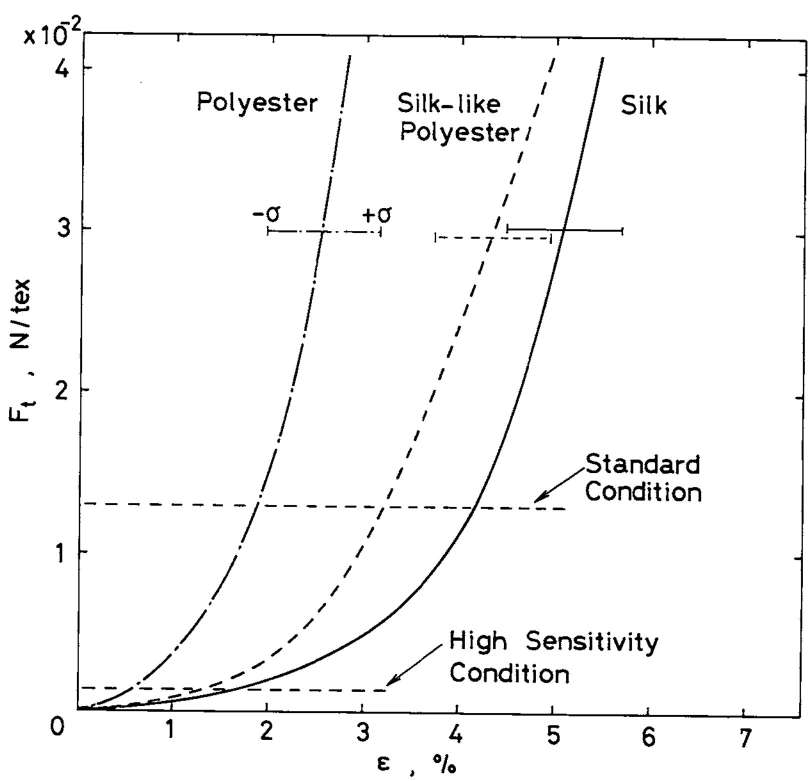

Fig. 7 Tensile properties of silk, polyester and silk-like polyester yarns having weave crimp.

weft yarns sampled from five weaves in each group. It is noted that tensile property of silk yarns is quite similar to that of polyester yarn, although that of silk-like polyester yarn is quite different from these yarns and shows very stretchable.

The results of yarns having weave crimp are shown in Fig. 7. The behaviour of the tensile property is quite different from the results shown in Fig. 6. Silk yarn shows more stretchable than silk-like polyester yarn at small tensile force. Therefore, weave crimp has very large effect on tensile property of yarn. The order of yarn stretchability corresponds to the deformability of weave as lateral compressional property of yarn. The tensile force relating to fabric handle is very small and the tensile property which is more alike to the practical tensile property of yarn in weave is that of yarn having weave crimp.

4. Discussion

It is shown that silk fibroin fiber has a little crimp by measuring crimp shrinkage of fiber. If the crimp is removed by the process of making the raw yarn, it recovers again by the process of sericine removement. This phenomenon is just the same as that being done by finishing process in wool fabric production in which crimp of wool fiber is recoverd considerably by finishing process[3]. The silk weaves examined here are treated to remove the sericine after weaving, therefore, there remains a little crimp in a silk fibroin fiber. Fiber bundles or yanrs having large crimp shrinkage show bulkness[3] and stretchable in tensile property[11] and deformable in compressional property[11] in the case of wool. This may be also applied to the case of silk fiber.

Actually, lateral compressional property of silk yarn sampled from silk weave which is deformable in compressional property showed most deformable in yarn diameter. Lateral compressional property of yarn influences very much on tensile property of weave and makes weave more stretchable[12].

From the results of tensile property of yarn of which weave crimp is eliminated by the method mentioned before (2-3), it is supposed that not only weave crimp but also fiber crimp and gaps between fiber may be eliminated by the elongation of yarn. As the result, silk yarn does not show stretchable property. However, tensile property of silk yarn having weave crimp shows very stretchable property especially at the region of small tensile force. This stretchability is related to deformability of silk weave in compressional and tensile property. Therefore, tensile property of yarn with weave crimp is very important for evaluating the stretchability of yarn in weave state and gives practical tensile property of yarn of which fiber has a little crimp and gaps between fibers.

In order to inspect regularity of crimp wave of silk fibroin fiber, the auto-correlation coefficient and the cross-correlation coefficient are calculated for some fibers as follow:

$$\mathit{Auto\text{-}corr.\ Coef.}\ (m) = \frac{\sum_{n=1}^{N-m} A_n \cdot A_{n+m}}{\sigma_A \cdot \sigma_A \cdot (N-m)} \quad \cdots\cdots (6)$$

$$Cross\text{-}corr.\ Coef.(m)=\frac{\sum_{n=1}^{N-m} A_n \cdot B_{n+m}}{\sigma_A \cdot \sigma_B \cdot (N-m)} \qquad (7)$$

$$where\ \sigma_A=\sqrt{\frac{\sum_{n=1}^{N} A_n^2}{N}} \quad \sigma_B=\sqrt{\frac{\sum_{n=1}^{N} B_n^2}{N}}$$

where, A_n, B_n ; radius of the crimp wave.
N ; devision number of the crimp wave.
n, m ; the devided point of the crimp wave.

The Auto-correlation coefficient of the crimp wave of a silk fibroin fiber is shown in Fig. 8 for three samples and the cross-correlation coefficient of the crimp wave between two adjacent fibers is shown in Fig. 9 for three pairs. These fibers are sampled arbitrarily and observed two-dimensionally by putting the fiber between two glass plates. Both correlations are very small and this means that the wave length and phase difference are quite different within a fiber and between fibers. Therefore, crimp of silk fibroin fiber is quite random and irregular. This random and irregular crimp makes fiber assembly bulky[13] and deformable in compressional property and also brings about high FUKURAMI.

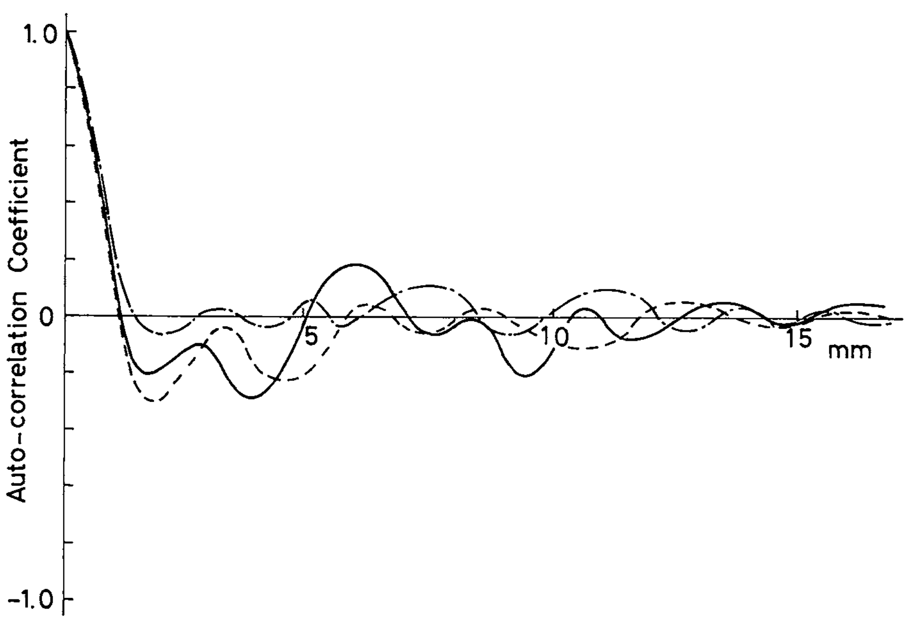

Fig. 8 Auto-correlation coefficient of a crimp wave of a silk single fiber for three examples sampled arbitrarily.

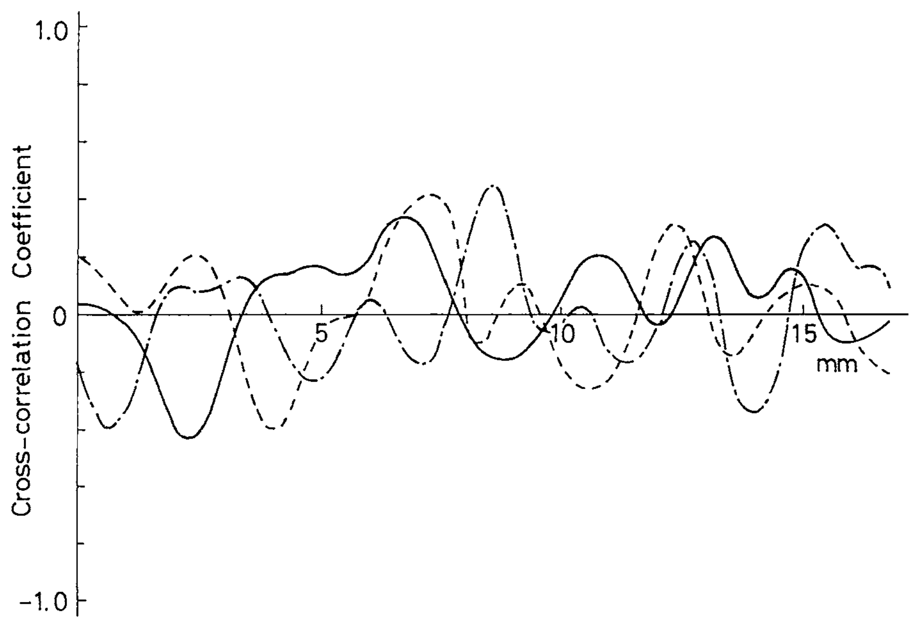

Fig. 9 Cross-correlation coefficient between crimp waves of two silk single fibers for three pairs sampled arbitrarily.

5. Conclusions

Silk weave shows deformable and stretchable properties in compressional and tensile properties especially in the small load (strain) region. The reason of the property is analyzed by inspecting fiber shapes and yarn mechanical properties and following results are obtained:

(1) Silk fibroin fiber has a small crimp, if it is decreased by the process of making raw silk yarn, it recovers again in the process of sericine removement.

(2) Silk yarn shows very deformable in lateral compressional property and very stretchable in tensile property because of the fiber crimp and the weave crimp of yarn.

(3) Shape of the silk fiber crimp is very random and irregular, and this crimp brings about high FUKURAMI.

References

1). Matsudaira, M. and Kawabata, S., submitted to J. Text. Inst.
2). Mauersberger, H. R. (Editor), "Matthews' Textile Fibers", Wiley, New York, 576, 1954.
3). Matsudaira, M., Kawabata, S. and Niwa, M., J. Text. Inst., **75**, 267, 1984.
4). Kawabata, S., Niwa, M. and Matsudaira, M., J. Text. Mach. Soc. Japan (English ed.), **31**, 7, 1985.
5). Wada, O., J. Soc. Fiber Sci. Tech. Japan **37**, P-429, 1981.
6). Mitsuishi, Y., J. Soc. Fiber Sci. Tech. Japan, **38**, P-42, 1982.
7). Kawabata, S., J. Text. Mach. Soc. Japan, **26**, P721, 1973.
8). Matsudaira, M. and Kawabata, S., submitted to J. Text. Inst.
9). Kawabata, S., "The Standardization and Analysis of Hand Evaluation", The Text. Mach. Soc. Japan,

Osaka, 2'nd ed., 28, 1980.

10). Matsudaira, M., Kawabata, S. and Niwa, M., J. Text. Mach. Soc. Japan, **37**, T49, 1984.

11). Matsudaira, M., Kawabata, S. and Niwa, M., J. Text. Inst., **75**, 273, 1984.

12). Niwa, M., Sakaguchi, H. and Kawabata, S., Proceedings of 13th Text. Res. Sympo. at Mt. Fuji, p. 18, 1984.

13). Yamaguchi, S. and Kawabata, S., J. Text. Mach. Soc. Japan, **25**, T83, 1972.