Size Effect of Tensile Property and in-Situ Observation of Fracture Behavior of Bamboo Fiber

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Abstract- The fundamental characteristics on size effect of mechanical property and fracture mechanics of natural bamboo fiber was described in this paper. Bamboo fiber taken by steam explosion method was prepared to investigate size effect on mechanical property of the fiber with diameter around 0.2 mm and gage lengths of 10 mm to 100 mm. Tensile stress-strain curves of the bamboo fibers at all gage lengths exhibited a linear response behavior. It was apparent that tensile strength and fracture strain depend on the gage length based on experiment and statistical approach by *Weibull* analysis. In addition, the in-situ observation of fracture behavior during tensile deformation was conducted using the fiber length of 25 mm. Based on the observation results, it was obvious that fracture behavior of bamboo fiber was splitting morphology, which consists of interfacial debonding between cells and broken cells in the fiber.

Keywords – Bamboo Fiber, Tensile Test, In-Situ Observation, Fracture Behavior

I. INTRODUCTION

In the past few decades, research and engineering interest in industrial material field has been changed from monolithic materials to functional and/or reinforced composite materials. Most composite materials consist of a selected reinforcing material and a compatible resin to obtain the specific properties desired. Typically, glass, carbon and aramid fiber are used as reinforcing material to hope increment of physical properties in composite. However, these advantages cause environmental problems in disposal by incineration and pulverization. To overcome environmental demerits of composite, development of environmentally friendly composites is required in recent years [1].

Natural fiber has superior environmental performance as recyclability and lower pollutant emission [2]. Bamboo is a renewable resource and uses in many parts of the field, and has good characteristics as high strength, flexibility and rapid growth [3]. Researches [4-6] on bamboo fiber reinforced polymer matrix are shown, and mechanical properties, composite forming and modified fiber surface by chemical or other treatments are described. However, these research results are not enough to discuss effectiveness of bamboo fiber reinforcement. At present study, tensile test of bamboo fiber is conducted to investigate stress-strain response, while the strain ranges from initial loading to fracture. Furthermore, In-Situ observation of tensile test has been used to characterize the deformation and fracture behavior of a bamboo fiber. The aim of this work is to clarify the fracture mechanism and to obtain basic information about the bamboo fiber in detail.

II. Experimental Procedure

A. *Bamboo fiber –*

Bamboo fiber purchased from BAN Co. (Tokushima, JAPAN). Bamboo fiber means bamboo fiber bundle that small cells assemble as shown in Figure 1. Bamboo fiber was obtained from steam explosion method of pressure and temperature profile as shown in Figure 2. The fiber with diameter around 0.2 mm and gage length, A of 10 mm, 25 mm, 50 mm and 100 mm were taken. The xylem (soft-wall cell) on the fiber was removed by moist cotton paper, and

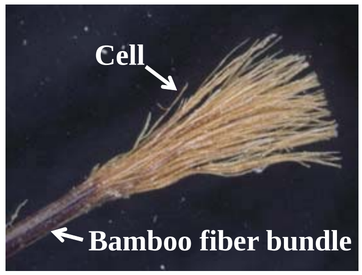

Figure 1. Photograph of bamboo fiber bundle and cell

then fiber were dried ranging at 40 °C (313 K) to 50 °C (323 K) for 24 hours. The bamboo fiber after dry treatment has water content of 4.41 %. Diameter and cross section area of the fiber were determined by reference [7]. Tensile specimen is shown in Figure 3. Tenth specimens are prepared for tensile test at various gage length. Tensile test in accordance with JIS R7606 standards were carried out at initial loading rate of 1.0 mm/min. Figure 4 shows the tensile testing equipment aided with a personal computer containing “EXCEL software”. In this system, tensile load is measured by one load cell (TCLZ-200NA, Tokyo Sokki Kenkyujo Co.) with capacity of 200 N, and displacement is measured by laser displacement sensor (KEYENCE CORP., IL-030) in pursuit on loading axis to movement. Load and displacement data were conducted and stored in digital storage oscilloscope (YOKOGAWA WE-7000) to the personal computer by a USB (Ver.2.0) interface. The elastic modulus, tensile strength and failure strain were calculated from the stress-strain curve.

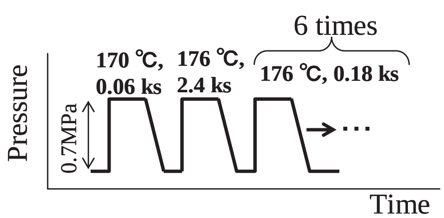

Figure 2. Schematic illustration of the steam explosion method to extract bamboo fiber

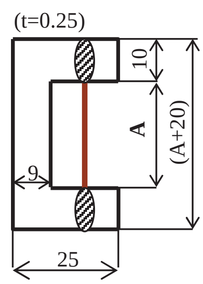

Figure 3. Schematic illustration of the configuration and each size in tensile specimen of the bamboo fiber used in this study

B. *In-situ observation during tensile test –*

Tensile test was conducted in-situ using a digital microscope in Figure 5 for bamboo fiber specimen of 25 mm length at initial loading rate of 1.0 mm/min. The tests were interrupted fifth times until maximum stress as shown in the stress-strain curve of Figure 6.

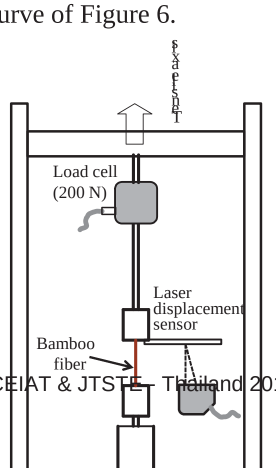

Figure 4. Schematic illustration of the tensile testing equipment of the bamboo fiber at various gage lengths

Figure 5. Schematic drawing of the in-situ observation method during tensile deformation of the bamboo fiber at loading speed of 1 mm/min and gage length of 25 mm

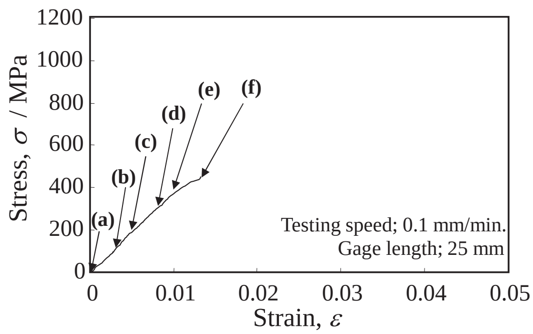

Figure 6. Stress-strain curve of the interrupted tensile test of the bamboo fiber at quasi-static strain rate

III. Results and Discussion

A. Tensile properties –

Figure 7 shows typical stress-strain curve of tensile test at various gage length specimen. It appreciated that the bamboo fiber exhibits a linear elastic material [8] at all of test in spite of different gage length. In addition, all fibers fractured at maximum stress. Figure 8 shows the variation of the tensile strength, σ_B and failure strain, ε_f with gage length of bamboo fiber specimen. It is apparent that the σ_B and ε_f increase rapidly below a gage length of 25 mm. Even above 50mm, the σ_B and ε_f decrease slightly with gage length of the specimen. Average tensile strength and failure strain for gage length of 100 mm are about 50 % lower than that of 10 mm. Note that long length of bamboo fiber over 50 mm degrades their mechanical properties. On the other hand, Young's modulus of bamboo fiber [9] is range between from 15 to 20 GPa and almost same without gage length.

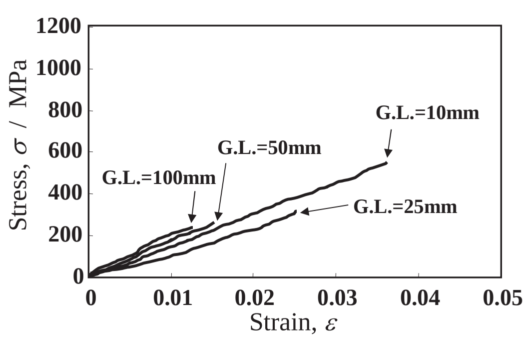

Figure 7. Typical stress-strain curve of the bamboo fiber at various gage length

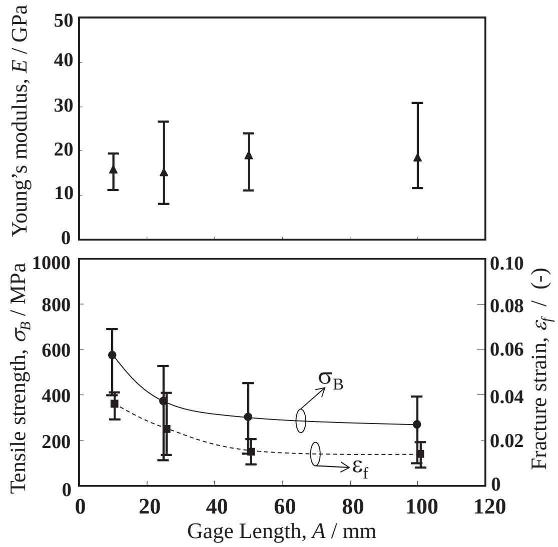

Figure 8. Change of the tensile strength, σ_B, fracture strain, ε_f and Young's modulus of the bamboo fiber at various gage lengths

The classical theory of the statistical strength of brittle materials was known as *Weibull* analysis [10]. In a previous study by authors [8], the mechanical property of bamboo fiber at elevated temperatures was revealed both experimentally and *Weibull* theoretically. To examine the size effect on strength of the bamboo fiber, *Weibull* statistical theory is applied. The strength of the fiber obeys the single *Weibull* cumulative distribution function, *i.e.*

$$F(x)=1-\exp(-(x/\eta)^m) \qquad (1)$$

Where $F(x)$ is the failure probability of the bamboo fibers under an applied stress no greater than x, η and m are the scale and shape parameters of *Weibull* distribution, respectively. $F(x)$ was given from mean rank method. Figure 9 shows the *Weibull* plots of the tensile strength at different gage length specimens. The *Weibull* shape parameter, m, which means variance of strength [14], were 5.81, 2.41, 2.40 and 2.16 at gage length of 10 mm, 25 mm, 50 mm and 100 mm, respectively. It was revealed that the width of the variance of strength is increasing with increasing fiber gage length of testing specimen.

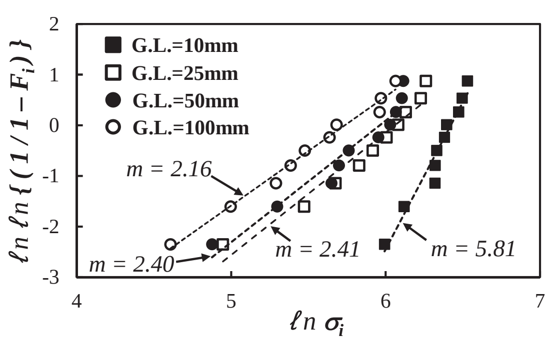

Figure 9. Sequential observations of the initial deformation to fracture of bamboo fiber. (a) to (f) refers to points of symbol in Figure 6

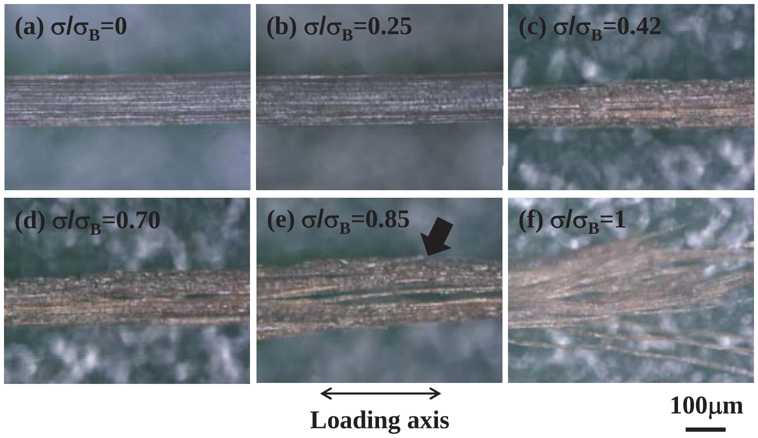

Figure 10. Sequential observations of the initial deformation to fracture of bamboo fiber. (a) to (f) refers to points of symbol in Figure 6

Figure 10 shows the failure morphology sequences of the bamboo fiber observed consequently at six different stress levels as shown in Figure 6. Naturally, stress-strain curve in Figure 6 also exhibited a linear response behavior until peak point, and then fractured at that point, as Figure 7 [8]. In Figure 10, there is no damage and no defect of bamboo fiber until $\sigma/\sigma_B=0.25$. This finding raise the possibility that high accuracy Young's modulus and Poisson's ratio might directly measure by in-situ observation. When the deformation of the bamboo fiber reaches $\sigma/\sigma_B=0.42$, multiple interfacial debondings are observed between cells on direction of loading axis. Consequently, due to stress concentration, the debonding cracks of the cells growth and coalesce along to the axis. A broken cell is seen at a part of arrow in Figure 10 (e) with deformation σ/σ_B=0.85. After that, the bamboo fiber is fractured by splitting morphology deformed to σ/σ_B=1. Thus, it is obvious that fracture mechanism of bamboo fiber bundle consists of initial and coalescence of interfacial debonding between cells, broken cells and splitting failure.

IV.CONCLUSION

Based on the results obtained in this study from the tensile test of its test of in-situ using digital microscope of bamboo fiber treated the steam explosion method and gage length dependency on fiber mechanical properties by means of experimental and *Weibull* theoretical approach, the following conclusions can be made;

(1) Stress-strain curve of bamboo fiber exhibited a linear response behavior until peak stress point, and then fractured at that point.

(2) It was apparent the tensile strength, σ_B and failure strain, ε_f increase rapidly below a gage length of 25 mm. Furthermore, mechanical properties of the fiber have distinctly the size effect. It was revealed that the width of the variance of strength is increasing with increasing fiber gage length of testing specimen based on statistical approach by *Weibull* analysis. On the other hand, Young's modulus was almost same without gage length.

(3) From in-situ observation during tensile test, it was obvious that fracture mechanism of bamboo fiber bundle consists of initial and coalescence of interfacial debonding between cells, broken cells and splitting failure.

REFERENCES

[1] H. Larbig, H. Scherzer, B. Dahlke and R. Poltrock, "Natural Fiber Reinforced Foams Based on Renewable Resources for Automotive Interior Applications," Journal of Cellular Plastics, vol. 34, pp. 361-379, 1998.

[2] X. Lu, M. Q. Zhang, M. Z. Rong, G. Shi, G. C. Yang and H. M. Zeng, "Self-reinforced melt processable composites of sisal," Adv. Compos. Lett., vol. 8, pp. 231-236, 1999.

[3] K. Okubo, T. Fujii and N. Yamashita, "Improvement of Interfacial Adhesion in Bamboo Polymer Composite Enhanced with Mirco-. Fabricated Cellulose," JSME International Journal, Series A, vol. 48, pp. 199-204, 2005.

[4] S. Jain, R. Kumar and U. C. Jindal, "Mechanical Behavior of Bamboo and Bamboo Composite," J. Materials Science, vo. 27, pp. 4598-4604, 1992.

[5] S. Jain, U. C. Jindal and R. Kumer, "Development and Fracture Mechanism of the Bamboo/Polyester Resin Composite," L. Mater. Sci. Lett., vol. 12, pp. 558-560, 1993.

[6] A. V. Rajulu, S. A. Baksh, G. R. Reddy and K. N. Chary, "Chemical Resistance and Tensile Properties of Short Bamboo Fiber Reinforced Epoxy Composites," J. Reinforced Plastics and Composites, vol. 17, pp. 1507-1511, 1998.

[7] K. Tanabe, T. Matsuo, A. Gomes, K. Goda and J. Ohgi, "Strength Evaluation of Curaua Fibers with Variation in Coross-Section Area," J. Sci. Mat. Sci., vol. 57, pp. 454-460, 2008, (in Japanese).

[8] N. Yamamoto, A. Takahashi and T. Toyohiro, "Tensile Properties of Natural Bamboo Fiber at Testing Temperature up to at 473K," International Journal of Innovations in Engineering and Technology, Special Issue – JTL-AEME, pp. 37-43, 2014.

[9] K. Okubo, H. Takagi and K. Goda, "Composites Science/Technology and New Challenges for Tomorrow's Applications," J. Soc. Mat. Sci. Japan, vol. 55. pp. 438-444, 2006, (in Japanese).

[10] Cedric. W. Richards, "Engineering Material Science," Prentice-Hall of Japan INC., p. 352, 1961.