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NOTE

Effects of specimen configuration and measurement method of strain on the characterization of tensile properties of paper

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Abstract Uniaxial-tension tests of copy paper were conducted to measure the tensile properties, including Young's modulus, proportional limit stress, and tensile strength in the machine direction (MD) and cross direction (CD) using straight and dog-bone-shaped specimens. In the tests using the straight specimen, the distance between the grips was varied. Additionally, the tensile strain was obtained from the crosshead movement and elongation between the lines photographed by a CCD camera. When using a straight specimen in the MD, the grip distance influenced the Young's modulus value, and the tensile strength was markedly lower than that of the dog-bone-shaped specimen. In contrast, the tensile properties in the CD could be obtained even when using the straight specimen while reducing the influence of stress concentration at the grip.

Keywords Tensile properties · Uniaxial-tension test · Machine compliance · Contact-free method · Crosshead movement

Introduction

Paper is one of the principal wood products used for packages and containers; it is important to know the mechanical properties of paper for its effective utilization. In characterizing the mechanical properties of paper, a uniaxial-tension test is conducted more frequently than other tests, such as compression, shear, and bending tests, which are often difficult to perform because of the thinness of paper. Various studies have characterized the tensile properties of paper by uniaxial-tension tests [1–14]. Additionally, methods for the tension test have been determined for Technical Association of the Pulp and Paper Industry (TAPPI), International Organization for Standardization (ISO), and Japanese Industrial Standard (JIS) [15–18]. The standardization in these major standards indicates the importance of the tensile properties of paper obtained from the uniaxial-tension tests.

According to these standards, a straight specimen with the width of 15 mm is used. The tensile strain is determined by dividing the elongation with the initial distance between the grips. There are two concerns in these standardized methods. One is that the tensile strength cannot be measured accurately because of the stress concentration imposed at the grip. When using a straight specimen, failure is often induced at the grip and the tensile strength is measured to be lower than the realistic value. To reduce this concern, a dog-bone-shaped specimen is usually used for other materials, such as solid wood, plastics, and metals. The problem caused by the stress concentration is encountered during the measurement of the tensile strength of paper. The other concern involves the measurement of the tensile strain from the elongation between the grips. The elongation is usually determined from the crosshead movement; however, the elongation may also contain the effects of machine compliance, such as the backlash and deformation of the fixture and the slippage between the specimen and fixture [19, 20]. In the uniaxial-tension test of solid wood, plastics, and metals, the tensile strain is usually measured by bonding a strain gauge on its surface or using an extensometer or an LVDT (linear variable differential transducer) to reduce these effects. However, because of its thinness, it is difficult to measure the strain of paper by bonding a strain gauge. Perkins and McEvoy

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[21] compared the values of the Young's modulus obtained from the output of an LVDT and crosshead movement and suggested that the Young's modulus value obtained from the output of the LVDT was 20 % larger than that obtained from the crosshead movement. Nevertheless, the stiffness of the apparatus for measuring the strain measurement may often be greater than that of the paper; therefore, the reaction force from the apparatus may restrict the deformation of the paper specimen. Kimura et al. [6] indicated that the Young's modulus obtained from the crosshead movement decreased as the grip distance decreased. They also suggested that the Young's modulus value obtained from the tension test was lower than that obtained from the vibrating reed method even when using a sufficiently long specimen. Nevertheless, it is dubious that the Young's modulus values obtained from the uniaxial-tension and vibrating reed methods are comparable.

To overcome the obstacles described above, the tensile strain at the region separating the grips can be measured by a contact-free method using a dog-bone-shaped specimen. Choi et al. [22] and Enomae [23] applied a digital image correlation (DIC) technique for the analysis of strain distribution in paper. Their methods are effective for determining the strain distribution, which is often inhomogeneously induced. Nevertheless, this method is rather complicated and excessive for determining the tensile properties described above. Recently, Yokoyama and Nakai [12, 13] obtained the off-axis elastic constants and tensile strengths of several papers by directly measuring the tensile strain at a gauge section using a CCD camera and a digital image sensor. Their method is attractive because it is simpler than the DIC.

In this study, uniaxial-tension tests were performed on copy paper in the machine direction (MD) and the cross direction (CD) using straight and dog-bone-shaped specimens. In the straight specimen, the distance between the grips was varied and the tensile strain was determined from the crosshead movement and from the elongation between the lines drawn at the mid-length of the specimen. By comparing the Young's modulus, the proportional limit stress, and the tensile strength between the straight and dog-bone-shaped specimens, the effects of the grip distance and the measurement method of tensile strain on the characterization of tensile properties were examined. From the analyses, a method for characterizing the tensile properties of paper is suggested.

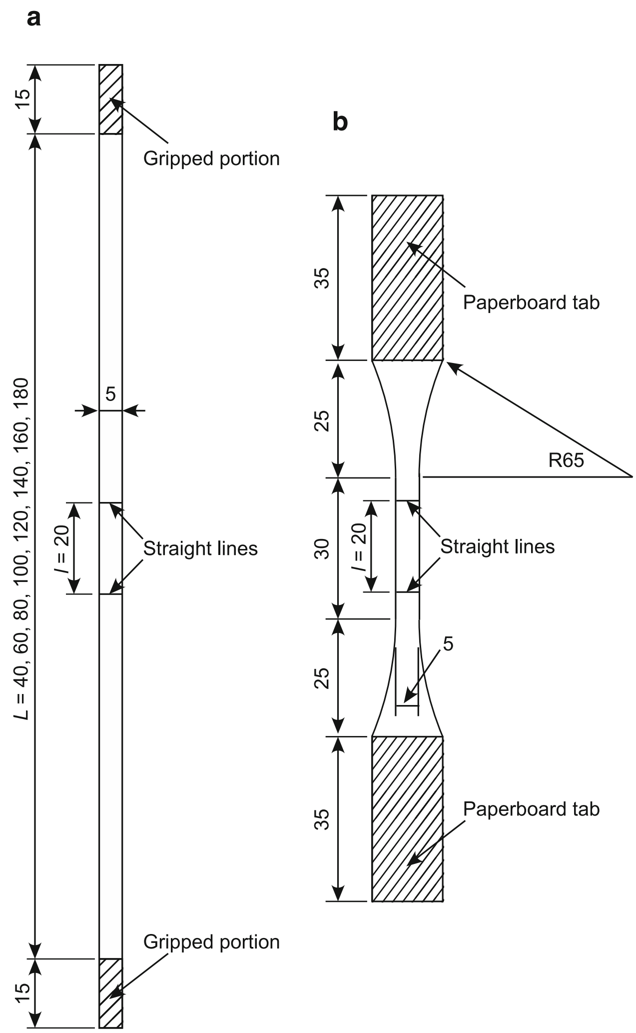

Fig. 1 Diagram of the uniaxial-tension test specimen. **a** Rectangular specimen and **b** Dog-bone-shaped specimen with paperboard tabs. Unit: mm

Materials and methods

Materials

Commercial copy paper (Type 6200, Ricoh Company, Ltd.) was used in this study. Uniaxial-tension tests in the MD and CD were performed, and the tensile properties, including the Young's modulus, the proportional limit stress, and the tensile strength, were obtained. The MD and CD were identified according to the results obtained in a previous study [14]. Initially, each specimen was cut into the width of 15 mm to measure the thickness according to JIS P8118-1998 [24] using a micrometer (PPM-25, Mitsutoyo, Kawasaki, Japan) with a constant pressure of 50 kPa applied by a pair of flat circular ground faces of 14.3 mm in diameter. Using the specimen with the initial configuration, the basis weight, thickness, and density of each specimen were measured and were 71.2 ± 0.5 g/m^2, 95 ± 1 μm, and 745 ± 32 kg/m^3, respectively. Then, the samples were cut into the straight and dog-bone-shaped specimens as shown in Fig. 1. The specimens were prepared in a room conditioned at a constant temperature of 20 °C and 65 % relative humidity (RH). Ten specimens were prepared per test condition. For the straight specimens, the effects of specimen length and the measurement method of tensile strain on the tensile properties described above were examined. The specimen length was varied from 70 to 210 mm by 20 mm increments. A pair of 20 mm distant straight lines was drawn at the mid-length as shown in Fig. 1. The initial distance between the lines was defined as l.

Tension tests

The tension tests were conducted using an Instron-type universal test machine (Shimadzu Autograph AG-100kNG, Shimadzu Co., Ltd. Kyoto, Japan). The specimen was gripped using Instron-type universal tension test fixtures. In a previous study conducted by Kimura et al. [6], the gripping force was applied using pressure-adjusted fixtures that could be controlled by compressed air. In this study, the gripping force was applied by tightening the screws set in the fixture. The distance between the grip edges, defined as L, was varied from 40 to 180 mm at 20 mm increments. Before testing, a small pretension load of 0.1 N was applied to remove slack from the specimen. The tension load was applied at a crosshead speed of L/100 mm/min until failure was induced in the specimen. In the standards described above, the crosshead speed is determined to be 20 mm/min [15–18]. According to several previous studies on wood-based materials [25, 26], however, there was a concern that the strain rate effect might have a significant influence on the measurement of the mechanical properties. Additionally, Kimura et al. [6] and Yokoyama and Nakai [12] conducted the tension tests under the crosshead speed of 4 and 3 mm/min, respectively. From these previous studies, the crosshead speed was determined to be slower than the standardized one [15–18]. During the tension test, the load and crosshead movement were measured using a load cell (Shimadzu SBL-50 N, capacity = 50 N, sensitivity = 1 mV/V) and an LVDT (Tokyo Sokki CDP-50, Tokyo Sokki Kenkyujo Co., Ltd. Tokyo, Japan, capacity = 50 mm, sensitivity = 200 × 10^{-6}/mm), respectively. The load P and crosshead movement ΔL were recorded using a data logger (Tokyo Sokki DC-204R) at intervals of 0.5 s. In contrast, the elongation between the lines drawn on the specimen surface, defined as Δl, was photographed using a CCD camera at intervals of 0.5 s and analyzed using a high-speed digital image sensor (Keyence CV-5000SO, Keyence Corporation, Osaka, Japan). The distance between the straight lines at the gage region corresponded to about 130 pixel, and the position of the line edge was measured down to 1/1000 of a pixel (sub-pixel processing). The sampling by the CCD camera was synchronized with the measurement of elongation. It was confirmed that the effect of the sampling rate of the image sensor was not significant for the measurement of the tensile properties in this study.

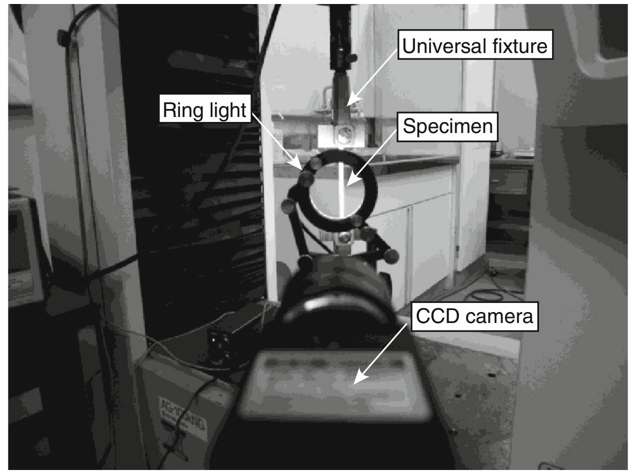

Fig. 2 Setup of the uniaxial-tension test of paper

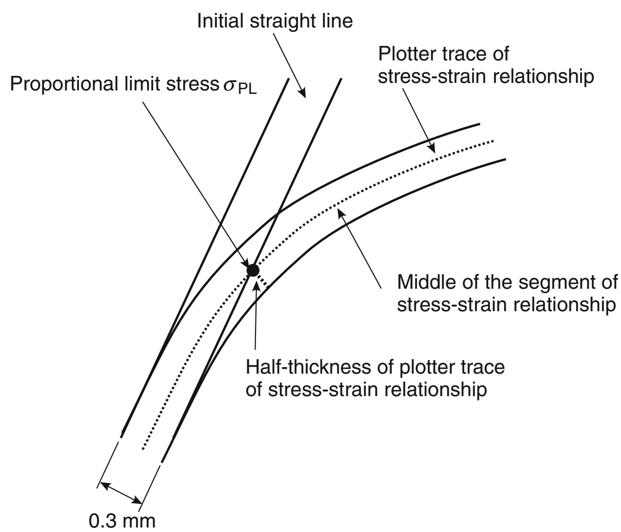

Fig. 3 Method of determination of the proportional limit stress σ_{PL}

Figure 2 shows the setup of the tension test apparatus. The tensile stress σ was obtained by dividing the applied load by the cross-sectional area of the specimen at the gauge region. In contrast, the tensile strains were obtained from the crosshead movement and elongation between the drawn lines, which were defined as ε_L (= $\Delta L/L$) and ε_l (= $\Delta l/l$), respectively. From the σ–ε_L and σ–ε_l relationships, the values of the Young's modulus E, the proportional limit stress σ_{PL}, and the tensile strength σ_F, corresponding to each specimen length were obtained. The E value was determined from the initial straight portion of the σ–ε_L and σ–ε_l relationships. As shown in Fig. 3, the σ_{PL} value was determined from the stress at the onset of nonlinearity where the half-thickness of the plotter trace of 0.3 mm

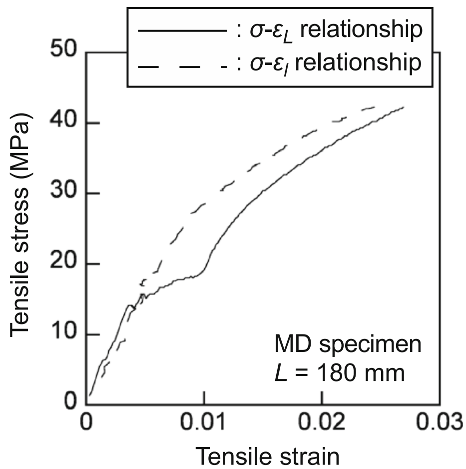

Fig. 4 Stress-strain diagrams obtained in the preliminary test using a specimen with the width of 15 mm

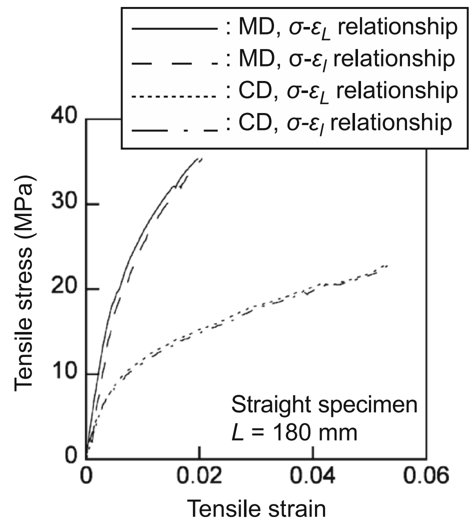

Fig. 5 Typical stress–strain diagrams obtained from the uniaxial-tension tests in the machine direction (MD) and cross direction (CD) of copy paper

deviated from the straight line [27, 28]. The σ_F value was determined from the maximum stress.

When conducting the tension test using a straight specimen, there was a concern that the tensile properties could not be measured accurately because failure was induced and propagated from the edge of the gripped portion due to the stress concentration. To reduce this concern, the dog-bone-shaped specimen shown in Fig. 1b was used. Paperboard tabs (0.7 mm thick) were bonded to each end of the dog-bone-shaped specimen using double-sided tape to avoid stress concentration at the grips [12–14]. A tension test of the dog-bone-shaped specimen was conducted using a similar apparatus for the straight specimen at a crosshead speed of 0.8 mm/min.

As described above, the width of the specimen was determined to be 15 mm by JIS P8113-2006 [18]; therefore, a tension test of the specimen with the width of 15 mm was preliminarily conducted. As shown in Fig. 4, a deviation appears from 15 to 20 MPa of the tensile stress in the σ–ε_L relationship. This phenomenon, which is not observed in the σ–ε_l relationship, was thought to be because of the slippage between the specimen and grips or that between the apparatuses equipped in the testing machine that could not be entirely reduced. This phenomenon could not be reduced even when the grip length was enlarged and gripping force was increased. Therefore, there was a concern that the proportional limit stress could not be accurately measured from the σ–ε_L relationship because of this crooking. To reduce the crooking deviation in the σ–ε_L relationship, the width of the specimen was reduced to 5 mm in this study, and the concern on the slippages described above could be entirely eliminated.

Results and discussion

Figure 5 shows the typical σ–ε_L and σ–ε_l relationships of the straight MD and CD specimens obtained from the tension tests conducted at a grip distance L of 180 mm. As described above, there was a concern that the σ–ε_L relationship deviated from the σ–ε_l relationship because of machine compliance from the take-up of play, the deformation of the fixture, and the slippage between the specimen and fixture, which would enhance the displacement measured by the crosshead movement. Nevertheless, the tension load was small enough to reduce the machine compliance, so the σ–ε_L and σ–ε_l relationships coincide well with each other for both MD and CD specimens.

Figure 6 shows the values of the Young's modulus E, the proportional limit stress σ_{PL}, and the tensile strength σ_F corresponding to the distance between the grips L. In the MD, the E values obtained from the σ–ε_L and σ–ε_l relationships are constant and coincide well with each other when the L value ranges from 100 to 180 mm. Statistical analysis revealed that in this range of L, there are no significant differences between the E values obtained using the straight specimen and dog-bone-shaped specimen (for a significance level of $p = 0.05$). Although Perkins and McEvoy [21] and Kimura et al. [6] noted the inaccuracy of the measured Young's modulus by the crosshead movement, the Young's modulus can be accurately obtained by measuring the crosshead movement in this range of L even when using a straight specimen. In contrast, the E values decreased as L decreased for L values <100 mm. Statistical analysis revealed that the E values obtained from the σ–ε_L

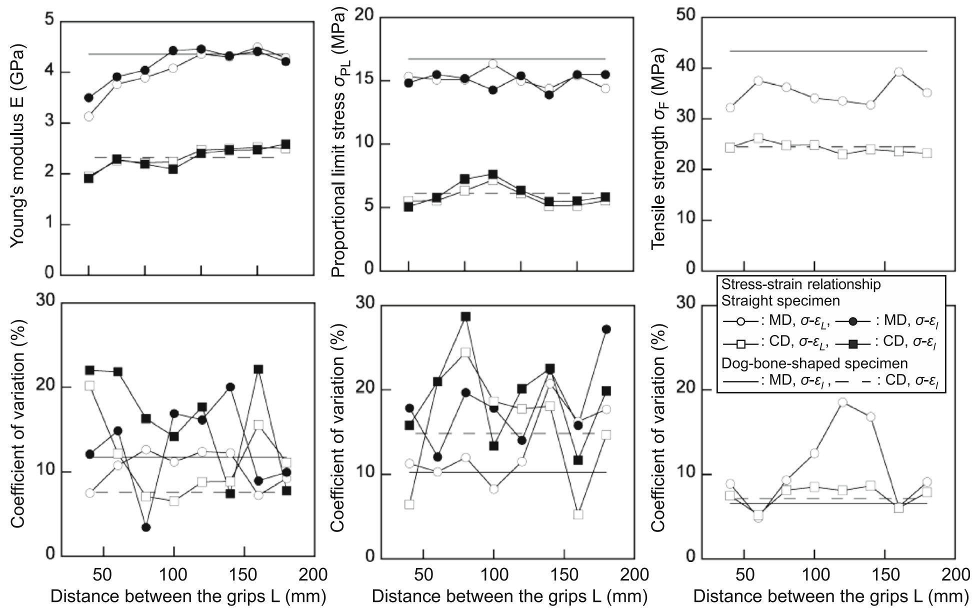

Fig. 6 Dependence of the Young's modulus *E*, proportional limit stress σ_{PL}, and tensile strength σ_F on the distance between the grips *L* and coefficient of variations of these properties

and σ–ε_l relationships were significantly lower (for a significance level of $p = 0.01$) than that of the dog-bone-shaped specimen when *L* was 40–60 and 40 mm, respectively. The decrease of the *E* value was because of the stress concentration at the edge of the grip. The stress concentration enhances the increase in tensile strain at the region near the grip. When the grips are close to each other, the region away from the stress concentration decreases relative to the region subjected to the stress concentration. Although the distance between the grips was 80 mm in the dog-bone-shaped specimen, the stress concentration was reduced effectively at the tapered portion, so the Young's modulus could be measured accurately. In contrast, the *E* values of the CD straight specimen obtained from the σ–ε_L and σ–ε_l relationships are approximately constant and coincide well with that of dog-bone-shaped specimen for the entire range of *L*. Therefore, the influence of specimen configuration and strain measurement are not significant in measuring the Young's modulus in the CD.

The σ_{PL} value obtained from the straight MD specimen is less than that of the dog-bone-shaped specimen. The stress concentration described above may decrease the σ_{PL} value. Nevertheless, statistical analysis revealed that the difference between the σ_{PL} values obtained from the straight and the dog-bone-shaped specimens was not significant. In contrast, the σ_{PL} value obtained from the straight CD specimen coincides well with that of the dog-bone-shaped specimen.

Figure 7 shows the photograph of the specimens in failed uniaxial-tension tests. In the MD straight specimen, failure was induced at the rectangular edge of a gripping fixture in the straight specimen. Finite element analysis on the tension test of fiber-reinforced plastics (FRP) revealed that the shear stress component is not homogeneously distributed along the gripped portion, but it is approximately 4-times larger at the rectangular edge than the averaged shear stress [29]. The failure in the MD straight specimen might, therefore, be induced due to the extreme stress concentration at the edge of a gripping fixture. In contrast, failure was induced at the gauge portion in the dog-bone-shaped specimen (Fig. 7a). Therefore, the value of σ_F obtained from the straight specimen was significantly lower (by 20 %) than that obtained from the dog-bone-shaped specimen. The low value of σ_F was commonly found in the preliminary test conducted using the straight specimen with the width of 15 mm. In contrast, failure was induced at the gauge portion in the CD straight specimen as observed in the dog-bone-shaped specimen (Fig. 7b). Therefore, the σ_F value obtained from the straight specimen coincides well with that of the dog-bone-shaped specimen. As described above, the use of straight specimen is determined for the tensile test of paper in TAPPI T404 and T494, ISO 1924-2-2008, and JIS P8113-2006 [15–18]. These standards suggest that the gripping of the specimen between a cylindrical and a flat surface or between two cylindrical surfaces is desirable for the line contact between the fixture and specimen to prevent the specimen from the problem with slippage. However, the use of flat clamping surfaces is also allowed if only tensile strength is to be measured because the problems with slippage, which may occur and yield misleading elongation measurements, have no effect on the measurement of tensile strength alone. Although the effect of gripping fixture was not examined in this study in detail, the use of flat clamping

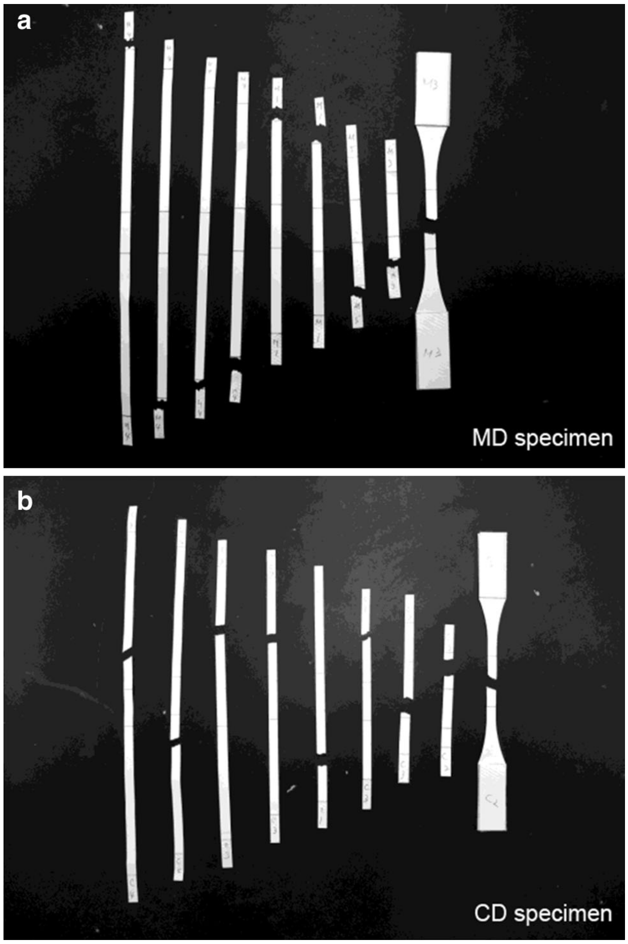

Fig. 7 Typical specimens failed in the uniaxial-tension tests. From left to right: straight specimen with grip distance *L* of 180, 160, 140, 120, 100, 80, 60, and 40 mm, and dog-bone-shaped specimen

surfaces is not recommended even for the measurement of tensile strength because the stress concentration at the rectangular edge of flat clamping surface enhances the failure of specimen.

From the results of the uniaxial-tension tests, it is possible to measure the Young's modulus in the MD from the crosshead movement using the straight specimen when the distance between the grips is large enough. In contrast, it is difficult to measure the tensile strength using the straight specimen. The measurement of crosshead movement and use of straight specimens are determined in the standards demonstrated above. These standardized methods are effective in determining the Young's modulus and the proportional limit stress in the MD. To obtain the tensile strength in the MD, however, the use of a dog-bone-shaped specimen is preferable to a straight specimen. In contrast, it is promising to determine the tensile properties in the CD of paper from the crosshead movement using a straight specimen, as determined in the standards demonstrated above.

Conclusions

Uniaxial-tension tests of copy paper were conducted using straight and dog-bone-shaped specimens. The tensile properties such as the Young's modulus, the proportional limit stress, and the tensile strength in the machine direction (MD) and the cross direction (CD) of the paper were obtained from the stress–strain diagram, and the effects of testing conditions on these properties were examined. The conclusions are summarized as follows:

1. The influence of the machine compliance due to the deformation and take-up of play in the test machine and fixture was not significant.
2. The Young's modulus in the MD could be measured accurately when using a specimen with a sufficiently long distance between the grips. When the grip distance was not long enough, the Young's modulus value was significantly lower because of stress concentration at the edges of the grips.
3. The tensile strength in the MD obtained using the straight specimen was significantly lower than that of the dog-bone-shaped specimen because of failure at the edges of the grips induced by stress concentration.
4. The tensile properties in the CD could be obtained accurately even when using the straight specimen.

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References

1. Cox HL (1951) The elasticity and strength of paper and other fibrous materials. Br J Appl Phys 3:72–79
2. Jones AR (1967) An experimental investigation of the in-plane elastic moduli of paper. Ph.D thesis, Georgia Institute of Technology, Atlanta, GA
3. Baum GA, Habeger CC, Fleischman EH (1981) Measurement of the orthotropic elastic constants of paper. IPC Tech Paper Ser 117:1–25
4. Mann RW, Baum GA, Habeger CC (1979) Determination of all nine orthotropic elastic constants for machine-made paper. IPC Tech Paper Ser 84:1–17
5. Schulgasser K (1983) The in-plane Poisson ratio of paper. Fibre Sci Technol 19:297–309
6. Kimura M, Nakao T, Katoh M (1985) Experimental method for calculating Young's modulus of paper from elongation test (in Japanese). Jpn TAPPI J 39:1057–1062
7. Rowlands RE, Gunderson DE, Suhling JC, Johnson MW (1985) Biaxial strength of paperboard predicted by Hill-type theories. J Strain Anal 20:121–127
8. Suhling JC, Rowlands RE, Johnson MW, Gunderson DE (1985) Tensorial strength analysis of paperboard. Exp Mech 20:75–84
9. Caulfield DF, Gunderson DE (1988) Paper testing and strength characteristics. In: Proceeding of the TAPPI 1988 paper preservation symposium. TAPPI Press, Washington, pp 31–40

10. Mäkelä P, Östlund S (2003) Orthotropic elastic–plastic material model for paper materials. Int J Solid Struct 40:5599–5620
11. Castro J, Ostoja-Starzewski M (2003) Elasto-plasticity of paper. Int J Plasticity 19:2083–2098
12. Yokoyama T, Nakai K (2007) Evaluation of in-plane orthotropic elastic constants of paper and paperboard. In: SEM annual conference and exposition on experimental applied mechanics, 6/3-6/6, 2007, Springfield, MA, http://sem-proceedings.com/07s/sem.org-2007-SEM-Ann-Conf-s66p02-Evaluation-In-plane-Orthotropic-Elastic-Constants-Paper-Paperboard.pdf. Accessed March 27, 2014
13. Yokoyama T, Nakai K (2009) Orientation dependence of in-plane tensile properties of paper: Experiments and theories (in Japanese). In: Japan Society of Mechanical Engineering M&M Conference, 7/24-7/26, 2009, Ehime, Japan, http://ci.nii.ac.jp/els/110008064818.pdf?id=ART0009607486&type=pdf&lang=jp&host=cinii&order_no=&ppv_type=0&lang_sw=&no=1395903812&cp=. Accessed March 27, 2014
14. Yoshihara H, Yoshinobu M (2013) Off-axis tensile strength and evaluation of the in-plane shear strength of paper. Holzforschung (in press)
15. TAPPI Standard (1992) T404. Tensile breaking strength and elongation of paper and paperboard (using pendulum-type tester)
16. TAPPI Standard (2001) T494. Tensile breaking properties of paper and paperboard (using constant rate of elongation apparatus)
17. ISO Standard (2008) 1924-2-2008. Paper and board—determination of tensile properties—part 2: constant rate of elongation method (20 mm/min)
18. JIS Standard (2006) P8113-2006. Paper and board—determination of tensile properties—part 2: constant rate of elongation method
19. Yoshiki M, Takehana M (1958) Research on the joints in wooden ships II. Young's modulus and bearing strength of wood in compression (in Japanese). Zosen Kyokai Ronbun-shu 102:251–259
20. Yoshihara H (2000) Influence of specimen's height on the measurement of compressive properties of wood and a simple method for evaluating the Young's modulus by means of compression tests (in Japanese). Mokuzai Kogyo 55:400–404
21. Perkins RW Jr, McEvoy RP Jr (1981) The mechanics of the edgewise compressive strength of paper. Tappi 64(2):99–102
22. Choi D, Thorpe JL, Hanna RB (1991) Image analysis to measure strain in wood and paper. Wood Sci Technol 25:251–262
23. Enomae T (2007) Application of image correlation technique to determination of in-plane deformation distribution of paper (in Japanese). J Jpn Soc Nondestruct Insp 56:561–566
24. JIS Standard (1998) P8118-1998. Testing method for thickness and bulk density of paper and paperboard
25. McNatt JD (1970) Design stresses for hardboard-effect of rate, duration and repeated loading. For Prod J 20(1):53–60
26. Suzuki S, Saito F (1991) Effects of environmental factors on the properties of particleboard II. Effects of moisture and loading rate (in Japanese). Mokuzai Gakkaishi 37:31–38
27. Davies P, Blackman BRK, Brunner AJ (2001) Mode II delamination. In: Moore DR, Pavan A, Williams JG (eds) Fracture mechanics testing methods for polymers, adhesive and composites. Elsevier, Amsterdam, pp 307–333
28. Yoshihara H (2014) Plasticity analysis of the strain in the tangential direction of solid wood subjected to compression load in the longitudinal direction. BioResources 9:1097–1110
29. Cunningham ME, Schoultz SV, Toth JM Jr (1985) Effect of end-tab design on tension specimen stress concentrations. ASTM STP 864:253–262