TECHNIQUES *by A. Vorakunpinij, D.W. Coffin, and C.C. Haberger*

A NEW DEVICE FOR MEASURING TENSILE AND COMPRESSIVE CREEP IN PAPER

The converting and end-use performance of paper is affected by its viscoelastic properties. For example, the creep response of a corrugated box subjected to a compressive stacking load governs the service lifetime of the box. Characterization of the compressive creep behavior of paper is essential for furthering the performance of packaging. Correlation of the compressive creep behavior of corrugated board to the behavior of the components, the liners, and the medium, is desired. Unfortunately, paper being a thin sheet material is inherently difficult to test in compression. Tension, on the other hand, is relatively easy to test, and it would be beneficial if one could predict the compressive creep behavior from the tensile response and other sheet characteristics that are routinely measured. Researchers have characterized fairly well the tensile response of paper,[1–4] and the focus is not on the methods of testing. However, to test a paper sheet in edgewise compression and avoid buckling, an apparatus must provide lateral support, or a piece of paper must be formed into a cylinder or box. If one wants to test a flat sheet of paper in compression, the creep apparatus needs to be capable of minimizing the effect of the lateral force while avoiding buckling of the sample. Various descriptions of compressive creep methods have been presented,[5–10] yet there is no widely accepted method. In addition, very little has been published on the relationship between compression and tension. The motivation for the apparatus described herein is to develop a simple method that could be used to measure both tensile and compressive creep in a similar manner. To the authors' knowledge, no available creep data for both compression and tension have been collected from the same equipment. Recently, a creep apparatus with column support showed plausibility for testing both tensile and compressive creep[8]; however, a measurement of tensile creep was limited by the strain gage range.

The apparatus evaluated in this paper was developed to determine uniaxial tensile and compressive creep for paper. This new device was able to test creep in either tension or compression depending on how the sample was mounted. The apparatus was modified from a concept of a flat plate support method developed for measuring compressive strength.[11] The principal design has rigid flat aluminum plates supporting the specimen laterally to prevent buckling of the specimen under compressive stress.

CREEP APPARATUS

Figure 1 shows a schematic of flat plate support consisting of two pairs of flat aluminum plates, i.e., (1) a set of plates mounted on low-friction linear bearings and (2) a pair of removable flat plates. The plates were used to laterally support the removable plates and a specimen. The plate **A** was attached to a low-friction linear bearing and could move freely along the load direction. The plate **B** was suspended over a low-friction linear bearing attached to the base and had free lateral movement but no movement in the loading direction. The dimensions of a sample holder were 8 inches in length by 1.5 inches in width by 0.5 inch in thickness. The sample holder **C** was mounted to the plate **A**, while the sample holder **D** was fixed to the plate **B**. The sample holder **D** had two small rectangular openings (1 inch in length by 0.20 inch in width). These openings were to allow free movement of magnets mounted directly to the specimen and were used with a Hall effect sensor for the displacement measurements. An eyelet bolt was attached to the plate **A**. A wire, contacting a low-friction pulley and passing through a hole on the table, was connected between the eyelet and a hook. The hook was used to attach a dead load. The weight of hook and wire was approximately 23 grams. Four testing units were constructed, placed on a table, and enclosed by a chamber, allowing for a controlled humidity environment. Dead weight was applied underneath the table.

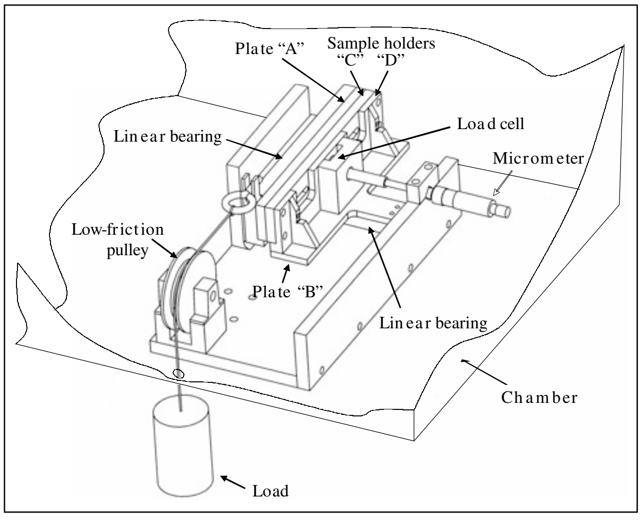

Fig. 1: Schematic of a tensile-compressive creep tester

A 100-N compressive miniature load cell from Entran Devices was placed between the plate **B** and a micrometer in order to measure the amount of lateral force. A micrometer head was soldered into a hole and attached to the load cell. When the micrometer was advanced, the plate **B** moved closer to the plate **A**, and a voltage proportional to the compressive force was sent to a computer. A program written with LabView was created to control the humidity and record all voltage signals into the computer.

The humidity-generating system supplied conditioned air by mixing wet and dry air. The mixed air was sent to the cham-

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ber. The relative humidity in the chamber was controlled by a customized feedback-loop-control program. The wet air was produced by bubbling air through the water column (3 inches in diameter by 5 feet in height). Wet air traveled from the top of the water column through a cap. Then the wet air was divided into four tubes and injected underneath the chamber at each corner. The wet air was mixed with dry air near each corner to provide the proper relative humidity to the chamber. In general, equilibrium conditions were reached within 20 to 30 minutes. Temperature and relative humidity were measured by the HMP 233 transmitter from Vaisala, which sent signals to a computer through an analog/digital board (A/D board).

MEASUREMENT OF CREEP DEFORMATION

There were two independent sets of displacement gages for each testing unit. Each set consisted of a sensor and a magnet. The sensor, a HAL805 Hall effect sensor from Micronas GmbH, measures magnetic-field changes between the sensor and the magnet.[12] As shown in Fig. 2, each sensor was glued on the edge of a drilled rectangular opening of plate D. The magnet was mounted to a lightweight plastic block and attached on the paper surface by two-sided tape. The dimensions of the magnet were 5 mm in diameter by 2 mm in length, and the lightweight plastic block were 5 by 5 by 7 mm, respectively. The HAL805 is a magnetic field sensor with a voltage output based on the Hall effect. The power supply used to provide the excitation voltage for the HAL805 sensor was ± 15 volts. All voltage signals from sensors were sent through an A/D board, which was connected to the computer. To utilize the full range of the sensor, voltage span was set to the extreme displacement range. Then a calibration was made against the actual displacement from a micrometer in order to obtain a calibration curve. The distance between the sensor and the magnet was calibrated in the range of 0.5 and 1.0 cm. It should be noted that the correlation of reading voltage and actual displacement was nonlinear, and the calibration curve used was

$$y = \frac{1.05446}{x^{0.5}} - \frac{0.05692}{x} + 0.01534 \qquad (1)$$

where x is the reading voltage and y is the actual displace-

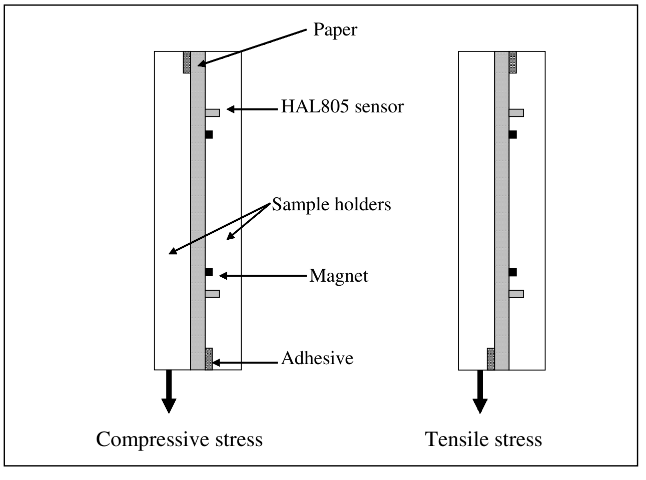

Fig. 2: Schematic of sample preparation

ment between the magnet and the sensor. Total gage length was the distance between the two magnets. Then creep strain was calculated from the displacement changes of the two magnets, which was relative to the HAL805 sensors. This value was obtained by dividing the total deformation by the initial gauge length. The use of the Hall sensors allowed for non-contact strain measurement and more importantly provided a gauge length that did not include the samples ends, which were in shear.

SAMPLE MOUNTING

Since the creep apparatus was able to measure both tensile and compressive creep, the sample mounting depended upon the desired loading, as depicted in Fig. 2. Mounting adhesive was prepared by mixing equal parts of a two-component Epoxy 907 from Miller-Stephenson Chemical. All specimens were cut to 1 inch in width and 8 inches in length. Then a thin layer of the adhesive was applied on the paper surface at one side of each end (0.5-inch long). Next, the paper was sandwiched between the sample holders without external pressure. The adhesive in the sandwich was generally allowed to cure at least 12 hours. After curing, each magnet, mounted to the lightweight plastic block, was attached on the paper surface at the opening area of the drilled rectangular opening of the sample holder **D**.

REDUCING FRICTIONAL EFFECTS

Due to the flat plate-support design, friction impacts the creep results. For a preliminary study of the static friction coefficient in this research, many chemicals were tested by applying them on a sheet of 75-g/m^2 copy paper. Copy paper was chosen as a reference because it has a relatively smooth surface. Various chemicals and treatments were tried to reduce the coefficient of friction in an attempt to minimize these effects. The static frictional coefficient was measured by the Amontons II apparatus according to ISO test method 15359.[13]

Teflon coating typically provides a coefficient of friction less than 0.10 in the dry state.[14] We found that a Teflon coating on the mounting blocks significantly reduced the friction at the paper-aluminum plate. To test different chemical treatments of the paper, Teflon tape was mounted on a stationary sled. A selected chemical was applied on the surface of the copy paper before the sheet was placed on a movable horizontal table. There were three selected chemicals with four testing conditions. First, a stearic acid, was utilized in a similar manner to use in previous work for reducing the frictional coefficient.[15] The stearic acid was prepared at 5 mmol/L by dissolving it in acetone. After complete mixing, the solution was sprayed on a sheet of paper. The sheet was then dried under restraint at 23°C and 50% relative humidity (RH). A second material, paraffin wax, was tested in the second condition. This paraffin wax was previously used in a cold corrugating process[16] to reduce friction. It was produced by mixing stearin, graphite, and silicone oil and by then molding the mixture into solid bars. A treatment could be accomplished by abrading the paraffin agent onto the sheet. The number of paraffin passes could cause differences in static coefficients of friction, as shown in Table 1. The third condition used commercial graphite powder. The powder was distributed on the sheet surface before measurement. The

Table 1—Number of paraffin wax passes on the first static frictional coefficient

NUMBER OF PASSES ON PARAFFIN WAX TREATMENT	STATIC FRICTIONAL COEFFICIENT ± S.D.
1	0.257 ± 0.016
2	0.167 ± 0.006
3	0.169 ± 0.015
10	0.177 ± 0.010

last condition was to abrade paraffin wax and then to additionally spray commercial graphite powder onto the paper surface. The results of static frictional coefficient were compared with a control experiment, in which no chemical was applied on the paper surface (see Table 2).

The preliminary tests for static frictional coefficients shown in Table 2 suggest that paraffin wax provided a minimum value of the static frictional coefficient. Therefore, the combination of paraffin wax on the sheet and Teflon tape on the aluminum plates was selected for these creep studies.

TEST RESULTS

Tensile Creep

To verify the results of tensile creep, two different samples were tested and compared with results from a traditional tensile creep tester at the Institute of Paper Science and Technology.[17] The first sample was a 205-g/m^2 commercial linerboard. The second sample was a laboratory sheet made with the Noble & Wood sheet machine. It had a basis weight of 160 g/m^2. For the laboratory-made sheet, the furnish was a never-dried bleached northern softwood kraft pulp supplied by Domtar. The pulp was beaten to a freeness level of approximately 550 Canadian Standard Freeness (CSF) in a laboratory Valley beater.[18] After a sheet was formed, it was pressed at 50 psi for 5 minutes and then 2 minutes, respectively, before being fully restraint-dried for 20 minutes in the Emerson dryer.

Table 2—Preliminary results of static frictional coefficient

LUBRICANT MATERIALS	STATIC FRICTIONAL COEFFICIENT OF PAPER[(1)] AGAINST TEFLON-TAPE SURFACE
No chemical—controlled experiment	0.374
Stearic acid in acetone	0.284
Paraffin wax[(2)]	0.167
Graphite powder	0.259
Paraffin wax[(2)] + graphite powder	0.230

[(1)] Sample was copy paper.
[(2)] Paraffin wax was applied on paper surface with two passes.

The same 9027-gram tensile load was applied to each sample. The linerboard was only tested in the cross machine direction (CD). The load was equal to 30% of the laboratory sheet's 50% RH tensile strength and 53% of the CD linerboard's 50% RH tensile strength. All tensile creep experiments were performed at 23°C and 50% RH.

A major difference between this new device and the traditional tensile creep tester was the lateral support. In order to compare tensile creep results, the applied lateral force from this apparatus had to be minimized. However, there was a limit to increasing the gap between the sample holders **C** and **D** because a sample would not be parallel to the loading direction. This caused some error in the strain measurement. The tensile creep curves were compared after eliminating any initial deformation.

Figures 3 and 4 illustrate mean tensile-creep curves for the CD linerboard and laboratory sheet, respectively. The mean

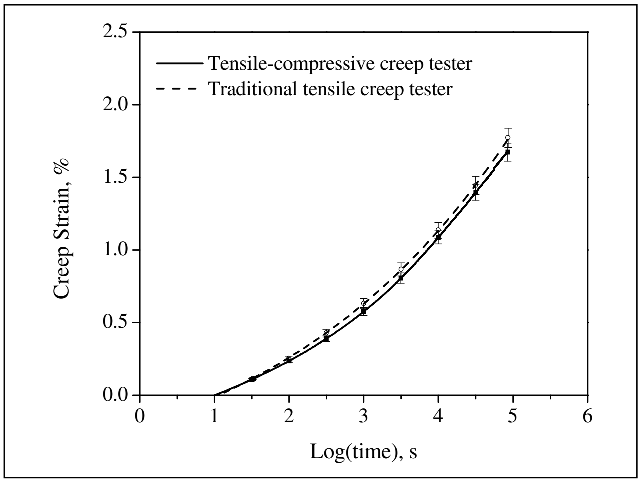

Fig. 3: Mean tensile-creep curves for the 205-g/m^2 CD linerboard at 53% of the 50% RH breaking load. The error bars show 95% confidence intervals.

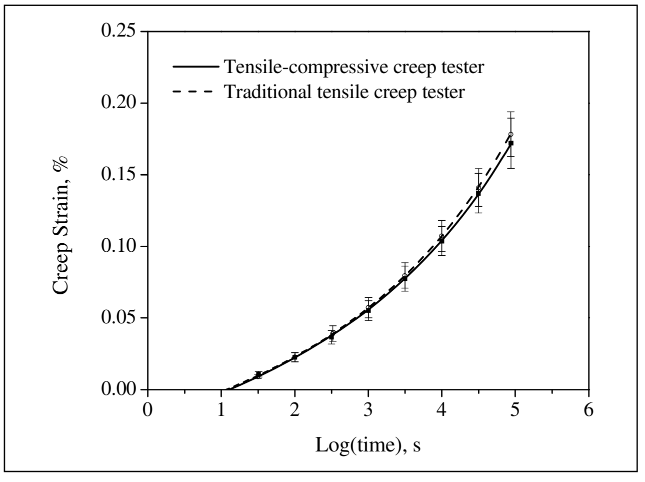

Fig. 4: Mean tensile-creep curves for the 160-g/m^2 laboratory-made sheet at 30% of the 50% RH breaking load. The error bars show 95% confidence intervals.

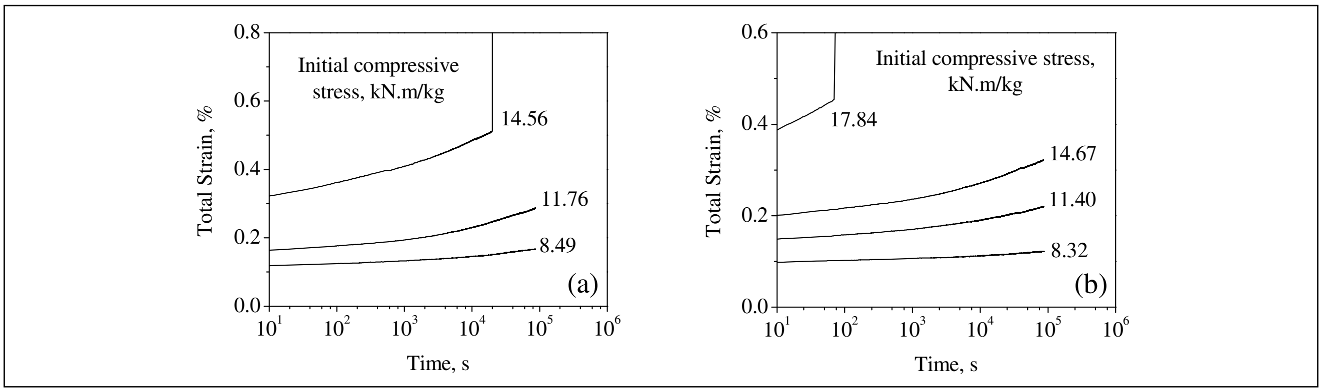

Fig. 5: Compressive creep curves at different initial compressive stresses with an average initial lateral force of (a) 8.84 N and (b) 26.24 N

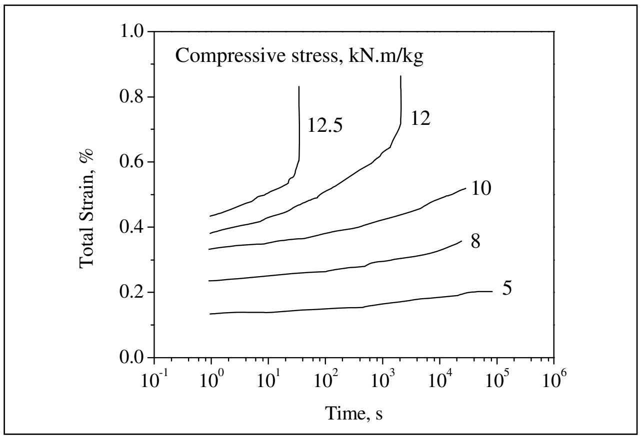

Fig. 6: Compressive creep of a 185-g/m^2 linerboard in the machine direction[8]

tensile-creep strain for both samples was slightly lower for the new creep tester. It was noticed that the variation of tensile creep from both samples was larger as time increased. This may be primarily attributed to a variation in the sheet. The mean tensile creep was comparable for both samples. Note that the laboratory-made sheet exhibited less creep strain than the CD linerboard, showing that the correlation between the two testers is good for both small and large creep strains.

Compressive Creep

Attempts to verify the apparatus for compressive creep were made using 85-g/m^2 laboratory-made linerboard. This basis weight should allow comparison of the results with previous research[8] at similar sheet properties even though the sheets were manufactured differently. In the previous research, Haraldsson et al.[8] examined a 185-g/m^2 commercial linerboard in the machine direction (MD) at 50% RH and 23°C. The MD compressive strength index of their specimen was 27.4 N.m/g.

A similar pulp (never-dried, bleached northern softwood kraft pulp with 550 CSF) was formed in the Formette Dynamique sheet former.[19] Each wet sheet was couched off the wire with blotters and transferred to a combination nip/press drum dryer. The felt tension of the drum dryer was set at 20 psig. At the dryer, each wet sheet was fed in while the felt was moving. When a sheet was completely sandwiched in between the drum and the felt, the motor for the felt drive was stopped for restraint drying of the wet sheet. A sheet was completely dried after 20 minutes. The sheets were conditioned at 90% RH for 24 hours. After that, they were stored at 20% RH for 24 hours. Finally the sheets were held at 50% RH for at least one week before the creep tests were performed. During all of these conditioning steps, the temperature was held at 23°C. The average basis weight of this laboratory-made linerboard was 184.4 g/m^2, and the MD compressive strength index was 26.4 N.m/g.

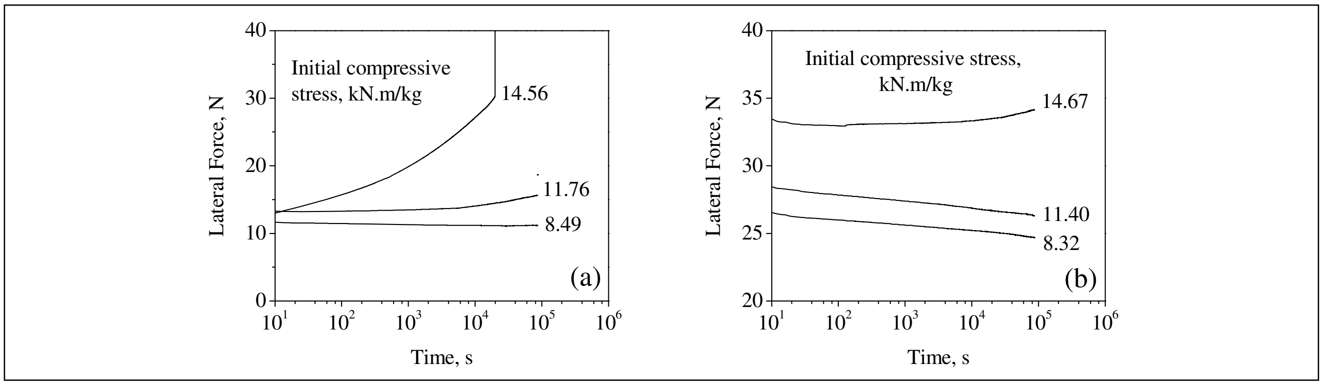

Fig. 7: Lateral force at different initial compressive stresses with an average initial lateral force of (a) 8.84 N and (b) 26.24 N

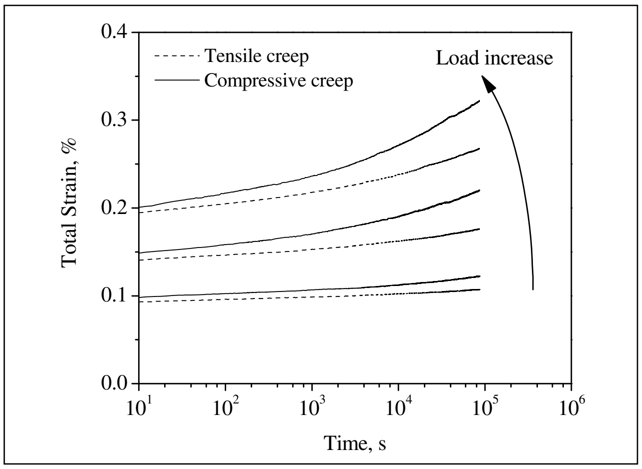

Fig. 8: Tensile and compressive creep curves under the same lateral force

All compressive creep tests were performed at 23°C and 50% RH. The compressive creep tests needed to have some lateral forces applied to the sample to minimize buckling. After the sample was glued and mounted on the creep tester, the system was controlled for 24 hours to reach steady-state conditions. At steady state, the lateral forces were defined as "initial lateral forces." The load was then applied.

Figures 5a and 5b show compressive creep curves at two different average initial lateral forces: 8.84 N and 26.24 N, respectively. Each figure shows creep curves for different levels of compressive dead load (initial compressive stress) without correcting for the frictional effects. If the initial lateral force was not adequate, the strain was more sensitive to load level. In fact, total strain increased dramatically when the paper began to buckle between the plates (see Fig. 5a at 14.56 kN.m/kg or Fig. 5b at 17.84 kN.m/kg). At the buckling point, the slope of a creep curve changed immediately. These results are in agreement with a previous study on compressive creep,[8] as depicted in Fig. 6. It was noticed that their samples buckled earlier than our samples if compared at the same compressive stress. Hence, the column lateral support may require higher force to prevent early localized buckling compared with the flat plate support.

Figures 7a and 7b illustrate lateral force over time due to the applied creep stresses in Figs. 5a and 5b, respectively. The instantaneous change of lateral force appeared as a result of initial loading. The amount of instantaneous change in lateral force depends upon the magnitude of the compressive stress and initial lateral force. Compressive creep data show two opposite trends as follows: (1) the lateral force was slightly reduced during creep at low compressive stresses, and (2) the lateral force increased over time at greater compressive stresses. The gradual decrease in lateral force during creep could be caused by stress relaxation of paper in the thickness direction. On the other hand, an increase of lateral force over time would indicate the resistance the plates offer to restrict buckling.

The advantage of this tester is that tensile and compressive creep for paper can be conducted under the same loading conditions. As shown in Fig. 8, comparisons of the tensile and compressive creep response with varying dead load can be found under the same lateral force.

CONCLUSIONS

A new apparatus based on the flat plate support was constructed for measuring uniaxial tensile and compressive creep. The lateral support supplied by the plates could significantly reduce sample buckling in compression except at large loads. The equipment construction and sample preparation used in the experiment are simple. A non-contact strain measurement allowed for strain measurements away from the glued edges. The device allowed for comparisons of the intrinsic tensile and compressive creep response under similar loading conditions. The new apparatus showed satisfactory results in both stress directions, compared with another creep tester and previous study. The device should be a useful tool in the investigation of similarities and differences in tensile and compressive creep for paper.

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