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# Effect of Humidity Conditions on Bending Creep Performance of Finger-Jointed Woods*1

Han-Min Park*2 and Hee-Seop Byeon*2†

## ABSTRACT

To evaluate the durability of finger-jointed woods according to change of humidity conditions, four types of finger-jointed woods glued with different kinds of adhesives and finger pitches were made with Sitka spruce, and the effect of humidity conditions on creep performances was investigated.

The shape of creep curves differed among humidity conditions, and the inclination of creep curves was greatest in 85%RH, and lowest in 65%RH. Their creep curves showed a linear behavior beyond approximately one hour, regardless of humidity conditions. The $A$ values of the creep curves fitted to power law increased with increasing relative humidity, whereas the $N$ values were in order of 30 > 85 > 65%RH unlike the $A$ values. The initial deformation increased with increasing relative humidity, whereas the creep deformation unlike the initial deformation was in order of 85 > 30 > 65%RH, and it was found that the creep deformation of finger-jointed woods indicated the smaller amount in air-dry moisture content rather than in a low moisture content less than 30%RH. Finger-jointed woods with 6.8 mm (L) pitch had the greater creep amount than in those with 4.4 mm (S) pitch in all humidity conditions. The difference of creep amount between both adhesives in all humidity conditions was small. Relative creep at 240 hr was greatest as 62.2~71.9% in 85%RH, and the values indicated 2.1~2.6 times that of 30%RH and 3.0~3.6 times that of 65%RH and were equal or slightly greater than that of solid spruce.

*Keywords* : finger-jointed wood, humidity, adhesive, pitch, creep, relative creep

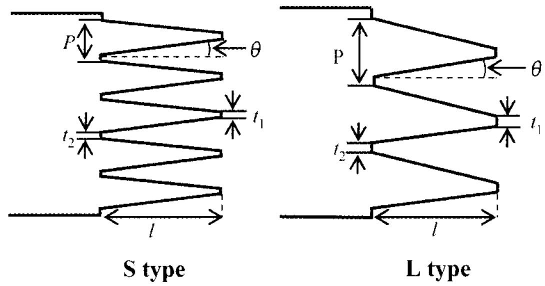
## 1. INTRODUCTION

As woods and wood-based materials are used as a structural material for buildings, it is important to grasp their creep behaviors under various conditions such as applied loads and humidity conditions. A lot of researches on creep behaviors of woods and wood-based materials have been performed (Schniewind, 1968; Fushitani and Bono, 1975; Nakai, 1978; Arima *et al.*, 1981; Jang, 1989; Hong and Arima, 1993; Hoyle *et al.*, 1994; Hong and Park, 2006). However, there are little researches on creep behaviors of finger-jointed woods. In a previous report (Park *et al.*, 2005a), the effects of finger pitches and adhesives on bending creep performances of finger-jointed woods under 65%RH were investigated. It was observed that the difference

*1 Received on June 27, 2007; accepted on August 9, 2007.
*2 College of Agri. & Life Sci., Inst. of Agri. & Life Sci., Gyeongsang Nat'l Univ., Jinju 660-701, Korea.
† Corresponding author : Hee-Seop Byeon (hsbyeon@gnu.ac.kr)

of creep amount by changing of finger pitches of finger-jointed woods was small, but there were marked differences in creep amount of finger-jointed woods by changing adhesives. And it was found that the creep performances of finger-jointed woods glued with aqueous vinyl urethane (AVU) resin had a small creep amount like that glued with resorcinol-phenol formaldehyde resin type adhesive.

In this study, following the previous report (Park *et al.*, 2005a), in order to evaluate the durability of finger-jointed woods according to change of humidity conditions, four type finger-jointed woods with different kinds of adhesives and finger pitches were made with Sitka spruce. Effect of humidity conditions on creep performances of finger-jointed woods was investigated.




(Unit : mm)

| | S | L |
|---|---|---|
| $P$ | 4.4 | 6.8 |
| $l$ | 15.3 | 15.3 |
| $\tan^{-1}\theta$ | 13.48 | 7.57 |
| $t_1$ | 0.95 | 1.05 |
| $t_2$ | 0.80 | 0.90 |
| $t_1$-$t_2$ | 0.15 | 0.15 |

Fig. 1. Dimension and finger profile.

Notes; $P$: pitch, $l$: Length of finger, $t_1$: Tip width, $t_2$: Root width, $\theta$: Slope angle of finger, S: Finger-jointed wood types with small finger pitch (4.4 mm), L: Finger-jointed wood types with large finger pitch (6.8 mm).

# 2. MATERIALS and METHODS

## 2.1. Specimen Preparation

Sitka spruce (*Picea sitchensis* Carr.) was selected for this study. Longitudinal elements without visible defects measuring 22 (T) × 22 (R) × 400 (L) mm were cut from the Sitka spruce. Density and static MOE of the elements were measured, and their ranges were in 0.416 ~ 0.465 Mg/m$^3$ and 10.5 ~ 15.2 GPa. The elements were classified without density and static modulus of elasticity (MOE) bias among three humidity conditions. The centers of the longitudinal elements were cut to make fingers with 4.4 mm (S) and 6.8 mm (L) pitches as shown in Fig. 1. Resorcinol-phenol formaldehyde (RPF) resin and aqueous vinyl urethane (AVU) resin formulated for room temperature cure were used. The finger-jointing parts were pressed under a pressure of 3.92 MPa for 20 seconds, and cured for more than a week in a room maintained at 20°C and 65% RH. And then the finger-jointed wood specimens of 20 (T) × 20 (R) × 360 (L) mm were completed. The number of specimen for each type was 3, respectively.

## 2.2. Bending Creep Test

Bending creep test for finger-jointed wood specimens was conducted by four-point loading. The span was 300 mm, and the distance between a loading point and a supporting point was 100 mm. The stress corresponding to 25% of breaking stress obtained from static bending test was applied to each specimen. Three humidity conditions of 30, 65 and 85%RH were used with 20°C as constant temperature. Total creep time was for 240 hours (10 days). The deflection of the mid-span was measured with a dial gauge. The creep deflection was measured at interval of 0.5, 1, 3, 5, 10 minutes until 30 minute after initial deformation, and then was

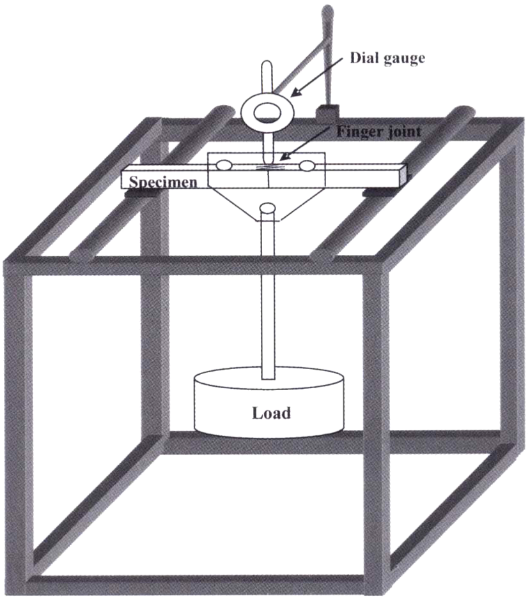



Fig. 2. Schematic diagram of bending creep test.

measured for 2 hours at interval of 30 minute. After 2 hours, it was measured at interval of 1, 2 and 3 hours until 10 hours, and then it was measured at interval of 12 hours for 2 days and at interval of 24 hours for 7 days. The schematic diagram of bending creep test is shown in Fig. 2. Total creep compliance $D(t)$ and creep compliance $D_c(t)$ (total creep compliance except for initial compliance) were obtained using Eqs. (1) and (2) as follows:

$$D(t) = \frac{\varepsilon(t)}{\sigma} = \frac{4bh^3y(t)}{Pl_1(3l^2 - 4l_1^2)} \qquad (1)$$

where $P$ is the applied load; $l$ is the span; $b$, $h$ are the width and depth of the specimen; $l_l$ is the distance between a loading point and a supporting point; and $y(t)$ is the creep deflection at time($t$).

$$D_c(t) = D(t) - D(0.008) \qquad (2)$$

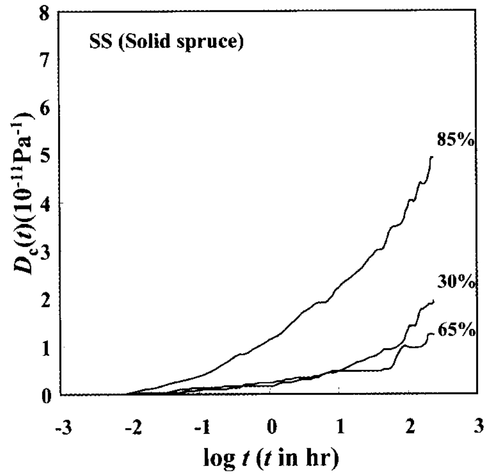



Fig. 3. Typical examples of creep curves for solid spruce under different humidity conditions.
Note; 30, 65 and 80% are the relative humidity conditions during creep test.

where $D(0.008)$ is the initial compliance at $t$ = 0.008 hr (30s).

## 3. RESULTS and DISCUSSION

### 3.1. Bending Creep Curves under Different Humidity Conditions of Finger-jointed Woods

Bending creep curves for solid spruce and finger-jointed woods under 30, 65 and 85%RH are shown in Figs. 3~5. Figs. 3 and 4 show the logarithm plots of time for typical examples of solid spruce and each type of finger-jointed woods and the difference among the humidity conditions was compared. The shape of creep curves showed the parabolas which the upper right-side increased in all humidity conditions, and it was found that the inclination of their creep curves had the highest value in 85%RH condition and the lowest in 65%RH. The difference of the creep curves between finger-jointed woods glued with RPF resin and AVU resin

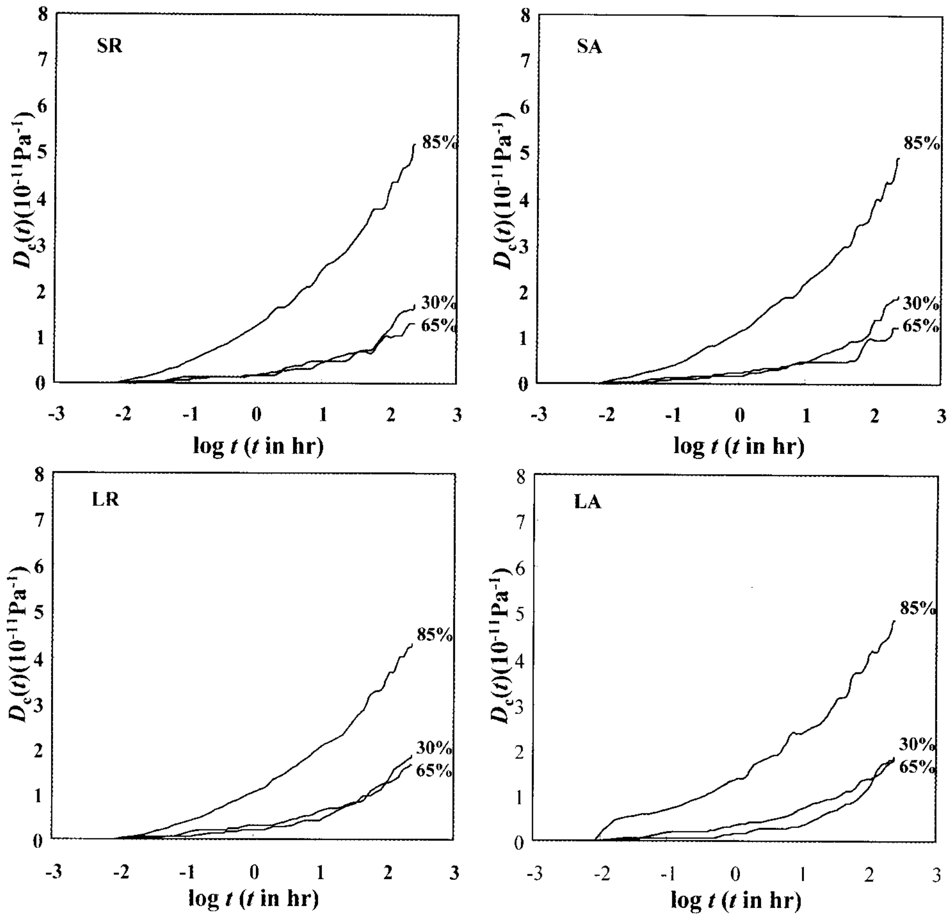



Fig. 4. Typical examples of creep curves of finger-jointed woods under different humidity conditions.
Notes; SR: Finger-jointed woods with 4.4 mm (S) pitch and RPF resin, LR: Finger-jointed woods with 6.8 mm (L) pitch and RPF resin, SA: Finger-jointed woods with 4.4 mm (S) pitch and AVU resin, LA: Finger-jointed woods with 6.8 mm (L) pitch and AVU resin. 30, 65 and 85%: See note in Fig. 3.

was very small, regardless of humidity conditions.

Fig. 5 shows the double logarithm plots of creep compliance and the time for typical examples of solid spruce and each type of finger-jointed woods, and the comparison for each type of finger-jointed woods under different humidity conditions was performed. There were differences in creep curves among three humidity conditions, and their creep curves showed a linear behavior beyond approximately one hour. The creep curve ($D_c(t)$) was expressed by the following equation (power law) :

$$D_c(t) = At^N \quad (3)$$

where $A$ and $N$ are constants, and $t$ is time.

It has been reported in many papers (Kitahara and Perng, 1965; Schniewind, 1968; Nakai, 1978; Saito *et al.*, 1980; Arima *et al.*, 1981; Morizumi, 1981; Hoyle *et al.*, 1994; Aratake and Arima, 1995, 1996; Aratake *et al.*, 2002;

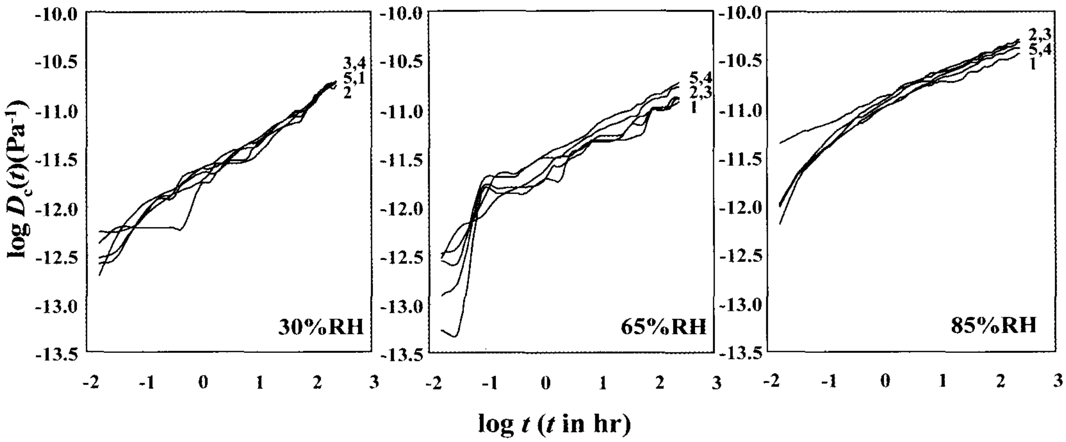



Fig. 5. Double logarithm plot of creep deformation and time for typical examples of each type of finger-jointed woods under 30, 65 and 85%RH.

Notes; 1: SS, 2: SR, 3: SA, 4: LR, 5: LA.
SS, SR, SA, LR and LA are the same as in Figs. 3 and 4.

Table 1. Results of bending creep tests for finger-jointed woods under different humidity conditions

| Type | RH (%) | Density (Mg/m$^3$) | $N$ | $A$ ($10^{-11}$Pa$^{-1}$) | $D$(0.008) ($10^{-11}$Pa$^{-1}$) | $D$(240) ($10^{-11}$Pa$^{-1}$) | Relative creep (%) |
|---|---|---|---|---|---|---|---|
| SS | | 0.427 | 0.390 | 0.198 | 7.54 | 2.26 | 30.0 |
| SR | | 0.440 | 0.403 | 0.238 | 7.64 | 2.12 | 27.8 |
| SA | 30% | 0.438 | 0.416 | 0.227 | 7.80 | 2.27 | 29.0 |
| LR | | 0.427 | 0.428 | 0.233 | 8.05 | 2.44 | 30.3 |
| LA | | 0.434 | 0.461 | 0.198 | 7.79 | 2.46 | 31.6 |
| SS | | 0.429 | 0.266 | 0.349 | 7.67 | 1.44 | 18.8 |
| SR | | 0.444 | 0.316 | 0.274 | 7.38 | 1.49 | 20.2 |
| SA | 65% | 0.443 | 0.317 | 0.283 | 7.53 | 1.46 | 19.4 |
| LR | | 0.437 | 0.309 | 0.340 | 8.49 | 1.78 | 21.0 |
| LA | | 0.431 | 0.304 | 0.358 | 8.46 | 1.84 | 21.8 |
| SS | | 0.454 | 0.333 | 0.886 | 8.34 | 5.20 | 62.4 |
| SR | | 0.430 | 0.338 | 1.05 | 8.55 | 6.15 | 71.9 |
| SA | 85% | 0.446 | 0.346 | 0.877 | 8.65 | 5.38 | 62.2 |
| LR | | 0.431 | 0.328 | 0.978 | 8.90 | 5.67 | 63.7 |
| LA | | 0.438 | 0.316 | 1.11 | 8.88 | 5.99 | 67.5 |

Notes; Each value is the average of three measurements, RH: Relative humidity, SS: Solid spruce, SR: Finger-jointed woods with 4.4 mm pitch and RPF resin, SA: Finger-jointed woods with 4.4 mm pitch and AVU resin, LR: Finger-jointed woods with 6.8 mm pitch and RPF resin, LA: Finger-jointed woods with 6.8 mm pitch and AVU resin. $N$ and $A$: constant values in the exponential regression equation between creep compliance and time ($D_c(t) = At^N$), $D$(0.008): Initial compliance at 0.008 hr, $D_c$(240): Creep compliance at 240 hr except for initial compliance ($D$(240) − $D$(0.008)).

Park *et al.*, 2002, 2005a, 2005b, 2006, 2007) that the creep curves of wood and wood-based materials were fitted to power law.

The fitted values of $N$ and $A$ were shown in Table 1. In the logarithmic regression of the Eq. (3), the correlation coefficients were in the range of 0.994 ~ 0.999 in 30%RH, 0.984 ~ 0.995 in 65%RH and 0.986 ~ 0.990 in 85%RH. The $A$ value corresponding to creep deformation at 1 hour after initial deformation was highest in 85%RH and lowest in 30%RH, and it was found that this value increased with increasing relative humidity. However, the $N$ values which expressed as the inclination of creep compliance from 1 to 240 hours after initial deformation were highest in 30%RH ($N$=0.390 ~ 0.428), and then were in 85%RH ($N$=0.316 ~ 0.346), and were lowest in 65%RH ($N$=0.266 ~ 0.317). From Eq. (3), it is able to be changed with $D_c(t)/A = t^N$, and this $N$ value increases with increasing $D_c(t)/A$, thus finger-jointed woods, with the higher creep compliance from 1 to 240 hours than creep compliance by 1 hour after initial deformation, have a higher $N$ value. The $N$ values of finger-jointed woods under 30%RH were similar to those of Douglas-fir and Japanese cedar solid woods under humidity change (Hoyle *et al.*, 1994; Aratake *et al.*, 2002), and those for 65 and 85%RH were slightly greater than those of Japanese cedar and kastura solid woods (Arima *et al.*, 1981), lauan plywood (Nakai, 1978; Arima *et al.*, 1981) and cross-laminated woods with 45° annual ring angle in the core (Park *et al.*, 2002, 2005b), and were similar to those of cross-laminated woods with 0° and 90° annual ring angles (Park *et al.*, 2002).

## 3.2. Initial Deformation and Creep Deformation of Finger-jointed Woods under Different Humidity Conditions

The results of bending creep test for solid spruce and finger-jointed woods under three humidity conditions are shown in Table 1. The Effects of humidity conditions on initial compliance ($D$(0.008), creep compliance at 0.008 hr) and creep compliance ($D_c$(240), creep compliance at 240 hr except for initial compliance) of finger-jointed woods are shown in Fig. 6.

Initial compliances of finger-jointed woods glued with resorcinol-phenol formaldehyde (RPF) resin tended to increase with increasing humidity on the whole, whereas there was little difference of initial compliances among three humidity conditions. The values were higher in finger-jointed woods with 6.8 mm pitches than in those with 4.4 mm pitches. The creep compliances of finger-jointed woods glued with RPF resin were in order of 85 > 30 > 65%RH unlike the initial compliances. For finger-jointed woods with 4.4 mm (S) pitches, the ratios of creep compliances among humidity conditions were in 30 : 65 : 85%RH = 1.00 : 0.703 : 2.90, and that with 6.8 mm (L) pitch was in 1.00 : 0.730 : 2.32, and it was found that the extent of the decrease in 65%RH was greater in finger-jointed woods with 4.4 mm (S) pitch than in that of 6.8 mm (L) pitch. These values were found to have a small difference as compared with 1.00 : 0.637 : 2.30 of solid spruce. The reason why creep compliances of finger-jointed woods in 65%RH condition were smaller than that in 30%RH condition is considered because in the 30%RH with a low moisture content, the deformation of hydrogen bonds was increased by decreasing moisture content, whereas in the 65%RH with air-dry moisture content, unstable hydrogen bonds which the deformation and breaks of intermolecular hydrogen bonds occurred in the creep progress were decreased by adsorbing small quantities of water. In the 85%RH with high moisture content, creep compliance increases because the intermolecular cohesion was decreased by absorbing large quantity water. This corresponded to the results reported by Suzuki *et al.* (1965) that creep amount except for initial deformation of solid cypress was smallest in 7 ~ 14% of air-dry

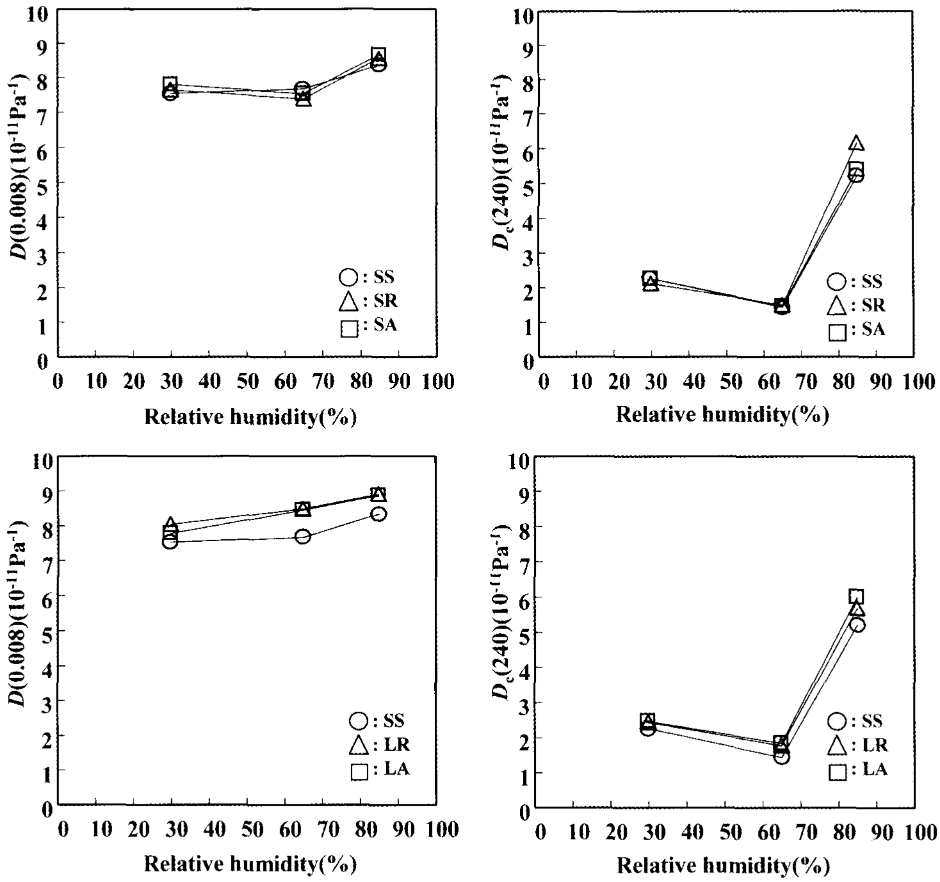



Fig. 6. Effect of humidity conditions on initial and creep deformations of finger-jointed woods.
Notes; SS, SR, SA, LR and LA are the same as in Figs. 3 and 4.

moisture content region, and then in 0~7% of a low moisture content region, and was greatest in more than 14% of a high moisture content region. A similar result was found in finger-jointed woods glued with AVU resin.

The initial and creep compliances showed the higher values than those of solid spruce on the whole and the extent was greater in the creep compliances than in the initial compliances, as well the creep compliance of finger-jointed woods with 6.8 mm pitches under 65%RH had the greatest difference as compared with that of solid spruce.

## 3.3. Relative Creep of Finger-jointed Woods under Different Humidity Conditions

Fig. 7 shows the relation between the relative creep of finger-jointed woods represented as the percentage of creep compliance at 240 hr to initial compliance and humidity conditions. For finger-jointed woods glued with RPF resin, the relative creeps were in order of 85 (63.7~71.9%) > 30 (27.8~30.3%) > 65%RH (20.2~21.0%). The relative creep values under 85%RH were slightly higher than in that of solid spruce under 85%RH, and their values showed

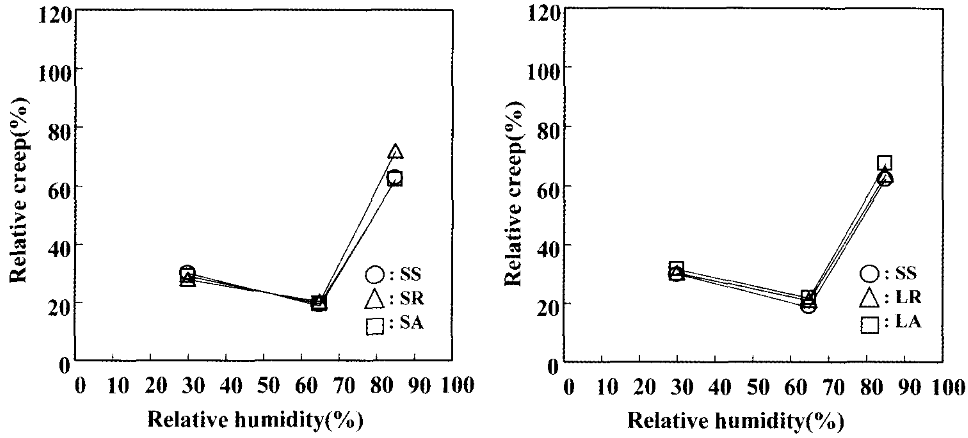



Fig. 7. Effect of humidity conditions on relative creep at 240 hr of finger-jointed woods.
Notes; SS, SR, SA, LR and LA are the same as in Figs. 3 and 4.

2.1 ~ 2.6 times that under 30%RH and 3.0 ~ 3.6 times that under 65%RH. A similar result was found in relative creep of finger-jointed woods glued with AVU resin.

## 4. CONCLUSIONS

Four types of finger-jointed woods glued with different adhesives and finger pitches were made with Sitka spruce and the effect of humidity conditions on bending creep performances of finger-jointed woods were investigated. The shapes of creep curves of finger-jointed woods markedly differed among humidity conditions and their creep curves showed a linear behavior beyond approximately one hour, regardless of humidity conditions. The $A$ values of the creep curves fitted to power law increased with increasing relative humidity, whereas the $N$ values were in order of 30 > 85 > 65%RH. The creep deformation of finger-jointed woods unlike the initial deformation was in order of 85 > 30 > 65%RH, and it was found that the creep deformation of finger-jointed woods indicated the smaller creep amount rather in air-dry moisture content than in a low moisture content less than 30%RH. Finger-jointed woods with 6.8 mm (L) pitch had the greater creep amount than in those with 4.4 mm (S) pitch in all humidity conditions. The relative creep was also in order of 85 > 30 > 65%RH, and their values for 85 %RH had 2.1 ~ 2.6 times that for 30%RH and 3.0 ~ 3.6 times that for 65%RH. In all humidity conditions, the differences of creep deformation and relative creep between RPF resin and AVU resin were small. Therefore, finger-jointed woods glued with RPF resin and AVU resin can be effectively used under air-dry humidity condition than in a low humidity condition less than 30%RH and a high humidity condition more than 85%RH, and it can be expected that AVU resin without formaldehyde emission as structural adhesives for finger-joints will be widely used.

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