Creep Behavior and Prediction of Fiber-Reinforced Polymer Reinforced Timbers Under Changing Temperature and Relative Humidity

In-Hwan Lee, Yo-Jin Song, and Soon Il Hong *

The creep behavior of fiber-reinforced polymer (FRP) reinforced larch laminar timber was studied with respect to temperature and humidity fluctuations. There was a control group of larch laminated with two small-diameter timbers with FRP (carbon FRP (CFRP), glass FRP (GFRP)) produced; the laminated lumber had the same cross-sectional area as the two laminated lumber specimens with reinforced tensile parts. A creep test with fluctuating temperature and humidity was conducted by applying a load of 25% of the bending strength of the control specimen. A total of 8 specimens, 2 for each type, were measured for creep deformation at 9:00 am and 6:00 pm daily for approximately 14,000 h. Temperature and humidity fluctuations were measured every hour. The equilibrium moisture content and humidity of the creep test space exhibited a proportional relationship, and the moisture content of each specimen did not show a noticeable correlation with humidity and equilibrium moisture content. The average relative creep was measured as approximately 0.67 for the control, 0.4 for Glulam, and 0.43 for both the CFRP- and GFRP-reinforced specimens. Thus, the creep deformation of all the reinforced pieces was confirmed to be lower than that of the control specimen.

DOI: 10.15376/biores.18.4.7239-7250

Keywords: Bending; Creep; CFRP; GFRP; Glulam; Timber

Contact information: College of Forest & Environmental Sciences, Kangwon National University, 1, Kangwondaehak-gil, ChunCheon-si, Gangwon-do, 24341, Republic of Korea;
** Corresponding author: hongsi@kangwon.ac.kr*

INTRODUCTION

The importance of carbon neutrality has grown as global warming accelerates. Hybrid engineered wood architecture has an average potential reduction effect of global warming of 26.5% compared to reinforced concrete buildings (Pierobon *et al.* 2019). Accordingly, wooden structures made of engineered wood have been increasingly applied worldwide. Engineered wood can secure a large indoor space with a column-beam structure and can also be used as a bearing wall. Research on engineered wood is steadily developing, enabling high-rise wooden structures (Pei *et al.* 2016; Nguyen *et al.* 2018; van de Lindt *et al.* 2019; Aloisio *et al.* 2020).

In this context, improving the strength of members under load is an important condition for high-rise wooden structures. The strength improvement of wood is achieved by reinforcing it with concrete, iron, or glass fiber. The small-diameter timber of the larch can be reinforced and laminated with fiber reinforced polymer (FRP) or steel bar, resulting in improvements of 6 to 37% of the compressive strength; moreover, the strength deviation of the small-diameter timber, which is relatively large, is also considerably reduced (Song *et al.* 2023). In this study, small-diameter timber was reinforced and laminated with FRP with higher specific strength than iron and easy molding. In a previous study, the bending strength performance of small-diameter timber reinforced with carbon FRP (CFRP) and glass FRP (GFRP) improved 45% and 18% compared to that of the control specimen, respectively. André and Johnsson (2010) indicated that the improvement in the physical performance of FRP-reinforced wood also improves its reliability.

In high-rise wooden structures, the strength of members is an important condition, but the deformation behavior in response to long-term loads should be reviewed. In particular, the creep experiment has been designed according to the long-term load of the reinforced specimen using thread materials, but this is still insufficient to adequately analyze a material. Creep quantities are generally measured in controlled temperatures and humidity, but most buildings are exposed to temperature and humidity variations. Wood is a material containing moisture, and its moisture content changes due to the influence of factors of the surrounding environment, such as temperature and relative humidity. Changes in the moisture content of wood affect its physical properties. Therefore, the creep deformation of wooden buildings varies depending on the temperature and humidity. That is, the 'mechano-sortive' behavior should be considered.

In this study, four specimens were produced: Stacked timber specimen, a stacked timber reinforced with CFRP, a stacked timber reinforced with GFRP, and a glulam(glued laminated timber). The prepared specimens were subjected to a long-term load by setting an appropriate stress level of the maximum load. The DOL (duration of load) specimens were continuously measured to analyze the effect of temperature, humidity, and moisture content on the deformation.

EXPERIMENTAL

Materials

Material and specimen fabrication

As experimental materials with an average moisture content of 16%, Japanese larch (*Larix kaempferi* Carr.) with an average air-drying specific gravity of 0.52, small-diameter timber (89 × 120 mm^2), and lumber (30 × 120 mm^2) were used. Anisotropic GFRP and unilateral CFRP were used as reinforcing materials (Fig. 1). For the adhesion between wood pieces, phenol-resorcinol formaldehyde (PRF) adhesive was used. For wood and CFRP and wood and GFRP, epoxy (PE-4100A) and vinyl acetate (MPU-500) adhesives, respectively, were used (Lee *et al.* 2015).

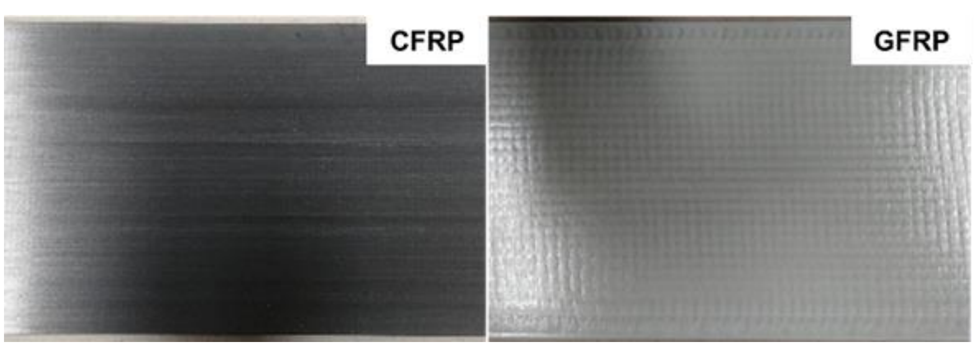

Fig. 1. CFRP (Carbon fiber reinforced polymer) and GFRP (Glass fiber reinforced polymer)

The stacked wood of each material was manufactured by bonding two small-diameter timbers at an adhesive coating amount of 300 g/m^2 and curing them at room temperature (20 to 25 °C) for 24 h at a pressure of 7 kg/cm^2. The 6-ply glulam was manufactured with the same coating amount and pressure as the small-diameter timber. Each reinforcing laminated wood was manufactured by bonding FRP to the outermost tensile portion of the bending member. In the CFRP reinforcement specimen, a unilateral CFRP reinforcement with a volume ratio of 1:0.0073 adhered to the outermost tensile area with epoxy adhesive; the GFRP reinforcement specimen was reinforced by bonding an anisotropic GFRP reinforcement with a volume ratio of 1:0.0197 with a vinyl acetate adhesive. A total of 24 specimens were produced, 6 for each type (Fig. 2).

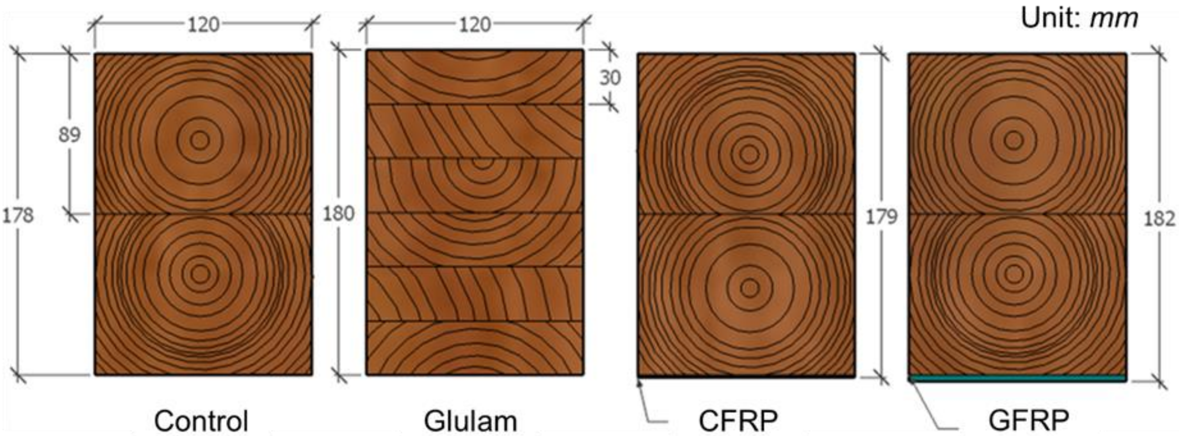

Fig. 2. Schematic of FRP specimens

Methods

Static bending strength performance evaluation

To determine the creep experimental load, a bending strength experiment of the control specimen was conducted with a four-point load in three equal parts. The distance between the points was 2700 mm and the load speeds were 10 mm/min.

Bending creep experimental method

The bending creep experiment was installed indoors where humidity fluctuations were severe due to the opening/closing of the window (Fig. 3).

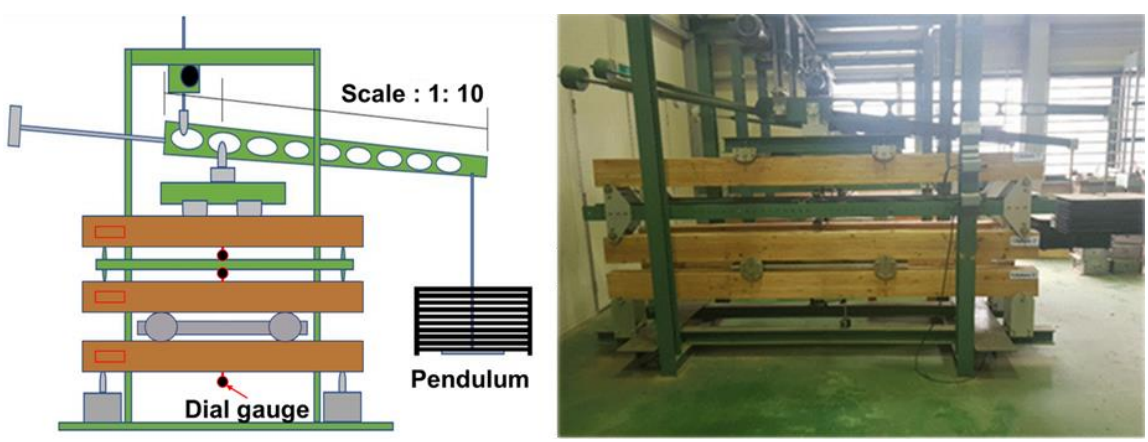

Fig. 3. Test setup for reinforced timber specimens

The creep experiment was performed under constant load of the stress level of 0.25 (1.5 ton) of the control specimens. The moisture content of the creep specimens was measured in the same area of each specimen using a high-frequency moisture content measuring device. Temperature and humidity fluctuations were measured at 1-h intervals. The deformation was measured with a displacement at the bottom center of the specimen.

RESULTS AND DISCUSSION

Creep Deformation of FRP Reinforced Laminated Timber

Evaluation of static bending strength performance of timber specimens

In order to set the stress level to be applied to the creep experiment, a bending strength experiment of the specimen was conducted. As a result of the experiment, the average maximum load of the four Control specimens was measured to be 60 kN. The bending strength was 9% for the Glulam specimen, 45% for the CFRP specimen, and 18% for the GFRP specimen (Table 1). The stress level of the creep experiment was set to 25% of the Control specimens maximum load of 60 kN, that is, 15 kN (1.5 t).

Table 1. Result of Reinforced Timber Specimens

Specimens	FRP Volume ratio (%)	P_{max} (kN)	MOR mean (MPa)	COV (%)	MOE mean (GPa)	COV (%)	Stress level (%)
Control	0	58.6 (1)	41.6 (1)	28.2	9.0 (1)	6.4	25
Glulam	0	64 (1.09)	49.4 (1.19)	9.3	10.4 (1.16)	3.4	23
CFRP	0.73	84.8 (1.45)	60.2 (1.45)	9.3	12.6 (1.40)	5.3	18
GFRP	1.97	69.1 (1.18)	49.1 (1.18)	9.9	9.0 (1.00)	5.1	22

Figure 4 shows the failure mode after the static bending strength test. The tensile parts of all specimen exhibited failure, and specimen reinforced with CFRP and GFRP suppressed the destruction of the reinforcement.

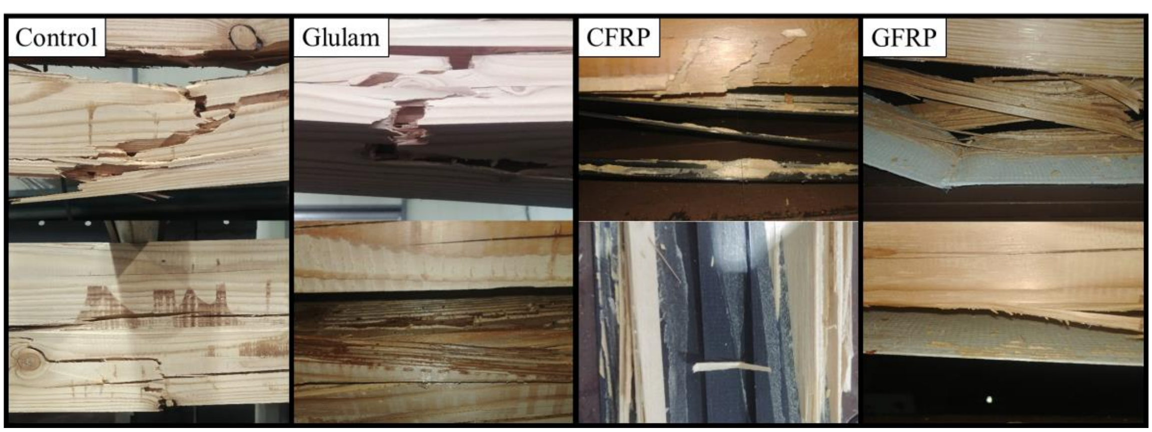

Fig. 4. Failure mode of bending strength specimen

Deformation behavior of relative humidity

Figure 5 shows the relative humidity of the place where the specimens were installed during the creep test. Due to the influence of the weather in Korea, where annual precipitation is concentrated in summer, the relative humidity of summer was measured as the highest at approximately 40 to 85%. The increased relative humidity in summer was maintained until fall, decreased to 25 to 55% in winter, and gradually increased from late spring.

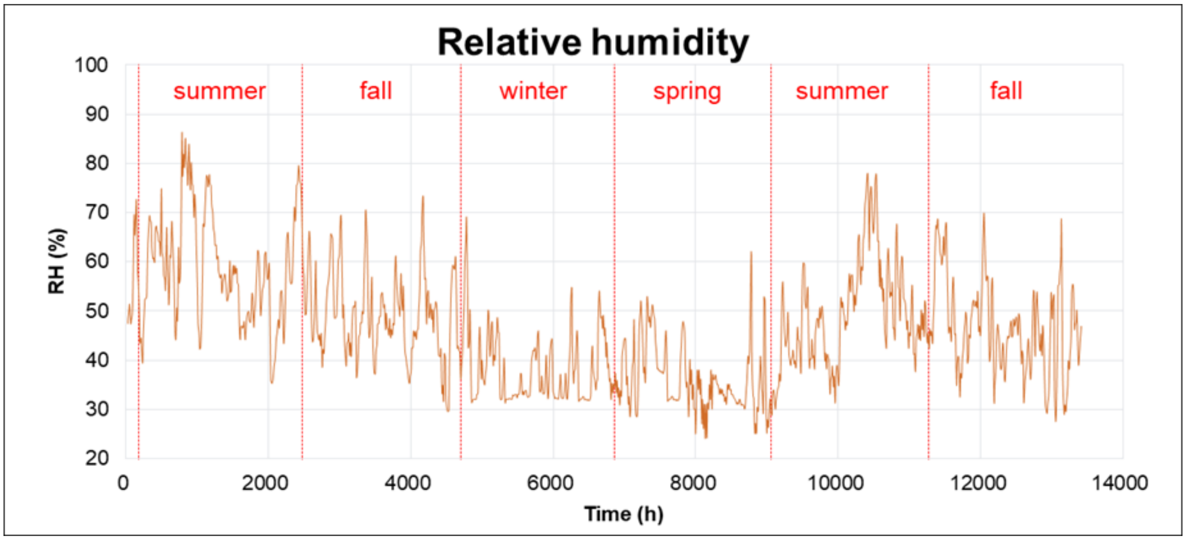

Fig. 5. Test setup for reinforced timber specimens

In general, moisture plays a fundamental role on the properties and behavior of any biologically derived material (Acharjee *et al.* 2011). It is well established that a change in a material's moisture content is influenced by a change in the relative humidity surrounding the material at constant temperature (Gronvall 2006).

Relative humidity measured during the experimental period was used to calculate the equilibrium 1 moisture content by the following equation,

$$\text{EMC (\%)} = \frac{1800}{W} \times \left(\frac{Kh}{1-Kh} + \frac{K_1Kh+2K_1K_2K^2h^2}{1+K_1Kh+K_1K_2K^2h^2}\right) \quad (1)$$

where $W = 349 + 1.29T + 0.0135T^2$; $K = 0.805 + 0.000736T - 0.00000273T^2$; $K_1 = 6.27 - 0.00938T - 0.000303T^2$; $K_2 = 1.91 + 0.0407T\text{-}0.000293T^2$; T represents temperature, and h represents humidity (Glass and Zelinka 2021).

Relationship between moisture content and equilibrium moisture content of the specimen

The relationship between the moisture content and the equilibrium moisture content of the specimens according to the change in temperature and humidity during the creep experiment is as follows. At the beginning of the investigation, when the sample was loaded, the difference between the moisture content and the equilibrium moisture was large. Since the creep stabilized after 2000 h, the moisture content and equilibrium moisture were measured similarly (Fig. 6). The variation in moisture content and equilibrium moisture content generally showed similar deformation behavior in summer and winter, but the pattern of deformation behavior was different in spring and autumn.

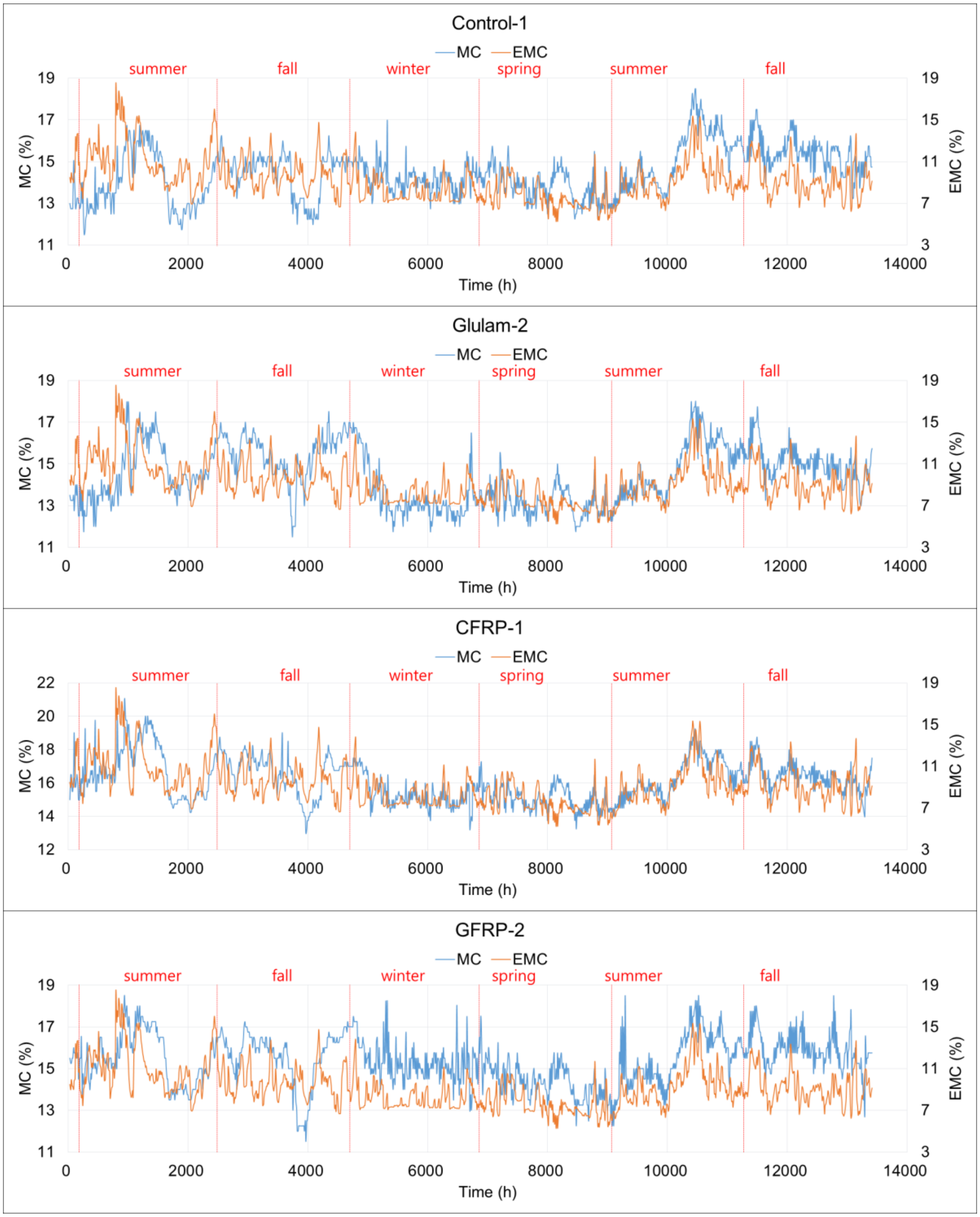

Fig. 6. Relationship between moisture content and equilibrium moisture content

Relative creep

The relative creep according to the temperature and humidity change was calculated using Eq. 2,

$$\text{Relative Creep} = \frac{\epsilon_t - \epsilon_0}{\epsilon_0} \tag{2}$$

where ϵ_t is the current deformation and ϵ_0 is the initial deformation.

After measuring during 13400 h, the relative creep values of the control specimen were measured as 0.63 and 0.70. The relative creep values of the Glulam specimen were 0.37 and 0.43. An increase in the relative creep value indicates an increase in bending deformation in the center of the specimen. The CFRP specimen reinforced with the tensile part of the control specimen had relative creep values of 0.40 and 0.46, which were lower than those of the control specimen; the relative creep values of the GFRP specimen were 0.40 and 0.46, similar to those of the CFRP reinforced specimen (Table 2). The relative creep value according to the type of reinforcement exhibited a small difference; therefore, the presence or absence of reinforcement seems to be important. The creep deformation was heavily affected by the load up to 2000 h, from which it stabilized, and mechano-sorptive deformation progressed according to temperature and humidity fluctuations (Fig. 7).

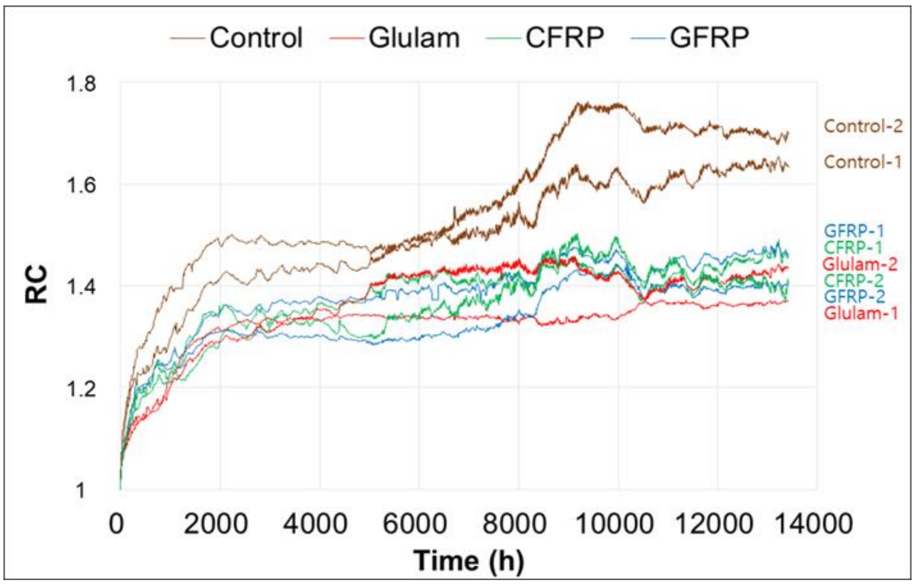

Fig. 7. Relationship between relative creep and time curve (RC: relative creep)

Table 2. Fluctuation between Relative Creep and Time

	2000 h	4000 h	10000 h	13400 h
Control-1	0.42	0.44	0.62	0.63
Control-2	0.48	0.48	0.75	0.70
Glulam-1	0.31	0.33	0.34	0.37
Glulam-2	0.29	0.35	0.42	0.43
CFRP-1	0.29	0.36	0.44	0.46
CFRP-2	0.35	0.33	0.48	0.40
GFRP-1	0.35	0.38	0.47	0.46
GFRP-2	0.31	0.30	0.44	0.40

Relative creep and moisture content

The relative creep and moisture content showed a generally inversely proportional relationship as the creep stabilized after 2000 h (Fig. 8). The moisture content during summer, where precipitation is concentrated, was inversely proportional to the relative creep due to high humidity for a long time. The relative creep and moisture content of 3000 h and 10,000 h during the winter period showed proportional behavior. After the creep deformation according to the load was stabilized, the mechano-sorptive deformation according to the change in moisture content of the member and the change in temperature and humidity was confirmed to be progressing.

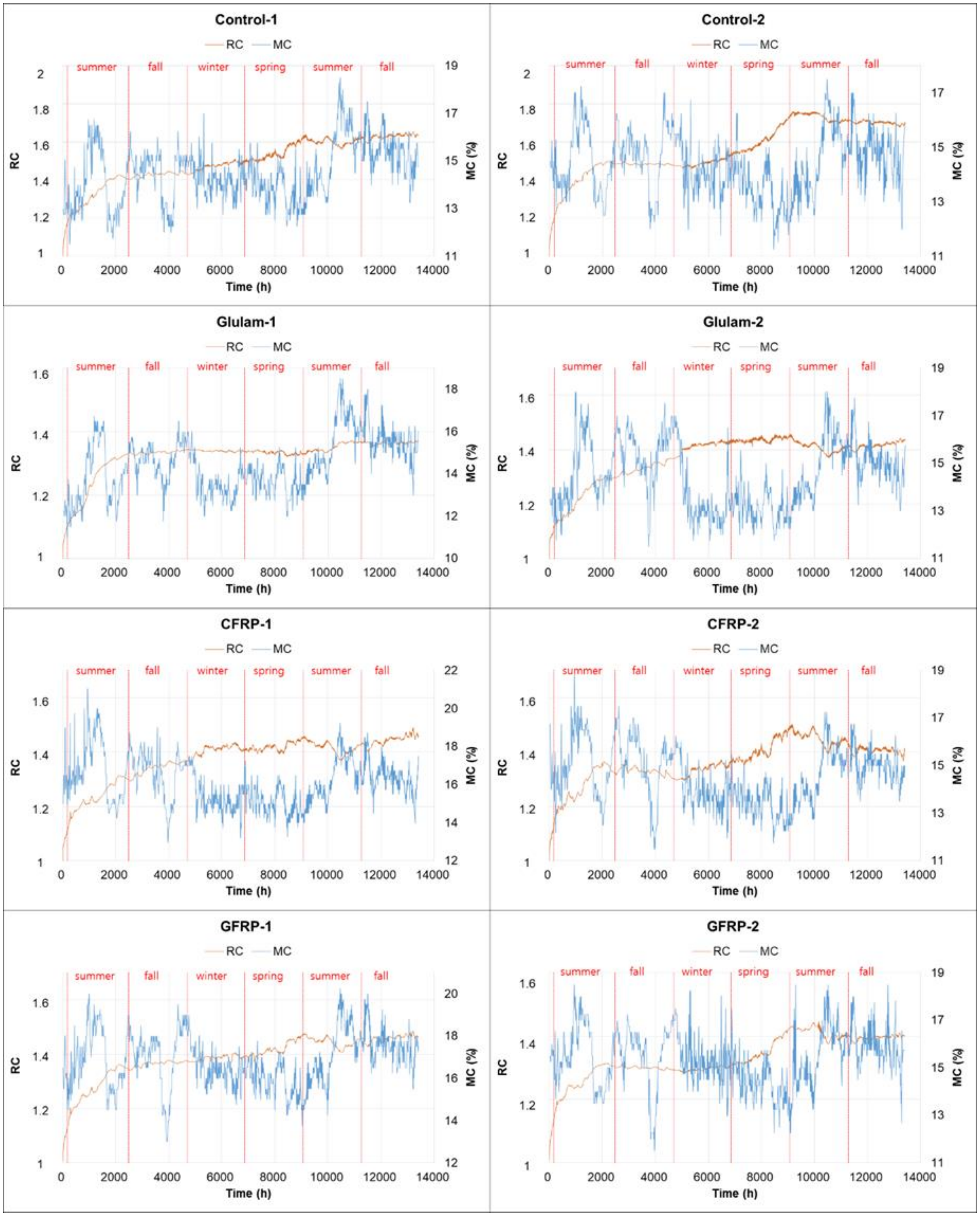

Fig. 8. Relationship between relative creep and moisture content

Prediction of creep coefficient and relative creep for reinforced small-diameter timber

For creep prediction, the creep coefficient and exponent (*a*, *n*) were calculated using the power model Eq. 3,

$$\frac{f_{(t)}}{f_0} = at^n \tag{3}$$

where f_0 is the initial strain amount, f_t is the amount of deformation over time, *a* and *n* are creep coefficient and exponent, and *t* is the load duration time

As shown in Fig. 9, the creep factors of the control specimen stacked with fallen pine wood were calculated as *a* = 0.37 and 0.40, and *n* = 0.28 and 0.28. The creep coefficients of the glulam specimen laminated with fallen pine boards were calculated as *a* = 0.25, 0.25, *n* = 0.19 and 0.27, and those of the stacked tree reinforced with CFRP were *a* = 0.25, 0.27, *n* = 0.28 and 0.26; for GFRP, the creep coefficients were calculated as *a* = 0.27, 0.27, *n* = 0.27 and 0.22.

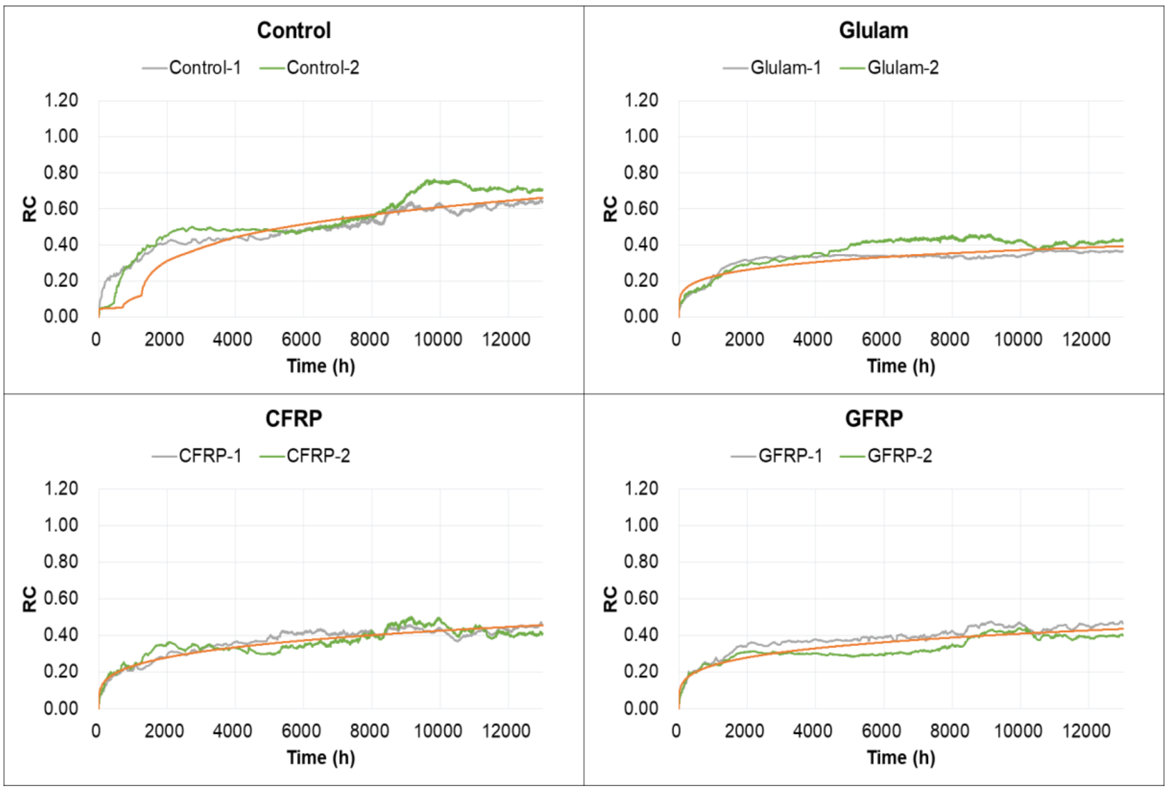

Fig. 9. Relative creep curve for calculating the creep coefficient

The relative creep of the same type of specimens showed similar tendencies; therefore, the reliability of the creep coefficient is considered to improve if the creep coefficient is calculated with an average tendency line. Thus, the relative creep graph of the same type was an average tendency line (Fig. 9), and the relative creep coefficient for each type was calculated (Table 3). This result was similar to the results obtained in other studies (*a* = 0.15 to 0.30 and *n* = 0.15 to 0.30; Ranta-Maunus and Kortesmaa 2000).

Table 3. Results of Creep Coefficient

Specimen	Creep Coefficient	
	a	*n*
Control	0.385	0.278
Glulam	0.252	0.217
CFRP	0.267	0.262
GFRP	0.268	0.238

Table 4 shows the predicted relative creep in the next 50 years with the creep coefficient calculated above. The predicted relative creep of the unreinforced control specimen is expected to deform 1.15 times the initial deformation; the predicted relative creep of the CFRP-reinforced specimen is expected to deform 0.75 times, and the GFRP-reinforced specimen is expected to exhibit relatively small deformation behavior. For glulam, an additional deformation of 0.59 times the initial deformation is predicted after 10 years; 50 years later, the predicted relative creep is 1.8 times for the control specimen, 0.84 times for the glulam, and 1.15 and 1.01 times for the specimens reinforced with CFRP and GFRP, respectively.

The creep test was conducted with pine timber, spruce glulam. The pine timber showed a relative creep 0.79 times higher in 3 years and 0.97 times higher in 7 years, and the relative creep of spruce glulam was 0.57 times in 3 years and 0.65 times in 7 years. The spruce glulam had a larger relative creep deformation than the larch laminated timber, and similar results were CFRP reinforced timber.

Table 4. Summary Prediction of Relative Creep Deformation of Specimens Under Long Term Loading (3 to 50 Years)

Prediction of Relative Creep of Specimens								
Specimen		Time (years)						
		3	7	10	20	30	40	50
Control	1	0.83	1.04	1.15	1.4	1.56	1.69	1.8
Glulam	2	0.46	0.55	0.59	0.69	0.75	0.8	0.84
CFRP	1	0.55	0.68	0.75	0.9	1	1.08	1.15
GFRP	2	0.52	0.63	0.69	0.81	0.89	0.95	1.01

CONCLUSIONS

1. Temperature and humidity, moisture content, equilibrium moisture content, and relative creep were measured. The relationship between humidity, equilibrium moisture content, and moisture content of the specimen was investigated and compared with the relative creep. The correlation coefficient of the relationship between humidity and the equilibrium moisture content was 0.95, and the deformation behavior was almost the same.
2. The correlation coefficients of the relationship between the moisture content and humidity of the specimen and the relationship between the moisture content and equilibrium moisture content were 0.10 to 0.34 and 0.08 to 0.31, respectively, showing insufficient proportional relationships.

3. The relative creep was considerably affected by the load up to 2000 h; after 2000 h, the creep deformation stabilized and was considerably affected by temperature and humidity.
4. After measuring during 13400 h, the average value of the relative creep was approximately 0.67 for the control specimen, 0.40 for the Glulam specimen, and 0.43 for both the CFRP and GFRP specimens; the relative creep values were 40%, 36%, and 36%, lower than that of the control specimen, respectively.
5. The moisture content and relative creep were generally inversely proportional or partially proportional due to other factors affecting the relative creep. No significant difference in the value of the relative creep according to the type of reinforcement was observed.
6. The creep coefficient was calculated with the relative creep, which was predicted after up to 50 years. The predicted relative creep of the unreinforced control specimen is expected to have 1.8 times more additional deformation than the initial deformation after 50 years, whereas the predicted relative creep of CFRP and GFRP-reinforced specimens is expected to have 1.15 times and 1.01 times less deformation after 50 years, respectively.

ACKNOWLEDGEMENT

This study was conducted as a basic research project supported by Korea Research Foundation with funding from the government (Ministry of Education) in 2016 (NO. R1D1A1B01011163)

REFERENCES CITED

Acharjee, T. C., Coronella, C. J., and Vasquez, V. R. (2011). "Effect of thermal pretreatment on equilibrium moisture content of lignocellulosic biomass," *Bioresource Technology*, 102(7), 4849-4854. DOI: 10.1016/j.biortech.2011.01.018

Aloisio, A., Pasca, D., Tomasi, R., and Fragiacomo, M. (2020). "Dynamic identification and model updating of an eight-story CLT building," *Engineering Structures* 213, article ID 110593. DOI: 10.1016/j.engstruct.2020.110593

André, A., and Johnsson, H. (2010). "Flax fiber-reinforced glued-laminated timber in tension perpendicular to the grain: experimental study and probabilistic analysis," *Journal of Materials in Civil Engineering*, 22(9), 827-835. DOI: 10.1061/(ASCE)MT.1943-5533.0000070

Glass, S., and Zelinka, S. (2021). "Moisture relations and physical properties of wood," in: *Wood Handbook Wood as an Engineering Material* (FPL-GTR-282), USDA Forest Products Laboratory, Madison, WI, USA.

Gronvall, H. J. (2006). *Exploring Techniques of Measuring Moisture-Content in Paperboard Tubes*, M.S. Thesis, University of Wisconsin--Madison.

Lee, I. H., Song, Y. J., Jung, H. J., and Hong, S. I. (2015). "Moment resistance performance evaluation of larch glulam joint bonded in glass fiber reinforced plastic rods," *Journal of The Korean Wood Science and Technology* 43(1), 60-67. DOI: 10.5658/wood.2015.43.1.60

Nguyen, T. T., Dao, T. N., Aaleti, S., van de Lindt, J. W., and Fridley, K. J. (2018). "Seismic assessment of a three-story wood building with an integrated CLT-lightframe system using RTHS," *Engineering Structures* 167, 695-704. DOI: 10.1016/j.engstruct.2018.01.025

Pei, S., van de Lindt, J. W., Popovski, M., Berman, J. W., Dolan, J. D., Ricles, J., Sause, R., Blomgren, H., and Rammer, D. R. (2016). "Cross-laminated timber for seismic regions: Progress and challenges for research and implementation," *Journal of Structural Engineering* 142(4), article ID E2514001-2. DOI: 10.1061/(asce)st.1943-541x.0001192

Pierobon, F., Huang, M., Simonen, K., and Ganguly, I. (2019). "Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the US Pacific Northwest," *Journal of Building Engineering* 26, article ID 100862. DOI: 10.1016/j.jobe.2019.100862

Ranta-Maunus, A., and Kortesmaa, M. (2000, July). "Creep of timber during eight years in natural environments," in: *World Conference on Timber Engineering*, Whistler, CA, (Vol. 31).

Song, Y. J., Lee, I. H., and Hong, S. I. (2023). "Creep performance and analysis of glass fiber reinforced glulam beams under the influence of climatic conditions," *Wood Material Science & Engineering*, 1-12. DOI: 10.1080/17480272.2023.2235677

Article submitted May 10, 2023; Peer review completed: June 3, 2023; Revised version received and accepted: August 23, 2023; Published: August 30, 2023.
DOI: 10.15376/biores.18.4.7239-7250