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ORIGINAL ARTICLE

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Creep of the beam in Japanese conventional structures composed of green and kiln-dried timber II: predictive model for relative deflections

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Abstract We conducted creep tests to evaluate creep behaviors of conventional Japanese framing (*jikugumi*) structures as reported in a previous article. We measured beam deflections of two structures: one of them was composed of only green timbers (G) and the other with only kiln-dried timbers (D). Besides the two structures, we prepared green and kiln-dried beams to measure moisture content (MC), weight, and dynamic Young's modulus (E_f) by the longitudinal vibration method. We attempted to predict deflections of beams in the structures by using experimental data for single beam specimens. The proposed simple predictive model was derived from two equations: a relation between MC and equilibrium moisture content calculated with temperature and relative humidity, and a relation between MC change and relative deflection change. Beam deflections were traced for 2.5 years, while the predictions were based on experimental data from loading to the 11th day of the test. It was assumed that sensitivity of deflection change to MC should differ during desorption or adsorption. Although annual cyclic changes were observed in E_f, there was no obvious relationship between E_f and beam deflection.

Key words Mechanosorptive creep · Equilibrium moisture content · Relative humidity · Temperature · Shrinkage

Introduction

Creep behavior under constant climatic conditions is generally known as time-dependent phenomena, and empirical creep equations have been often obtained by fitting data as functions of time.[1] The most popular equation is parabolic representation: $\gamma = \gamma_0 + at^m$, where γ is strain, γ_0 is instantaneous elastic strain, t is time, and a and m are constants. The empirical m values are independent of load, and dependent on materials at a low stress level, which is generally below the working stress.[2] However, wooden constructions such as houses usually exist under conditions of changing temperature and relative humidity (RH). The phenomenon of the deflection of a loaded beam increasing with moisture sorption is known as mechanosorptive creep. Grossman[3] pointed out that the primary characteristic of mechanosorptive effects is that they are independent of time. While beam deflection under varying climate should be divided into time-dependent and time-independent components of deflection, increase of beam deflection in constant creep is much smaller than additional deflections under cyclic humidity changes.[4] Therefore, we propose a simple predictive model for creep behavior in wooden structures without particular functions of time. Besides predictions of beam deflections, we also present some characteristics that might be related to creep behaviors.

Experimental

Creep tests were performed on two conventional Japanese framing structures for 2.5 years: one of them was composed of only green members (G) and the other with only kiln-dried members (D), as in the previous study.[5] Two beams for each structure were loaded, and the vertical displacement at the center on the upper side of each beam was measured every 24 h. Y denotes the total deflection. The beams were supported on columns, and the average (d_m) of vertical displacement near the beam–column joints on the upper face of each beam was also determined. The bending

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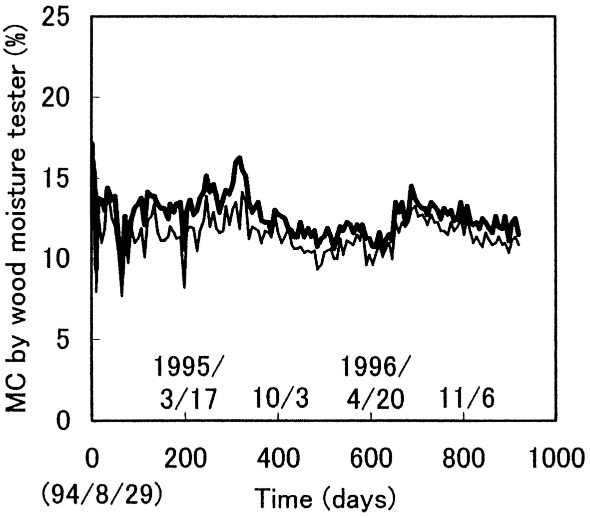

Fig. 1. Moisture content (*MC*) of single beam specimens measured by wood moisture tester over duration of the creep test. *Dark line*, green specimen; *light line*, kiln-dried specimens

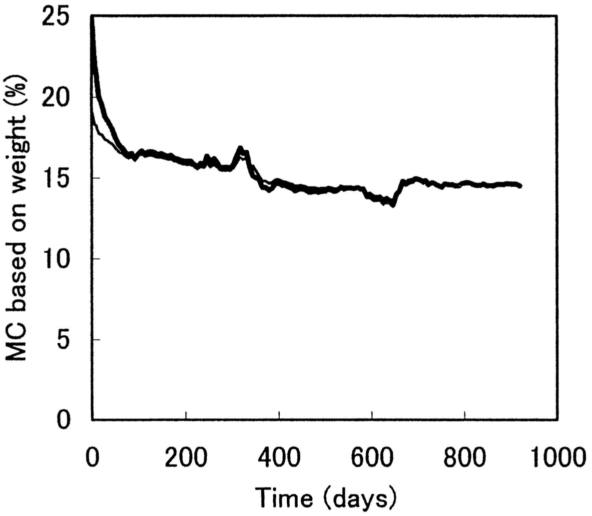

Fig. 2. MC of single beam specimens based on weight for duration of the creep test. *Dark line*, green specimen; *light line*, kiln-dried specimens

deflection (d_b) was calculated: $d_b = Y - d_m$. Shrinkage of the beam was measured as differences of vertical displacement between the upper and lower faces of each beam. Relative deflection on the i-th day (y_i) was defined as the ratio of deflection on the i-th day to initial deflection: $y_i = Y_i/Y_0$, and the date of load starting was set 0.

Besides the two test structures, green and kiln-dried beams were prepared to measure weight, moisture content (by wood moisture tester), and dynamic Young's modulus (E_f; by the longitudinal vibration method)[6] every 7 days. The single beam specimens were placed near the test structures. Temperature and RH were also measured with an auto climate reader near the structures. More detailed information is given in the literature.[7–14]

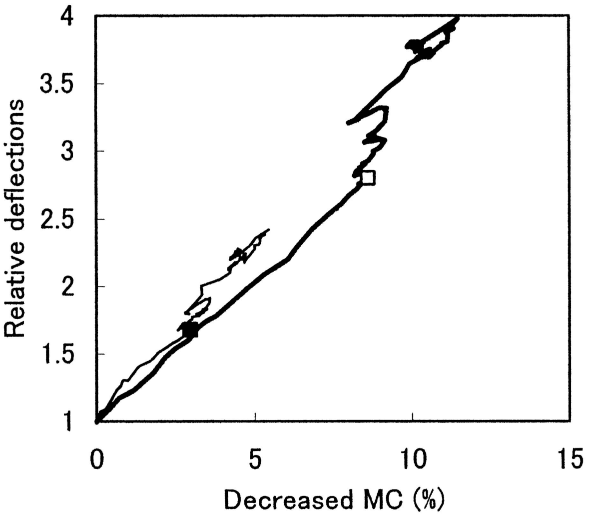

Fig. 3. Relationship between relative deflection and decreased MC. *Dark line*, green specimen; *light line*, kiln-dried specimens; *open square*, point passed 93 days after loading of green specimens; *filled square*, point passed 93 days after loading of kiln-dried specimens

Results and discussion

Relationship between relative deflection and moisture content

Figure 1 shows moisture content (MC) changes measured with a wood moisture tester for each single beam specimen. MC for G was slightly higher than that of D, and both of them showed variation. On the other hand, MC based on weight for both specimens coincided except for the initial 60 days as shown in Fig. 2. The MC based on weight was estimated on the assumption that MC was equal to equilibrium moisture content (EMC) on the last measured day when both MC and EMC were stable. Because the variations of the latter MC were smaller than that measured by the wood moisture tester, we used the MC based on weight as data for our predictive model. The MC on the i-th day was denoted as u_i.

Figure 3 shows the relationship between relative deflection and decreased moisture content ($= u_0 - u_i$). During the initial 3 months, relative deflections for G and D proportionally increased as MC decreased, and the slopes of the plots in Fig. 3 were almost equal. After the initial 3 months, the slope of relationships increased. The cause of this change is discussed in the following section. It was expected that initial changes of relative deflections could be expressed by using MC data.

Predictive model for relative deflections

First, we assumed that changes of MC should be caused by differences between MC and EMC, which was calculated using temperature and RH data by Simpson's formula.[15]

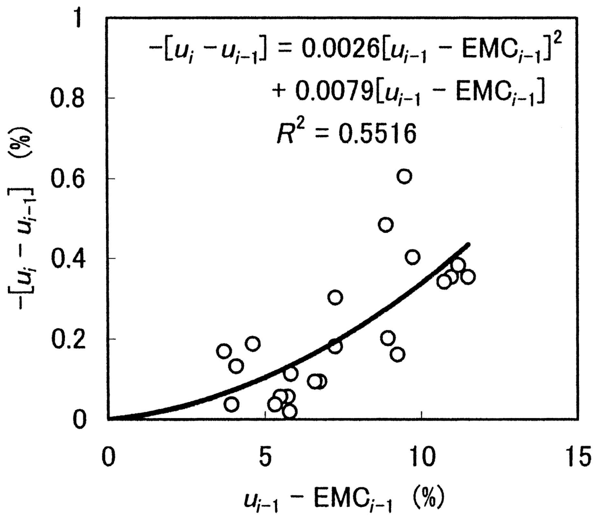

Fig. 4. Daily changes of MC. u_i, MC on i-th day; u_{i-1}, MC on (i–1)-th day after loading; EMC_{i-1}, (i–1)-th day equilibrium moisture content (EMC) calculated by Simpson's formula. Only data from the initial 11 days were used

MC for each day were derived from MC and EMC on the previous day:

$$u_i - u_{i-1} = f\left(u_{i-1} - \mathrm{EMC}_{i-1}\right) \tag{1}$$

where u_i is MC for a particular day, and u_{i-1} and EMC_{i-1} are MC and EMC on the previous day, respectively. The relationship between (u_i – u_{i-1}) and (u_{i-1} – EMC_{i-1}) during for an initial 11 days is shown in Fig. 4. The relationship was expressed as an approximate equation by the least square method using MC data for both green and kiln-dried specimens:

$$\left(u_i - u_{i-1}\right) = -0.0026\left(u_{i-1} - \mathrm{EMC}_{i-1}\right)^2 - 0.0079\left(u_{i-1} - \mathrm{EMC}_{i-1}\right) \tag{2}$$

The approximate equation is valid during the desorption process. Although change in MC in wood occurs with hysteresis,[16] we simply assumed that the rate of change of MC during absorption is equal to that during desorption when the difference between MC and EMC were the same in both process. Therefore, the approximate equation during absorption process was obtained by changing the sign of the first term:

$$\left(u_i - u_{i-1}\right) = 0.0026\left(u_{i-1} - \mathrm{EMC}_{i-1}\right)^2 - 0.0079\left(u_{i-1} - \mathrm{EMC}_{i-1}\right) \tag{3}$$

Next, we investigated the effect of MC changes on relative deflections. We assumed that changes in relative deflection per day should be dependent on changes in MC per day. Figure 5 shows the relationship between change of relative deflection and change of MC for data from the initial 11 days in a test of both G and D. The approximate equation obtained by the least square method is:

$$\left(y_i - y_{i-1}\right) = 0.2053\left(u_i - u_{i-1}\right) \tag{4}$$

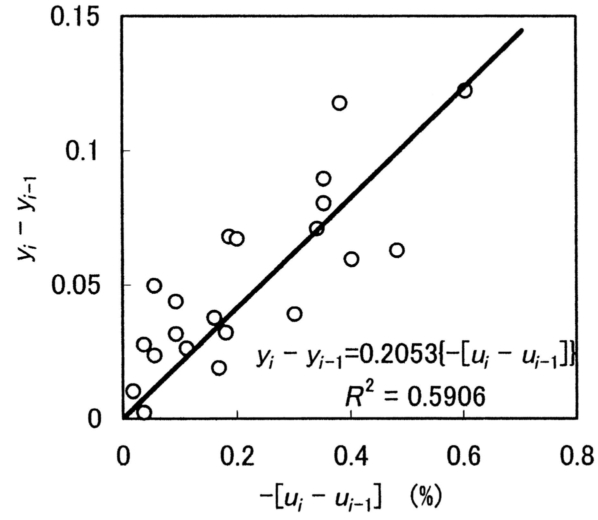

Fig. 5. Effect of MC changes on relative deflections (y). y_i, relative deflection on the i-th day after loading; y_{i-1}, relative deflection on the (i–1)-th day after loading

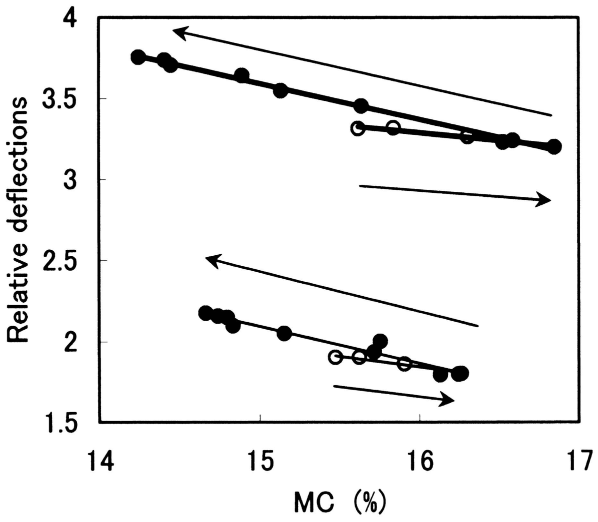

Fig. 6. Comparison of change in relative deflection for desorption and adsorption processes. *Filled circles*, desorption; *open circles*, adsorption; *heavy lines*, green specimens; *light lines*, kiln-dried specimens. *Arrows* show time direction

where y_i and y_{i-1} are the relative deflections on one day and the previous day, respectively. It should be noted that the relationship between relative deflection changes and MC changes was valid during the desorption process.

It was considered that the slope of curve for relative deflection change versus MC during the adsorption process might be different from the slope during the desorption process. The relative deflection is plotted against MC for days 296–380 in Fig. 6. This period was selected because other adsorption processes were very short. The slope of the relative deflection–MC curve for adsorption was smaller than that for desorption for each structure. The approximate equations obtained by the least square method for G structure were $y = -0.2225\ \mathrm{MC} + 6.9311$ ($R^2 = 0.9951$) during desorption and $y = -0.0972\ \mathrm{MC} + 4.845$ ($R^2 = 0.9554$) during

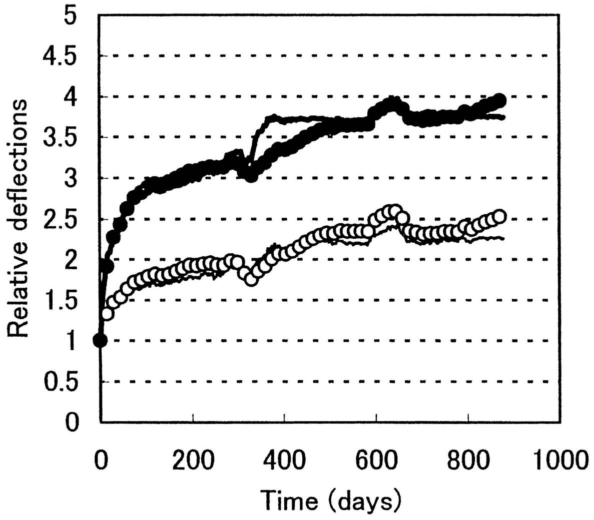

Fig. 7. Predictions of relative deflection. *Filled circles*, predictions for green specimens; *open circles*, predictions for kiln-dried specimens; *heavy line*, experimental data for green specimens; *light line*, experimental data for kiln-dried specimens

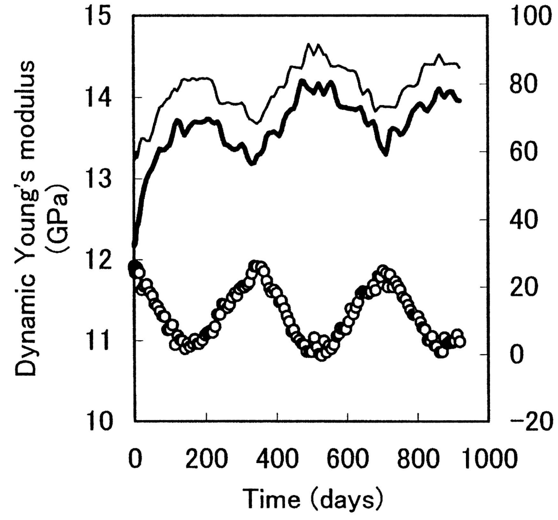

Fig. 8. Dynamic Young's modulus of single beam specimens over duration of creep test. *Heavy line*, green specimens; *light line*, kiln-dried specimens; *circles*, temperature. Dynamic Young's modulus was measured by the longitudinal vibration method

adsorption, where y is relative reflection, and R^2 is determination coefficient. Similarly for D, the equations are $y = -0.23$ MC + 5.5455 ($R^2 = 0.955$) during desorption and $y = -0.135$ MC + 4.0035 ($R^2 = 0.9626$) during adsorption. The ratios of the slopes during adsorption to the slopes during desorption were 0.437 for G and 0.587 for D, respectively. During adsorption, instead of the coefficient 0.2053 in Eq. 4, other coefficients were obtained by multiplying the coefficient and these ratios. Consequenctly, Eq. 4 was substituted into Eq. 5 for G and Eq. 6 for D, respectively, during adsorption.

$$(y_i - y_{i-1}) = 0.0897\,(u_i - u_{i-1}) \tag{5}$$

$$(y_i - y_{i-1}) = 0.1205\,(u_i - u_{i-1}) \tag{6}$$

Finally, the initial input MC values for Eqs. 2 and 3 were obtained from Eqs. 4–6 for each structure by calculating EMC from temperature and RH, and relative deflection for the following day. The initial MC values were 24.8% for G, and 19.1% for D. Temperature and RH on the following day were calculated to obtain the next relative deflections, and this process was repeated. Ranta-Maunus[17] and Hunt[18] distinguished mechanosorptive creep compliance during the first adsorption from compliance during sequent adsorption. Zou et al.[19] investigated bending creep behavior of wood under cyclic moisture changes, and showed that the first adsorption caused the largest deformation, followed by desorption. In our simple models, we did not adopt the coefficient during the first adsorption because MC values of both structures were higher than EMC when the loads were applied. The coefficient during the first adsorption should be used to predict deflections when air-dried or kiln-dried timbers are used with MC values below the EMC.

Figure 7 shows the predictions of relative deflection and experimental results. Both predictions were similar to the results, although some deviations between the predictions and the results were observed. After 1 year, the prediction curve for G increased slowly compared with the experimental data. These deviations might be caused by the effect of temperature on creep rate that was not considered in the predictive model. During the final days of the test, the predictions were larger than the results. This might be caused by an "exhaustion" process[4] that acted to decrease the creep increase per cycle as the number of moisture cycles increased. The predictive model did not consider this effect. However, it was clear that MC change was the primary factor to affect deflections. In the following discussion, we present long-term variations of some properties related to MC change.

Annual cyclic variation of dynamic Young's modulus

Figure 8 shows temperature and the variation of dynamic Young's modulus (E_f) measured by the longitudinal vibration method. Dynamic Young's modulus decreased in summer and increased in winter. This presented the question of how the cyclic variation of dynamic Young's modulus affected relative defection.

Variation of back-splitting

In Japan, columns are usually used with back splitting to reduce seasonal cracks. We measured the width of splits of four columns once a week for each structure. Changes in the average back-splitting of the columns are shown in Fig. 9. During the initial days of the test, back-splitting increased

Table 1. Chief passages of total deflection, bending deflection, and shrinkage

Days	Date[a]	Total deflection (mm)		Bending deflection (mm)		Shrinkage (mm)		Notes
		G	D	G	D	G	D	
0	29/08/94	4.64	4.53	3.58	3.60	0.00	0.00	Load starting
7	5/09/94	7.46	5.70	5.17	4.03	0.71	0.17	
30	28/09/94	10.44	6.65	6.49	5.16	2.45	0.65	
100	7/12/94	13.08	7.69	7.45	5.80	4.39	1.36	
365	29/08/95	17.06	9.48	8.52	6.54	6.56	2.14	
647	6/06/96	18.30	–	8.86	–	7.32	–	Maximum relative deflection in G
649	8/06/96	–	11.00	–	7.18	–	3.21	Maximum relative deflection in D
731	29/08/96	17.48	10.07	8.84	7.11	6.80	2.46	
878	23/01/97	17.28	10.27	9.01	7.35	6.72	2.52	Before removing loads
879	24/01/97	14.02	6.83	6.30	4.52	6.78	2.62	After removing loads
919	5/03/97	13.82	6.55	6.14	4.29	6.77	2.60	Final measurements

G and D, structures composed of green (G) and kiln-dried (D) members, respectively

[a] Date given as day/month/year

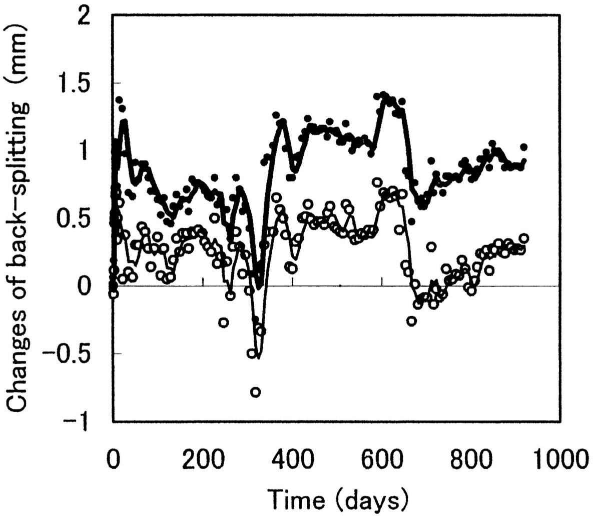

Fig. 9. Changes in back-splitting of columns. *Filled circles*, green specimens; *open circles*, kiln-dried samples; *heavy line*, third moving average of green specimens; *light line*, third moving average of kiln-dried specimens

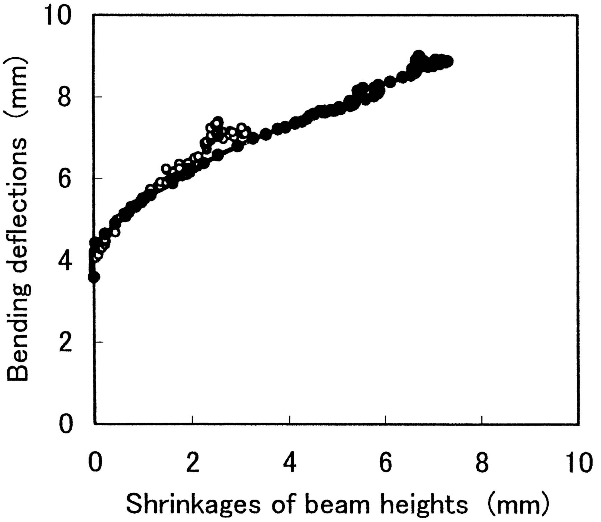

Fig. 10. Relationship between bending deflection and shrinkage of beam height. *Filled circles*, green specimens; *open circles*, kiln-dried specimens

rapidly, and then decreased. In the first rainy season (days 300–330), back-splitting decreased rapidly. Back-splitting in green specimens was larger than that in kiln-dried specimens.

Relationship between bending deflections and shrinkage of beams

Chief passages of total deflections, bending deflections, and shrinkage of beams are tabulated in Table 1. Total deflections were almost equal to the sums of bending deflections and shrinkage. It was assumed that there was a small effect of deformation of joints on total deflections. Figure 10 shows the relationship between bending deflections and shrinkage of beams. It was clear that lines for both G and D overlapped, and bending deflection was related to shrinkage. Changes of bending deflection per shrinkage change were larger during the initial days of the test than for the remainder. Another approach might be necessary to explain this phenomenon.

Conclusions

A simple predictive model for relative deflection of Japanese framing structures was proposed in this article. The model consists of two equations: a relation between MC and EMC, and a relation between relative deflection and MC. The constants of the equations were obtained using data from the initial 11 days of the test, except for coefficients during the adsorption process. The predicted curves overlapped with experimental data. However, further additions to the model may be necessary to adapt it to wooden structures composed of air-dried timbers.

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