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ORIGINAL ARTICLE

Long-term bending properties of cross-laminated timber made from Japanese larch under constant environment

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Abstract

Cross-laminated timber (CLT) has been used extensively in timber construction. CLT panels are typically used in roofs and floors that carry a continuous load, and it is important to examine the long-term loading capacity of CLT. However, studies that focus on the long-term loading capacity of CLT are limited. To this end, we conducted long-term out-of-plane bending tests on seven-layer CLT made from Japanese larch (*Larix kaempferi*) under constant environmental conditions, investigated creep performance and duration of load, and experimentally analyzed creep rupture behavior. The mean estimated relative creep after 50 years was 1.49. The sample showed a satisfactory resistance to creep as a building material. The duration of load of most of the specimens in this study was shorter than the conventional value of small clear wood specimens. Specimens had a lower duration of load capacity than solid lumber. According to the results of survival analysis, a loading level of 70% or more caused the initial failure of specimens. Creep rupture of most of the specimens occurred at less deflection than displacement at failure in the short-term loading test. Additional studies focusing on the effects of finger joints, transverse layers, and width of a specimen on creep rupture behavior are suggested.

Keywords: Creep, Creep rupture, Duration of load, Out-of-plane bending, Survival analysis

Introduction

Wood and wooden materials are important building materials. In recent years, timber construction has gained interest globally for use in many fields, such as residential, office, and school buildings [1]. One reason for this trend is the increased use of cross-laminated timber (CLT) [1]. CLT panels consist of several layers of lumber stacked crosswise and glued together on their wide faces [2]. Owing to this configuration, CLT is formed in a plate-like shape and can carry a load both in-plane and out-of-plane. This enables easy handling in construction and a high level of prefabrication, and thus, CLT construction can be competitive in mid- and high-rise buildings [2].

Owing to orthogonal layering, CLT has specific material properties derived from the anisotropy of mechanical characteristics of wood. For out-of-plane bending in CLT, several theories have been published to explain its bending stiffness and strength [2], and experimental studies have been conducted [3]. However, these studies have focused only on short-term loading, but wood and wooden materials can demonstrate other characteristic behaviors under a continuous load due to their viscoelasticity. When a load is maintained, time-dependent deformation occurs, adding to the initial elastic deformation. This deformation increase phenomenon is called creep. Creep is an important factor in determining the load a material can carry, ensuring long-term serviceability. Many studies have investigated the creep behavior of wood and wooden materials [4–12]. In addition, if the stress is sufficiently high, failure will occur under constant load. This failure phenomenon is called creep

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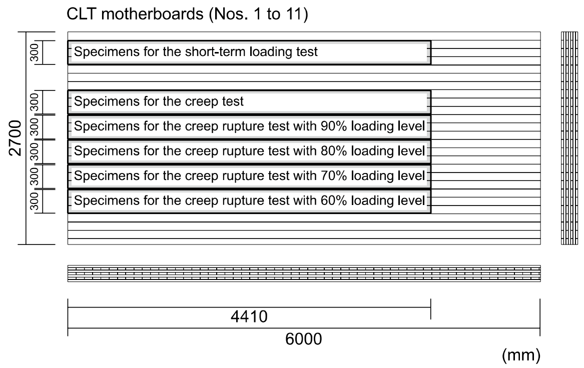

Fig. 1 Cutting pattern of specimens from CLT motherboards

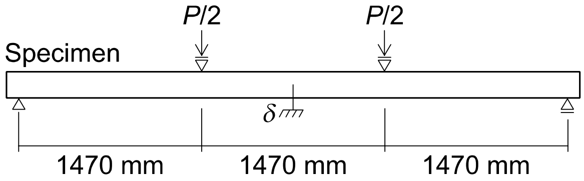

Fig. 2 Experimental setup for the short-term loading tests. *P* is load and *δ* is the displacement at a neutral axis of the specimen at span center

rupture [13]. The duration of load, the time during which a load acts until creep rupture, is an important factor in determining the load that a member can carry, ensuring long-term safety. Several studies have investigated the duration of load of wood and wooden materials [8, 11, 14, 15].

CLT panels that make up roofs and floors carry the mid- and long-term loads such as snow accumulation in some regions and the fixed load weight of a structure. Therefore, it is necessary to understand the long-term loading behavior of CLT. The creep performance and duration of load of CLT have been investigated [9–12], but these studies mainly focused on CLT made from Japanese cedar (*Cryptomeria japonica*) or kinds of spruce. To the best of our knowledge, there have been no reports that investigated the creep performance and duration of load of CLT made from Japanese larch (*Larix kaempferi*). Japanese larch is a major planted tree species in the cold climates area of Japan and has a high Young's modulus when used as timber. Therefore, CLT made from Japanese larch is suitable for structural materials, especially horizontal applications such as in floors or roofs. It can be used in various structural designs that require high stiffness of members, such as long floor spans or cantilever designs. Thus, it is important to investigate the creep performance and duration of load of CLT made from Japanese larch to ensure long-term serviceability and safety. In this study, we conducted long-term out-of-plane bending tests on seven-layer CLT made from Japanese larch, investigated creep performance and duration of load, and experimentally analyzed the creep rupture behavior.

Materials and methods

Specimens

CLT specimens contained seven layers with three cross-sections and were composed of Japanese larch. Laminae were 105 mm width and 30 mm thickness and adhered using an aqueous polymer isocyanate adhesive on the longitudinal connections and lamination. The criteria for stress grading of the laminae for manufacturing CLT panels were 11–13 kN/mm^2 in the outmost layers and 6–11 kN/mm^2 in other layers. Eleven CLT panels that have 2700 mm width and 6000 mm length (Nos. 1 to 11) were manufactured, and CLT specimens were cut from these panels. The dimensions of the CLT specimens were 300 mm width, 210 mm thickness, and 4610 mm length. The grain direction of the outmost layers was parallel to the long direction of the specimens. Six side-matched specimens were cut from each panel, including one specimen for the short-term loading test, one specimen for the creep test, and four specimens for the creep rupture test (Fig. 1). Therefore, the number of specimens were 11 for the short-term loading tests, 11 for the creep test, and 44 for the creep rupture test.

Short-term loading tests

Figure 2 shows the experimental setup for the short-term loading tests. A four-point bending test was conducted using a testing machine with a maximum loading capacity of 200 kN, and the cross-head moving speed was at 10 mm/min. The loading direction was out-of-plane of CLT. Following the Japanese Agricultural Standard for CLT [16], the support span was 21 times the specimen thickness and the loading points were along the trisected support span. Both the load (P) and displacement at a neutral axis of the specimen at the span center from the ground (δ) were measured. Then, the bending modulus of elasticity (E_m) and bending strength (σ_b) were, respectively, calculated as follows:

$$E_{\mathrm{m}} = 23\Delta PL^3/108\Delta\delta bh^3, \tag{1}$$

$$\sigma_{\mathrm{b}} = P_{\max}L/bh^2, \tag{2}$$

where $P_{\max}$ is the maximum load, ΔP is the load increase in an elastic range ($0.4P_{\max}$–$0.1P_{\max}$ for this study), $\Delta\delta$ is an increase in δ with ΔP, L is the length of the support span (4410 mm), b is the specimen width (300 mm), and h is the specimen thickness (210 mm).

The moisture content of the specimens was measured after the tests using the oven-dried weight of specimen pieces.

Creep tests

Figure 3 shows the experimental setup for the creep tests. The testing instruments are capable of loading approximately 17 times the suspended weight at the end of the moment arm. The tests were conducted at a constant temperature (20 °C) and relative humidity (65% RH) conditions. A four-point bending setup was used, which was equivalent to the short-term loading test. A gradual descent of the weight was used to load the specimens to avoid impact loading. The constant load applied to the specimens was 37% of the mean of the maximum load observed in the short-term loading test. A loading level of 37% is derived from the conventional allowable long-term stress in the Japanese building code as follows:

$$37\% = (2/3) \times 55\%, \tag{3}$$

where 2/3 is the factor of allowable short-term stress and 55% is the factor of the duration of load.

The deflection was measured at a neutral axis of the specimen at the span center (δ), with a yoke on one side of the specimen between the support span. The measurement start time was after loading, and the measurement interval was 1 min. The test periods ranged from 48 to 183 days because of interruption of constant environmental conditions and termination of a test.

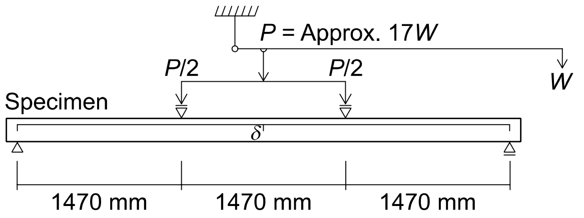

Fig. 3 Experimental setup for creep and creep rupture tests. P is load, W is suspended weight at the end of the moment arm, and δ is displacement at a neutral axis of the specimen at span center

Creep rupture tests

Creep rupture tests were conducted using the same testing instruments (Fig. 3) and conditions as those in the creep test. The constant load applied to each of the four side-matched specimens was 60%, 70%, 80%, and 90% of the mean of the maximum load observed in the short-term loading test. The deflection was measured at a neutral axis of the specimen at the span center (δ). The measurement was continued until specimen failure. The duration of load, which is the time to failure, was calculated as the duration between test start time and failure. The moisture content of the specimens was measured after failure using the oven-dry weight of specimen pieces.

Results and discussion

Short-term loading tests

Table 1 shows the results for the short-term loading tests, and Fig. 4 shows the load–displacement curves of all specimens. All specimens demonstrated a bending failure, and most were broken at a finger joint or knot in the tensile

Table 1 Results of the short-term loading tests

No	Density (kg/m^3)	P_{max} (kN)	δ_{max} (mm)	E_m (kN/mm^2)	σ_b (N/mm^2)	Time to failure (min)	MC (%)
1-C	518	69.73	55.98	8.50	22.8	5.4	9.6
2-C	513	81.66	63.74	8.43	26.7	5.9	9.3
3-C	530	70.08	56.81	8.56	22.9	5.4	9.0
4-C	520	73.45	53.82	9.28	24.0	5.2	9.3
5-C	513	79.42	66.83	8.33	26.0	6.0	9.0
6-C	515	68.12	53.99	8.69	22.3	5.2	9.3
7-C	504	73.88	57.61	8.39	24.2	6.6	8.9
8-C	514	83.37	70.11	8.36	27.3	6.5	9.7
9-C	512	66.55	61.11	7.99	21.7	5.6	8.9
10-C	515	78.50	65.33	8.55	25.7	6.1	9.0
11-C	518	95.36	71.26	8.86	31.3	6.5	8.9
Mean	516	76.37	61.51	8.54	25.0	5.9	9.1
SD	6	8.45	6.33	0.33	2.8	0.5	0.3

P_{max} is the maximum load, δ_{max} is the displacement at P_{max}, E_m is the bending modulus of elasticity (Eq. 1), σ_b is the bending strength (Eq. 2), MC is moisture content, and SD is the standard deviation

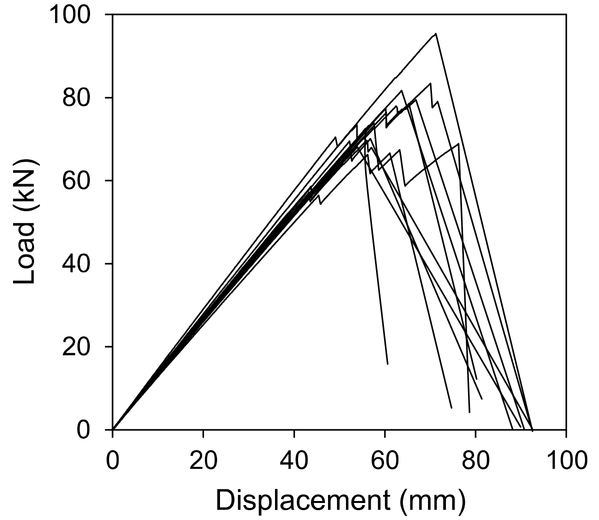

Fig. 4 Load–displacement curves of the short-term loading tests

Fig. 5 Failure of a short-term loading test specimen

surface (Fig. 5). The finger joint failure occurred in the wood portion rather than on the adhesive layer. All specimens reached failure after 5–7 min.

Creep tests

According to the result of the short-term loading test, the constant load used for the creep tests was 28.26 kN. Curve fitting to the experimental data of creep deflection was conducted on the basis of a phenomenological model as follows:

$$\delta_t = \delta_0 + mt^n, \tag{4}$$

where t is time, δ_t is the total deflection at time t, δ_0 is the initial deflection that includes elastic and plastic deflection, and n and m are constants.

This model is called the power law [4] and has been used in many studies [5, 6]. The constants m and n were obtained by fitting Eq. (4) to all experimental data using the "nls" function, which is a non-linear least squares method, in the statistics software R version 4.1.0 [17].

Figure 6 shows the relationship between the test period and relative creep (δ_t/δ_0). The solid line represents the experimental values, and the broken lines correspond to the estimated values obtained by curve fitting. The estimated values almost agree with the experimental values. Table 2 shows the results of the creep tests, including the estimated relative creep after 50 years (δ_{50y}/δ_0) as an index of long-term creep. It has been reported that additional deformation caused by creep may approximately equal the initial deformation in wood members [13]. Earlier studies on CLT concluded that creep performance was almost equivalent to that of solid lumber and wood-based materials in both a constant environment [11] and a variable environment [12]. All values of δ_{50y}/δ_0 were lower than 2.0 in this study, which agrees with the conventional values of wood and earlier studies on CLT. Therefore, seven-layer CLT made from Japanese larch shows satisfactory resistance to creep as a building material; however, this result was derived from the test conducted under constant environmental conditions. Creep deflection accelerates with a moisture content change, which is known as mechano-sorptive creep. Therefore, the result of this study is limited in constant environmental conditions, and additional creep tests might be required under variable environmental conditions.

Creep rupture tests

Duration of load

Table 3 shows the results of the creep rupture tests. Specimens with brank data (4–90 and 7–90) experienced failure before the completion of loading. Most specimens were broken at a finger joint or knot in the tensile surface, which was the same as the short-term loading test. Figure 7 shows the relationship between the duration of load and the loading level. Specimens with failure at less than 1 min after loading are not shown in Fig. 7. The solid line in Fig. 7 represents an empirical hyperbolic curve based on clear and small specimens [14], which is called the "Madison Curve" and expressed as follows:

$$y = 108.4x^{0.04635} + 18.3, \tag{5}$$

where y is loading level and x is time in seconds.

Many specimens had creep rupture earlier than the Madison curve. Especially, all specimens loaded with 70% and 60% loading levels had a shorter duration of load. It is generally assumed that the strength of wood members for a long-term period, which is 10 years or more, is approximately 60% of that for a short-term period [13]. In

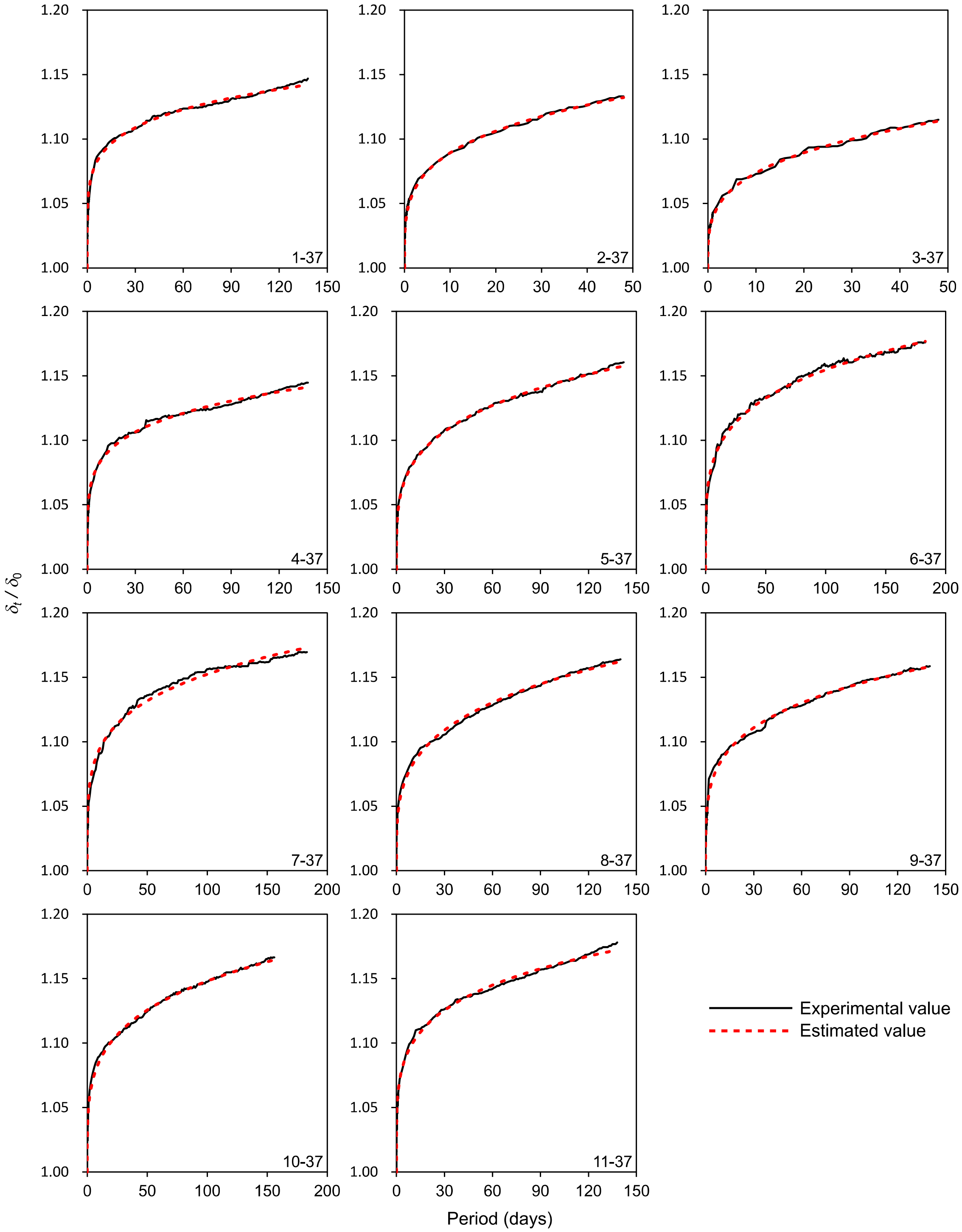

Fig. 6 Relationship between the test period and relative creep. δ_t is deflection at time *t* and δ_0 is initial deflection

addition, an earlier study concluded that CLT made from Japanese cedar had a duration of load almost equivalent to that for solid lumber [11]. No specimen had a duration of load longer than 1 year, even at a 60% loading level, in this study. It meant seven-layer CLT made from Japanese larch had a duration of load capacity lower than that of solid lumber and CLT made from Japanese cedar.

Table 2 Results of the creep tests

No	Density (kg/m^3)	Test period (days)	δ_0 (mm)	Estimated value		
				m	n	δ_{50y}/δ_0
1–37	511	138	21.04	0.357	0.174	1.33
2–37	506	48	22.72	0.184	0.251	1.59
3–37	525	48	19.50	0.102	0.277	1.59
4–37	517	138	20.67	0.301	0.186	1.35
5–37	507	142	21.37	0.158	0.250	1.53
6–37	513	183	21.14	0.238	0.221	1.49
7–37	504	183	21.81	0.272	0.211	1.46
8–37	513	140	20.67	0.143	0.259	1.57
9–37	517	140	20.93	0.196	0.231	1.49
10–37	512	156	21.56	0.189	0.238	1.51
11–37	507	138	21.55	0.294	0.208	1.48
Mean	512		21.18	0.221	0.228	1.49
SD	6		0.81	0.078	0.031	0.09

δ_0 is initial deflection, δ_{50y} is predicted deflection after 50 years, m and n are constants (see Eq. 4), and SD is the standard deviation

Survival analysis

Survival analysis is a collection of statistical procedures for data analysis for which the outcome variable of interest is time until an event occurs [18]. It is a popular data analysis approach in epidemiologic and reliability engineering. Because duration of load is time until a failure event occurs, survival analysis was conducted on duration of load in this study. Figure 8 shows survival curves derived from survival analysis using the Kaplan–Meier method, which is non-parametric method, and parametric model of the Weibull distribution. This analysis was implemented by the statistics software R version 4.1.0 [17]. One second was applied to the duration of load of specimens with failure before the completion of loading (4–90 and 7–90) for this analysis. The solid and broken lines represent survival curves obtained by the Kaplan–Meier method and the Weibull model, respectively. Kaplan–Meier survival curves in Fig. 8 represented experimental curves because data were not censored in this study. The survival curves derived on the basis of the Weibull distribution almost agreed with those of the Kaplan–Meier method. The probability density function of survival time based on the Weibull distribution used in this analysis is as follows:

$$f(t_s) = \lambda\gamma t_s^{\gamma-1} e^{-\lambda t_s^{\gamma}}, \tag{6}$$

where t_s is survival time in hours, $\lambda$is the scale factor, and γ is the shape factor.

The survival function $S(t_s)$ and hazard function $h(t_s)$ are as follows:

$$S(t_s) = e^{-\lambda t_s^{\gamma}}, \tag{7}$$

$$h(t_s) = \lambda\gamma t_s^{\gamma-1}. \tag{8}$$

The value of shape factor γ determines the characteristic of instantaneous failure rate, which is represented as the hazard function Eq. (8). When γ is less than 1.0, the failure rate is high at the early period and decreases with time. This type of failure was observed in the specimen loaded with 90% ($\gamma=0.306$), 80% ($\gamma=0.614$), and 70% ($\gamma=0.769$) loading levels in this study. When γ is 1.0, the failure rate remains constant. When γ is greater than 1.0 and less than 2.0, the failure rate is low at the beginning and gradually increases, reducing the rate of increase. When γ is 2.0, the failure rate increases with time linearly. When γ is greater than 2.0, the failure rate increases with time, increasing the rate of increase. The specimen loaded with a 60% loading level ($\gamma=2.194$) showed this type of failure. As a result, an initial failure was observed in specimens loaded with 90%, 80%, and 70% loading levels. The occurrence of initial failure is undesirable for safety in timber use. Thus, a 70% loading level or more should be avoided in CLT members made from Japanese larch. In addition, the creep rupture behavior changed between 70 and 60% loading levels. A long-term loading test with multi-levels less than 70% loading level and observation of survival curves would be required to determine allowable loading levels in long-term use of CLT made from Japanese larch.

Progress of deflection until failure

Figure 9 shows the deflection at the span center (δ) until failure. The creep behavior under continuous stress has three phases of deflection increase [19]. They are rapid increase in the early period (primary creep), relatively

Table 3 Results of the creep rupture tests

Loading level (%)	No	Density (kg/m^3)	Duration of load (min)	δ_{final} (mm)	MC (%)
60	1–60	509	182,344	51.81	9.5
	2–60	502	427,229	60.98	10.2
	3–60	509	225,096	47.17	9.9
	4–60	518	55,625	46.79	9.4
	5–60	518	91,382	51.83	9.3
	6–60	514	210,513	52.62	9.8
	7–60	513	161,047	61.58	10.1
	8–60	523	335,472	55.11	10.0
	9–60	512	361,090	65.53	10.2
	10–60	505	223,180	48.38	10.2
	11–60	502	167,463	44.57	9.8
70	1–70	504	59,856	55.36	9.7
	2–70	497	12,053	60.84	10.1
	3–70	516	10,495	54.93	9.9
	4–70	515	42,891	47.00	10.3
	5–70	523	88	42.33	9.7
	6–70	516	21,984	47.05	9.9
	7–70	515	616	43.35	10.1
	8–70	512	23,928	53.75	9.9
	9–70	508	56,128	55.42	10.7
	10–70	512	1858	44.46	9.6
	11–70	503	20,232	47.58	9.8
80	1–80	511	1576	51.63	9.9
	2–80	504	520	47.98	10.0
	3–80	522	75	52.41	10.2
	4–80	515	84	46.36	9.9
	5–80	515	170	52.38	10.0
	6–80	516	59	54.50	10.0
	7–80	507	3238	50.95	9.8
	8–80	525	2158	67.02	10.2
	9–80	513	393	54.30	10.6
	10–80	500	10,323	53.07	10.5
	11–80	518	182	63.44	9.6
90	1–90	523	648	54.17	10.0
	2–90	505	118	60.96	10.1
	3–90	522	3	52.29	10.5
	4–90	515	–	50.24	9.8
	5–90	511	806	56.86	10.0
	6–90	510	3929	60.53	10.3
	7–90	503	–	55.48	10.2
	8–90	512	0	55.02	9.9
	9–90	524	19	57.21	10.1
	10–90	515	90	58.52	10.0
	11–90	520	142	50.27	9.7

δ_{final} is the final recorded deflection before failure and MC is moisture content. Specimens with brank data had failure before the completion of loading

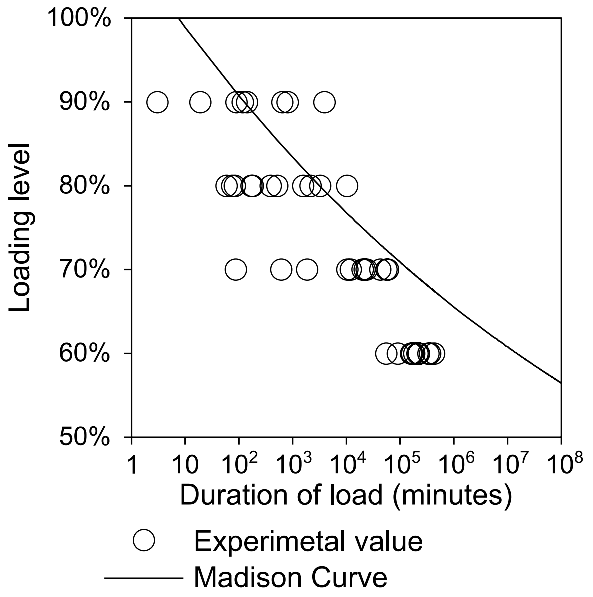

Fig. 7 Duration of load of the specimens. Three specimens loaded with 90% loading level showed failure within 1 min after loading and were not shown. Madison curve represents empirical hyperbolic curve (Eq. 5)

slow increase after primary creep (secondary creep), and rapid increase leading to a failure (tertiary creep). The tertiary creep of most of the specimens showed an extreme change in the increase rate of deflection after secondary creep in this study. Moreover, some specimens showed almost no tertiary creep. Several specimens showed a step-wise increase in deflection. It possibly meant that one-by-one failure in laminae at the tensile surface occurred. Specimens in this study had three laminae in width (Figs. 1, 5). Although one lamina broke, the other laminae might carry a continuous load. Specimens that showed almost no tertiary creep might have simultaneous failure in all laminae in the tensile surface. Then, the width of a specimen, which is the number of laminae in width on the tensile surface, could affect creep rupture behavior.

In addition, most creep rupture specimens showed lower last recorded deflection before failure than displacement at a maximum load in the short-term loading test that was 61.51 mm in mean (Table 1). The deformation at failure is approximately the same for a long-term and short-term loading test in the case of solid wood [13]. Then, CLT could have a different

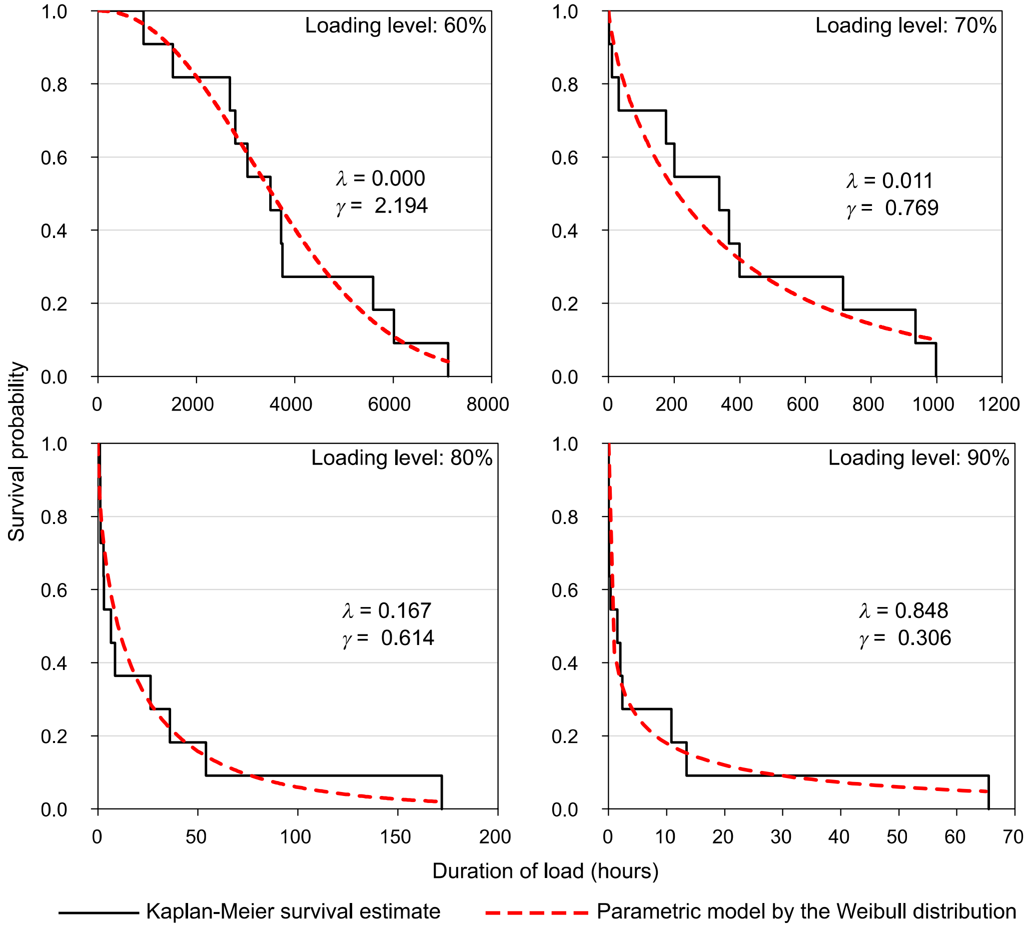

Fig. 8 Results of the survival analysis. λ and γ are scale and shape factors of the Weibull distribution, respectively (see Eq. 6)

manner of creep rupture from other wooden materials. Differences between CLT and other wooden materials are the existence of finger joints and transverse layers. They possibly influence long-term failure behavior.

Conclusions

We conducted long-term out-of-plane bending tests in a constant environment, investigated creep performance and the duration of load, and experimentally analyzed creep rupture behavior on seven-layer CLT made from Japanese larch. The results of the test were as follows:

1. Estimated relative creep after 50 years was 1.49 in mean. It was the lower value of relative creep compared to the conventional value of wood. Seven-layer CLT made from Japanese larch shows a satisfactory resistance to creep as a building material.
2. The duration of load of most of the specimens was shorter than the value for solid lumber. Especially, specimens loaded with 70% and 60% loading levels had a shorter duration of load than that.
3. Initial failure was observed in specimens loaded with 90%, 80%, and 70% loading levels in this study. A 70% loading level or more should be avoided in CLT members made from Japanese larch.
4. Most specimens showed extreme conversion from secondary creep to tertiary creep. Several specimens showed almost no tertiary creep before failure. Creep rupture of most of the specimens occurred at less deflection than displacement at failure in the short-term loading test. The effects of finger joints, transverse layers, and width of a specimen on creep rupture behavior should be estimated in future work.

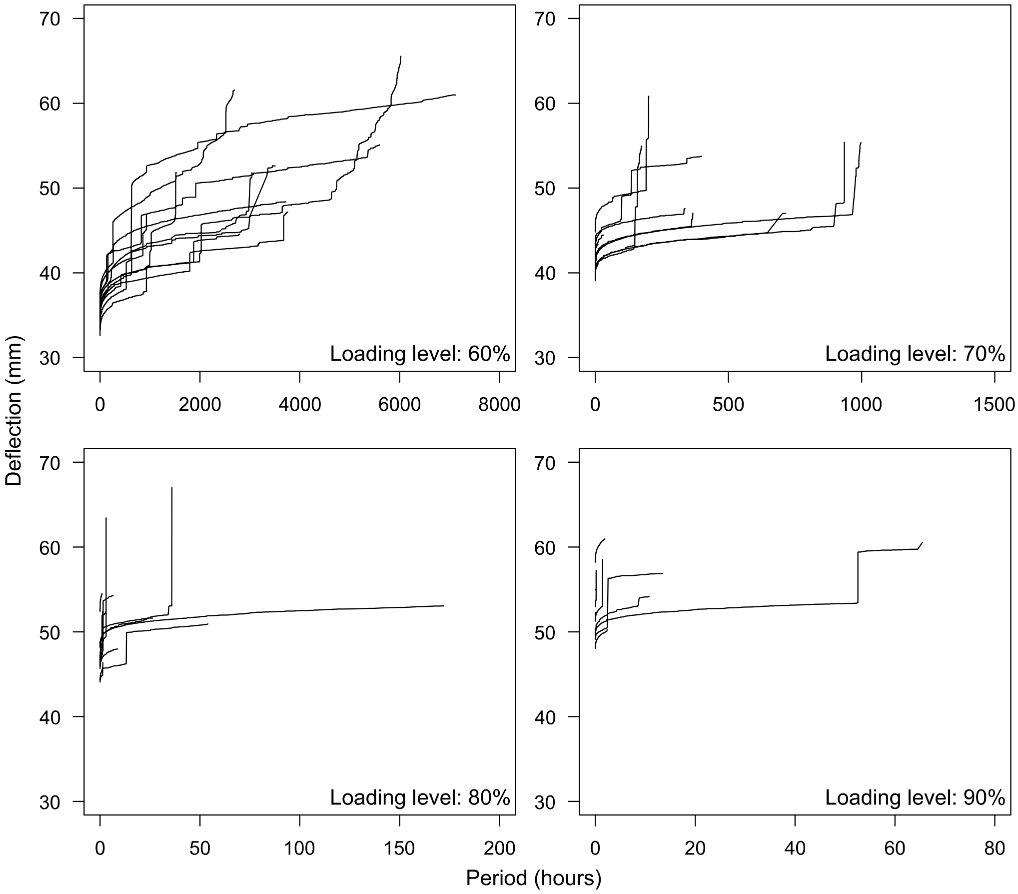

Fig. 9 Deflection at span center of specimens with time

Abbreviations

P: Load; δ: Displacement; E_m: Bending modulus of elasticity; σ_b: Bending strength; P_{max}: Maximum load; ΔP: Load increase in an elastic range; $\Delta\delta$: Displacement increase in an elastic range; L: Length of the support span; b: Specimen width; h: Specimen thickness; RH: The relative humidity; δ_{max}: Displacement at P_{max}; MC: Moisture content; SD: The standard deviation; t: Time; δ_t: Total deflection at time t; δ_0: Initial deflection; n: Constant; m: Constant; δ_{50y}: Estimated deflection after 50 years; δ_{final}: Final recorded deflection before failure; y: Loading level; x: Time in seconds; $f(t_s)$: The probability density function; t_s: Survival time in hours; λ: The scale factor; γ: The shape factor; $S(t_s)$: The survival function; $h(t_s)$: The hazard function.

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Authors' contributions

RT, YO, and KM planned the research. All authors contributed to preparing the specimens, conducting the tests, and analyzing the data. RT wrote the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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