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DURATION OF LOAD UNDER LONG-TERM BENDING LOAD OF LAMINATED VENEER LUMBER AND WOODEN I-BEAM

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ABSTRACT: A wide range of wooden materials have been developed and used in construction. Although wood-based composites are important structural materials, few studies focusing on their creep rupture properties have been reported. We conducted long-term bending tests and investigated long-term allowable loading levels of laminated veneer lumber (LVL) and wooden I-beams made of LVL flanges and oriented-strand-board (OSB) web. Creep rupture of wooden I-beam specimens occurred in their LVL flanges. At the same time, LVL and I-beam specimens showed similar estimated long-term (50 years) allowable stress levels, which were equal or higher values than that of lumber. Survival analysis of the obtained data indicated no effect of the specimen type (LVL or I-beam) on survival distribution. The duration of load of wood-based composite materials could be estimated based on that of its component members.

KEYWORDS: Creep rupture, Bending, LVL, Constant environment

1 INTRODUCTION

Wood and wooden materials are important building materials. In recent years, timber construction has attracted increasing interest globally for use in many fields [1]. A wide range of wooden materials has been developed and used in construction to make various construction design. Wooden I-beams, which are often called I-joists, are I-shaped engineered wood structural members. They consist of top and bottom flanges, typically of laminated veneer lumber (LVL) or solid sawn lumber, and the web made of plywood or oriented-strand-board (OSB). I-beams possess multiple advantageous properties, such as stiffness, strength, and light weight, and are well-suited for long-span joist and rafter applications [2].

Wood materials demonstrate characteristic behaviors under constant load. When the stress is sufficiently high, failure eventually occurs under constant load. This type of failure is called creep rupture [3]. Creep rupture is an important factor in timber construction, it must be considered to ensure the long-term safety of wooden structures. Several studies have investigated the creep rupture properties of solid lumber [4, 5, 6], wood-based structural panels [7], and cross-laminated timber [8, 9]. However, few studies have been conducted on the duration of load of wood-based composite materials such as wooden I-beams. At the same time, the bending performance [10, 11, 12], shear performance [10], and creep performance [11, 13, 14] of wooden I-beams have been comprehensively investigated. To the best of our knowledge, there have been no reports on the duration of load of wooden I-beams. In addition, wood-based composite materials often have large dimensions, then it is difficult to conduct long-term loading tests because it requires special equipment for long-term loading and takes a long time for the test. If the relationship between the creep rupture properties of a composite and those of its element is elucidated, the creep rupture properties of wood-based composites could be estimated based on tests of their elements with small dimensions. In the present study, we conducted long-term bending tests on LVL and wooden I-beams composed of LVL flanges and OSB web to investigate and compare their long-term bending properties.

2 MATERIALS AND METHODS

2.1 SPECIMENS

2.1.1 LVL

LVL specimens were comprised of eleven-ply veneer of Japanese Larch (*Larix kaempferi*) glued with phenol resin adhesive. Specimens were 53 mm in width (veneer face), 35 mm in thickness (lamination direction), and 700 mm in length. The criterion for stress grading was 120E of Japanese Agricultural Standard for LVL (12.0 kN/mm^2 in mean and 10.5 kN/mm^2 in lower limit for bending modulus of elasticity). LVL specimens were collected from nine LVL motherboards with 1200 mm width. Figure 1 shows the cutting pattern of LVL specimens. Nine specimens were cut from each LVL motherboard: five side-matched specimens for a short-term loading test and four specimens for a long-term loading test. Thus, the total numbers of LVL specimens were 45 and 36 for short-term and long-term loading tests, respectively.

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2.1.2 Wooden I-beam

Wooden I-beam specimens were composed of LVL flanges and OSB web glued together by resorcinol resin adhesive. LVL flanges had the same dimensions as LVL specimens and were end-matched with them. Thus, the number of I-beam specimens with side-matched flanges was 81: 45 for short-term and 36 for long-term loading tests. Figure 1 shows the cutting pattern of flanges of I-beam specimens. LVL flanges were 53 mm in width and 35 mm in thickness. The thickness of the OSB web was 9.5 mm. I-beam specimens were 235 mm in height and 4700 mm in length.

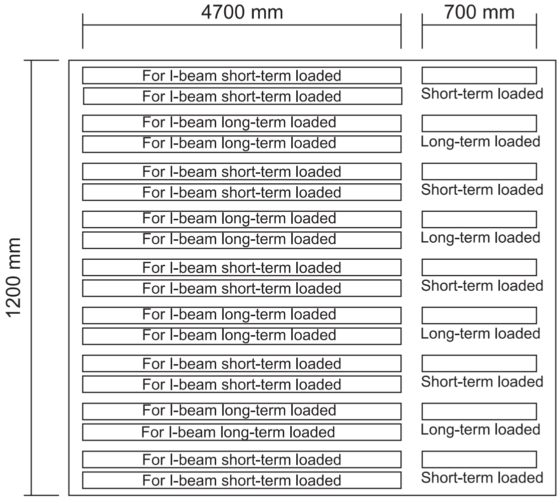

Figure 1: *Cutting pattern of LVL specimens from LVL motherboard*

2.2 SHORT-TERM LOADING TEST

2.2.1 LVL

LVL specimens were conditioned at 20°C and 65% relative humidity (RH) prior to the four-point bending test conducted using a testing machine (ORIENTEC Co. LTD; maximum loading capacity of 100 kN) in an unconditioned room. The specimens were loaded in the vertical direction to lamination at their third-point across a 630 mm supported span at a cross-head moving speed of 2 mm/min. Both the load (P) and displacement at the span center of a specimen from the ground (δ) were measured. Then, the bending modulus of elasticity (E_m) and the bending strength (σ_b) were, respectively, calculated as follows:

$$E_\mathrm{m} = \frac{23\Delta P L_1^3}{108\Delta\delta b h^3} \tag{1}$$

$$\sigma_b = \frac{P_\mathrm{max} L_1}{b h^2} \tag{2}$$

where P_max is the maximum load, ΔP is the load increase in an elastic range ($0.4P_\mathrm{max} - 0.1P_\mathrm{max}$ for this study), $\Delta\delta$ is an increase in δ with ΔP, L_1 is the length of the support span (630 mm), b is the specimen width, and h is the specimen thickness.

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

2.2.2 Wooden I-beam

I-beam specimens were conditioned at 20°C and 65%RH prior to the four-point bending test conducted using a testing machine (TOKYO KOKI TESTING MACHINE Co. LTD; maximum bending load capacity of 200 kN) in an unconditioned room. The specimens were loaded at their third-point across a 4410 mm supported span. The tests were conducted with lateral supports on a specimen to prevent horizontal buckling. Cross-head movement speed was 12 mm/min. The load (P) was measured and the maximum bending moment (M_max) was calculated as follows:

$$M_\mathrm{max} = \frac{P_\mathrm{max} L_2}{6} \tag{3}$$

where P_max is the maximum load, and L_2 is the length of the support span (4410 mm).

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

2.3 LONG-TERM LOADING TEST

Figures 2 and 3 show the experimental setup for the long-term loading tests for LVL and I-beam specimens, respectively. The testing instruments were capable of loading approximately 14 and 17 times the weight suspended at the end of the moment arm to specimens, respectively. The tests were conducted at a constant temperature (20°C) and relative humidity (65%RH). A four-point bending setup was used, which is equivalent to the short-term loading test. In the tests of I-beam specimens, lateral supports on the specimens were used to prevent horizontal buckling of the specimens. The mean maximum load of two both-side-matched short-term loading specimens to a long-term loading specimen was assumed to be the standard (100%) load of a long-term loading. The applied constant load (stress level: SL) was 90, 80, and 75% of the standard load. Thirty-six LVL and I-beam specimens were tested: 12 specimens for each stress level. The displacement was measured at a span center for LVL specimens and the moment arm for I-beam specimens at the measurement interval of 1 min. The measurements were proceeded until specimen failure. The duration of load (time to failure) was calculated as the duration between the completion of loading and specimen failure.

Figure 2: *Experimental setup for the long-term loading tests of LVL*

Figure 3: *Experimental setup for the long-term loading tests of I-beam specimens*

3 RESULTS AND DISCUSSIONS

3.1 SHORT-TERM LOADING TEST

Tables 1 and 2 show the results of the short-term loading tests. All specimens demonstrated bending failure. Most LVL specimens broke at a scarf joint on the tensile surface, and most I-beam specimens broke in the bottom LVL flange (tensile surface). Test duration from the beginning of loading to specimen failure was less than 10 min for most specimens.

Table 1: *Results of the short-term loading test for LVL*

	Density (kg/m^3)	MOE (kN/mm^2)	MOR (N/mm^2)	MC (%)	Test duration (minute)
Mean	621	12.60	57.0	10.2	6.4
SD	23	0.90	8.2	0.7	2.3
Max	667	14.46	75.4	11.6	13.6
Min	580	10.73	38.5	9.1	3.4

MOE: Modulus of elasticity (see Eq. (1)), MOR: Modulus of rupture (see Eq. (2)), MC: Moisture content, SD: Standard Deviation.

Table 2: *Results of the short-term loading tests for I-beams*

	M_{max} (kNm)	MC (%)	Test duration (minute)
Mean	14.9	9.6	4.9
SD	1.7	0.3	0.5
Max	18.1	10.5	6.4
Min	10.9	8.9	3.7

M_{max}: Maximum bending moment (see Eq. (3)), MC: Moisture content, SD: Standard Deviation.

3.2 LONG-TERM LOADING TEST

Tables 3 and 4 show the duration of load in the long-term loading tests. One I-beam specimen loaded at 80% stress level showed horizontal buckling before the completion of loading and this data was not used for analysis. In addition, specimens with blank data in Tables 3 and 4 experienced failure before the completion of loading. Two LVL specimens loaded at 75% stress level that did not fail and two I-beam specimens loaded at 90% stress level that showed horizontal buckling were censored (marked with an asterisk in Tables 3 and 4). Most LVL specimens broke at a scarf joint on the tensile surface and most I-beam specimens broke in the bottom LVL flange, similar to the short-term loading tests. Figures 4 and 5 show the relationship between the duration of load and stress level. Figures 6 and 7 show this relationship with the stress level converted to the ratio of practical stress to the overall mean value for short-term loading specimens. The black solid line in Figures 4–7 represents an empirical hyperbolic curve based on clear and small specimens [4]. This curve is called the Madison Curve, which is expressed as follows:

$$SL = 108.4t^{-0.04635} + 18.3 \tag{4}$$

where SL is stress level and t is time in seconds.

Most specimens show almost equal or longer duration of load than Madison Curve. These specimens exhibit equivalent long-term bending properties to clear solid lumber. The red and blue dashed lines are regression lines fitted by the following models:

$$SL = a_1 \ln(t) + b_1 \tag{5}$$

$$\ln(t) = a_2 SL + b_2 \tag{6}$$

where SL is stress level, t is time in seconds, and a_1, a_2, b_1, and b_2 are coefficients.

Table 5 shows regression coefficients, coefficients of determination, and extrapolation values of SL in 50 years (SL_{50y}) as a long-term performance of the specimens. Duration of load of specimens that showed failure before the completion of loading were assumed to be 1 s in the calculations. Those of censored specimens were assumed to be durations until censoring. First, I-beam specimens show better coefficients of determination of the stress level relative to the overall mean of short-term loading (SL_2). Second, SL_{50y} values for LVL and I-beam specimens are similar for the same stress level methodology. Finally, specimens in this study show equal or better long-term bending properties than lumber. Long-term strength of lumber is assumed to be 60% of short-term strength [3], and the Japanese building code assumes 55%. The Japanese building code assumes “long-term” as 50 years. Most SL_{50y} for all models in this study exceeds this value. I-beams with the composition and dimensions used in this study are widely employed in practice. Therefore, general I-beams may show equal or higher long-term bending strength than conventional wood members. Furthermore, long-term bending properties of I-beams could be estimated based on those of LVL members in which creep rupture of I-beams occurred. The reasoning behind these claims is discussed further in the next section.

Table 3: *Duration of load of LVL specimens*

SL_1	SL_2	Duration of load (second)	
0.90	0.91	2962	
0.90	0.89	1296867	
0.90	0.87	5426623	
0.90	1.01	-	
0.90	0.90	196321	
0.90	1.11	-	
0.90	0.96	-	
0.90	0.77	179	
0.90	0.98	-	
0.90	0.74	1981	
0.90	0.71	8219	
0.90	0.95	769	
0.80	0.69	15476105	
0.80	0.72	19373016	
0.80	0.95	17222	
0.80	0.96	1953918	
0.80	0.79	5407475	
0.80	0.82	236178	
0.80	0.63	55417421	
0.80	0.57	49179681	
0.80	0.79	1156993	
0.80	0.79	265990	
0.80	0.91	7363	
0.80	0.88	51869517	
0.75	0.67	42338326	
0.75	0.67	29914617	
0.75	0.67	99467792	*1
0.75	0.87	118791	
0.75	0.79	5097780	
0.75	0.79	2206961	
0.75	0.87	4977956	
0.75	0.74	3111670	
0.75	0.76	3558795	
0.75	0.76	90660315	*1
0.75	0.68	26321924	
0.75	0.82	848069	

Note: Blanks represent failure before the completion of loading. SL_1: Stress level relative to that of side-matched specimens, SL_2: Stress level relative to the overall mean of short-term loading, and *1: Censored specimens that did not fail.

Table 4: *Duration of load of I-beam specimens*

SL_1	SL_2	Duration of load (second)	
0.90	0.98	118	
0.90	0.92	1536	
0.90	0.81	1822	
0.90	0.93	3736	
0.90	0.99	793	
0.90	0.74	7952184	
0.90	0.81	120491	
0.90	0.88	1911	*2
0.90	0.98	848	
0.90	0.84	18304	
0.90	0.93	976	
0.90	0.85	1482538	*2
0.80	0.82	65908	
0.80	0.69	5824379	
0.80	0.84	72763	
0.80	0.78	404043	
0.80	0.87	NA	
0.80	0.70	3061833	
0.80	0.80	25404261	
0.80	0.86	-	
0.80	0.78	1335314	
0.80	0.84	14423	
0.80	0.82	31672	
0.80	0.86	4123	
0.75	0.72	570224	
0.75	0.74	9503275	
0.75	0.78	62135	
0.75	0.69	6833192	
0.75	0.78	3073888	
0.75	0.74	35189705	
0.75	0.65	6278815	
0.75	0.77	3140010	
0.75	0.78	502737	
0.75	0.87	159480	
0.75	0.71	31780333	
0.75	0.76	6665934	

Note: Blanks represent failure before the completion of loading. NA: Data not used for analysis due to horizontal buckling before the completion of loading, SL_1: Stress level relative to that of side-matched specimens, SL_2: Stress level relative to the overall mean of short-term loading, and *2: Censored specimens that showed horizontal buckling.

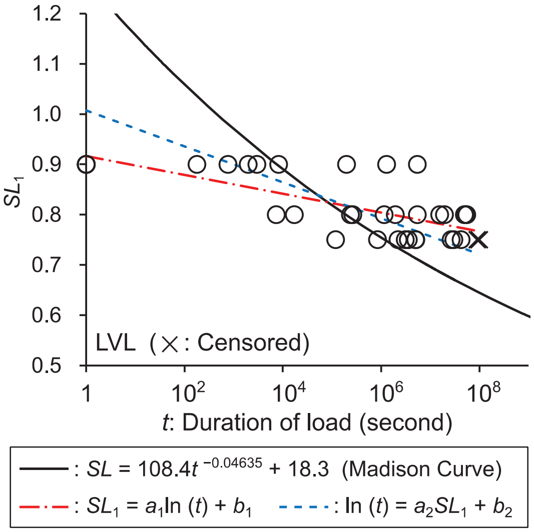

Figure 4: *Relationship between the duration of load and stress level for LVL specimens*
SL_1: Stress level relative to that of side-matched specimens.

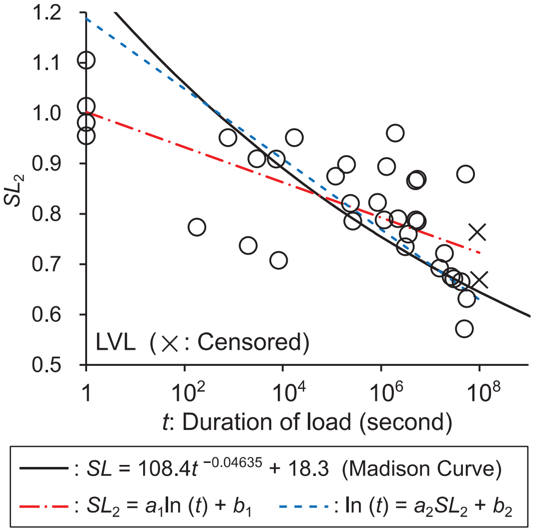

Figure 5: *Relationship between the duration of load and stress level for I-beam specimens*
SL_1: Stress level relative to that of side-matched specimens.

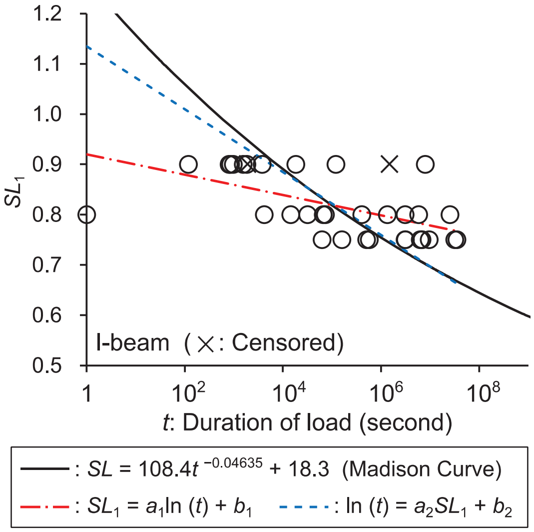

Figure 6: *Relationship between the duration of load and stress level (relative to the overall mean) for LVL specimens*
SL_2: Stress level relative to the overall mean of short-term loading.

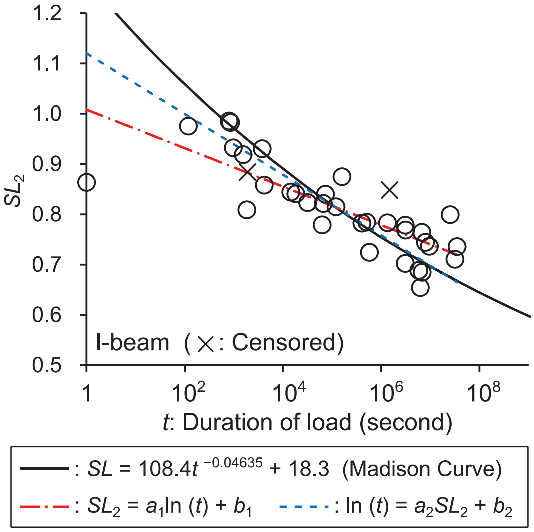

Figure 7: *Relationship between the duration of load and stress level (relative to the overall mean) for I-beam specimens*
SL_2: Stress level relative to the overall mean of short-term loading.

***Table 5:** Results of model fitting*

	Stress level	Model	Slope	Intercept	R^2	SL_{50y}
LVL	SL_1	Eq. (5)	−0.008	0.917	0.524	0.744
		Eq. (6)	−64.39	64.86	0.524	0.678
	SL_2	Eq. (5)	−0.015	1.003	0.501	0.681
		Eq. (6)	−32.98	39.18	0.501	0.546
I-beam	SL_1	Eq. (5)	−0.009	0.920	0.323	0.734
		Eq. (6)	−36.83	41.80	0.323	0.560
	SL_2	Eq. (5)	−0.017	1.008	0.634	0.656
		Eq. (6)	−38.19	42.77	0.634	0.565

SL_1: Stress level relative to that of side-matched specimens, SL_2: Stress level relative to the overall mean of short-term loading, R^2: Coefficients of determination, and SL_{50y}: extrapolation values of stress level in 50 years.

3.3 SURVIVAL ANALYSIS

Survival analysis is a collection of statistical procedures for data analysis in which the variable of interest is time until an event occurs [15]. It is a popular data analysis approach in epidemiologic and reliability engineering, which can be used for censored data. In the present study, survival analysis was conducted for the duration of load, which is time until failure. Figures 8–10 show survival curves derived from survival analysis using the Kaplan–Meier method (a non-parametric method). This analysis was performed using the statistical software R version 4.2.2 [16]. One second was used as the duration of load for specimens that failed before the completion of loading. Survival function shows no significant differences ($p > 0.05$) between LVL and I-beam specimens at all stress levels using the log–rank test. In addition, Cox proportional hazard model [17] was applied to data in this study as follows:

$$h(t|x) = h_0(t)\exp\,(\beta_1 SL_1 + \beta_2 x) \quad (7)$$

where $h(t|x)$ is the hazard function with covariance, $h_0(t)$ is baseline hazard, β_1 and β_2 are coefficients, SL_1 is the stress level relative to that of side-matched specimens, and x is specimen type (LVL: $x = 0$, I-beam: $x = 1$). The hazard function represents the instantaneous failure rate. This model assumes that the hazard ratio depends only on covariance, not on t. Table 6 shows the estimated values of the coefficients. The coefficient of specimen type (β_2) shows no significant differences. In this case, the hazard ratio of the I-beam specimen to the LVL specimen is exp (β_2). This value includes 1.0 in the confidence interval. Therefore, survival functions also show no significant differences between the LVL and I-beam specimens. Considering the discussion in this and former sections, the duration of load of I-beams could be evaluated from that of LVL, which is an element of I-beam in this study.

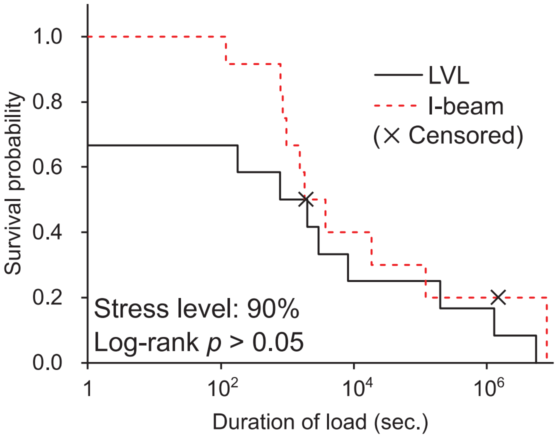

***Figure 8:** Kaplan–Meier curves for the stress level of 90%*

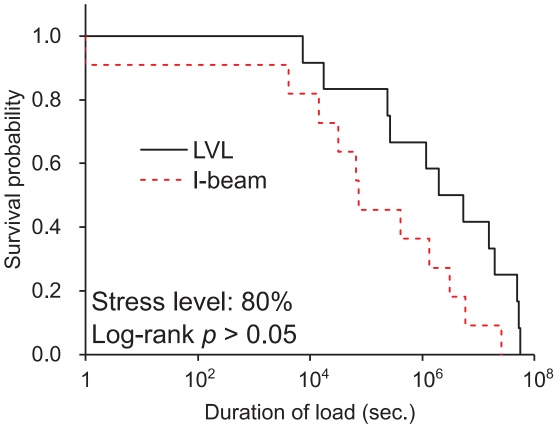

***Figure 9:** Kaplan–Meier curves for the stress level of 80%*

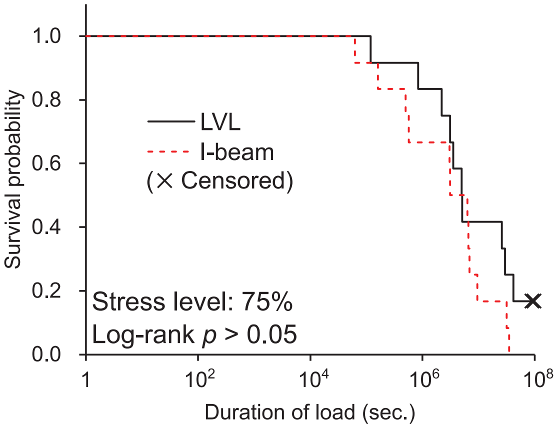

***Figure 10:** Kaplan–Meier curves for the stress level of 75%*

Table 6: *Coefficients estimated using the Cox proportional hazard model*

β_1	β_2	exp (β_1)	exp (β_2)
10.69*	0.383^{ns}	43868 (612– 3147000)	1.467 (0.883– 2.437)

*: p <0.000001, *ns*: not significant (null hypothesis is $H_0 = 0$), with 95% confidence interval.

4 CONCLUSIONS

Long-term bending tests were conducted on LVL and wooden I-beam specimens composed of LVL flanges and OSB web to investigate and compare their long-term bending properties. The results of this study are as follows.

1. Creep rupture of I-beam specimens occurred in the bottom LVL flange, in which the tensile stress occurred.
2. LVL and I-beam specimens showed similar estimated long-term (50 years) allowable stress levels in all fitted models.
3. Specimens in this study show equal or better long-term bending properties than lumber.
4. Survival analysis of the data in this study indicates no significant differences between survival distributions for the LVL and I-beam specimens. Additionally, the duration of load of I-beam specimens could be estimated from that of LVL flange members.
5. Thus, the duration of load of wooden composite materials may be estimated from that of element members that contribute to the failure mode of the composites.

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