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ORIGINAL ARTICLE

Reliability analysis and duration-of-load strength adjustment factor of the rolling shear strength of cross laminated timber

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Abstract In this study, the duration-of-load effect on the rolling shear strength of cross laminated timber (CLT), with different cross-sectional layups (five-layer and three-layer), was evaluated. A stress-based damage accumulation model is chosen to evaluate the duration-of-load strength adjustment factor of the rolling shear strength of CLT. This model incorporates the established short-term rolling shear strength of material and predicts the time to failure under arbitrary loading history. The model has been calibrated and verified based on the test data from low cycle trapezoidal fatigue tests (damage accumulation tests) in the previous study. The long-term rolling shear behaviour of CLT can then be evaluated from this verified model. As the developed damage accumulation model is a probabilistic model, it can be incorporated into a time based reliability assessment of the CLT products, considering short-term, snow, and dead load only loading cases. The reliability analysis results and factors reflecting the duration-of-load effect on the rolling shear strength of CLT are compared and discussed. The characteristic of this modeling theory lies in that the verified model is also able to predict the duration-of-load behaviour of CLT products under arbitrary loading history, such as long-term dead load case; then, these predictions of time to failure from the damage accumulation model can elucidate duration of load by the stress ratio evaluation approach. The results suggest that the duration-of-load rolling shear strength adjustment factor for CLT is more severe than the general duration-of-load adjustment factor for lumber; this difference should be considered in the introduction of CLT into the building codes for engineered wood design.

Keywords Cross laminated timber · Rolling shear · Duration of load · Reliability analysis · Damage accumulation model

Introduction

Cross laminated timber (CLT) is a wood composite product suitable for floor, roof and wall applications, and it consists of crosswise oriented layers of wood boards that are either glued by adhesives or fastened with aluminum nails or wooden dowels [1]. The CLT panel usually includes 3–11 layers, as shown in Fig. 1.

Rolling shear stress is defined as the shear stress leading to shear strains in a radial-tangential plane perpendicular to the grain. For general timber design, rolling shear strength and stiffness are not major design properties. For CLT, however, rolling shear strength and stiffness must be considered in some loading scenarios due to the existing cross layers [2, 3]. For example, when a CLT floor panel is supported by columns, highly concentrated loads in the supporting area may cause high rolling shear stresses in cross layers; the same concerns may arise for designing short-span floors or beams under out-of-plane bending loads. Under out-of-plane bending loads, for example, the CLT panel capacity can sometimes be governed by the rolling shear failure in the cross layers, as shown in Fig. 2

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Fig. 1 Layering of cross laminated timber (CLT)

Fig. 2 Rolling shear behaviour in CLT cross layers (shear behaviour in a plane perpendicular to the grain direction)

[4]. Therefore, there is a need to evaluate the rolling shear strength properties for more practical applications of CLT structures.

In general, wood is stronger under loads of short-term duration and is weaker if the loads are sustained. This phenomenon is called duration of load; the primary relationship between the stress ratio, also known as the load ratio (the ratio between the applied stress and the short-term strength) and the time to failure is commonly referred to as the duration-of-load effect. In fact, the duration-of-load effect is not introduced by material deterioration, such as biological rot; rather, it is an inherent characteristic of wood.

Although it is well known that the strength properties of wood products are influenced by the duration-of-load effect [5–9], there is very little research reported on studying the duration-of-load effect on the rolling shear strength of CLT. Therefore, more research work is needed to quantify the duration-of-load effect and to reduce the possibility of CLT rupture under long-term and sustained loading throughout its intended service life.

Li and Lam [10] performed short-term ramp loading tests and low cycle trapezoidal fatigue loading tests to accumulate damage in the research of the rolling shear duration-of-load behaviour of CLT. Five-layer and three-layer CLT products were investigated in the tests. In this research, basic short-term rolling shear strength distribution was first established by short-term ramp loading; the time to failure data from the low cycle trapezoidal fatigue loading tests was obtained to understand the development of deflection and damage accumulation process. The short-term rolling shear capacity is lower in the three-layer CLT in comparison to the five-layer CLT; based on the results from the short-term ramp loading tests, rolling shear strength properties of CLT beam specimens were evaluated. A stress-based damage accumulation model was used to investigate the duration-of-load effect on CLT rolling shear. The model was calibrated against the test data; the test results showed that the model predictions agreed well with the test data.

The verified model can then be used to quantify the rolling shear duration-of-load effect of CLT under other loading conditions. As the damage accumulation model is a probabilistic model, it can be incorporated into a time-reliability study. Therefore, a reliability assessment of the CLT products is performed considering short-term, snow, and dead load only loading cases. The reliability analysis results reflecting the duration-of-load effect on the CLT's rolling shear strength are discussed. The characteristic of this modeling theory lies in that the verified model can also predict the duration-of-load behaviour of wood-based products under arbitrary loading history, including long-term dead load cases; then, these predictions of time to failure from the damage accumulation model can elucidate duration of load. Therefore, the reliability investigation and the predictions of the time to failure from the model were able to provide guidance for the evaluation of the CLT rolling shear duration-of-load effect.

Damage accumulation model

The theory of the damage accumulation model is one of the key tools to investigate the duration-of-load behaviour in wood-based products [7, 11, 12]. A stress-based damage accumulation model was developed by Foschi and Yao [13] to consider the duration-of-load effect on the strength properties of dimensional lumber [6, 11]. The Foschi and Yao model considers the damage accumulation rate as a function of stress history and the already accumulated damage state as follows:

$$\begin{cases} \mathrm{d}\alpha/\mathrm{d}t = a(\sigma(t)-\tau_0\sigma_\mathrm{s})^b + c(\sigma(t)-\tau_0\sigma_\mathrm{s})^n\alpha \quad \text{if } \sigma(t) > \tau_0\sigma_\mathrm{s} \\ \mathrm{d}\alpha/\mathrm{d}t = 0 \quad \text{if } \sigma(t) \le \tau_0\sigma_\mathrm{s} \end{cases},$$

where α is the damage state variable ($\alpha = 0$ in an undamaged state and $\alpha = 1$ in a failure state); t is the time; $\sigma(t)$ is

Table 1 Calibration results for cross laminated timber (CLT)

	Mean	Standard deviation
Model parameters for five-layer CLT		
b	39.857	2.219
c	3.483×10^{-3}	2.446×10^{-3}
n	6.754	0.117
τ_0	0.194	0.247
Model parameters for three-layer CLT		
b	257.249	229.738
c	9.861×10^{-2}	1.104×10^{-5}
n	14.911	0.045
τ_0	0.059	0.001

the applied stress history; σ_s is the short-term strength; τ_0 is a ratio of the short-term strength σ_s; thus, the product $\tau_0\sigma_s$ is a threshold stress below which there will be no accumulation of damage; a, b, c, τ_0 and n are random model parameters.

The Foschi and Yao model was adopted in the current duration-of-load research of CLT rolling shear capacity. In the previous study [10], the stress-based damage accumulation models have been calibrated and verified in five-layer and three-layer CLT products (denoted as SPF5-0.4 and SPF3-0.4), by analysing the measured data from the tests, as given in Table 1 with the obtained model calibration results in terms of the mean and standard deviation of the lognormal distribution for each model parameter. The probabilistic model will be used in the time based reliability analysis, to quantify the rolling shear duration-of-load effect of CLT in the following sections.

Reliability analysis

Reliability analysis of short-term rolling shear strength of CLT

This section introduces the reliability analysis on the limit state of the short-term CLT rolling shear strength, when the duration-of-load effect is not considered. The objective of this reliability analysis is to evaluate the relationship between the reliability index β and the performance factor ϕ in design codes. To clarify, the reliability analysis with consideration of the effect of load duration on rolling shear will be addressed in the next section.

First, based on the ultimate strength limit state design equation from the design code [11]:

$$1.25D_n + 1.50Q_n = \phi \mathrm{RS}_{(0.05)} T_V, \tag{1}$$

where D_n is the design dead load which is normally computed using average weights of materials, and Q_n is the design live load which, in the case of snow plus associated rain for example, is taken from the distributions of annual maxima and corresponds to loads with a 1/30 probability of being exceeded (30 years return); ϕ is the performance factor applied to the characteristic strength ($\mathrm{RS}_{(0.05)}$).

This characteristic rolling shear strength $\mathrm{RS}_{(0.05)}$ is chosen to be the parametric 5th percentile rolling shear stress value evaluated by lognormal fitting technique [11]; the $\mathrm{RS}_{(0.05)}$ is calculated with consideration of the influence of higher loading rate, which is consistent with the model calibration process in the previous study [10], as obtained from the finite element evaluation results on the rolling shear strength corrected with the expected 15 % strength increase due to the higher loading rate for modeling purpose, as shown in Table 2. T_V is the ratio between load capacity and shear strength (in kN/MPa), which will be introduced in the next paragraph; therefore, $\mathrm{RS}_{(0.05)}$ is not dependent on the ratio T_V used.

T_V in Eq. (1) is defined as the ratio between the shear stress value and the sectional rolling shear load-carrying capacity calculated from different beam theories (the layered beam theory, the gamma beam theory and the shear analogy theory). For each beam theory, the relationship between the sectional load-carrying capacity and the shear stress value is introduced in the literature [14–17]. The calculated T_V values for five-layer and three-layer CLT are shown in Table 3.

From Eq. (1), the performance factor ϕ will affect the reliability index β. For instance, with a given ϕ, the performance function G for the calculation of the reliability index β is:

$$G = R - (D + Q)$$

in which, R is the random variable related to the rolling shear load-carrying capacity (based on the observation from the short-term ramp loading tests in the previous study) [10] corrected with the expected strength increase due to the higher loading rate for modeling purpose, which is consistent with the term $\mathrm{RS}_{(0.05)}$ in Eq. (1); D is the random dead load; Q is the random live load. Then, the ratio of the design dead load to the design live load is defined as (here chosen to be 0.25):

$$r = \frac{D_n}{Q_n},$$

therefore, the performance function G is:

$$G = R - \frac{\phi \mathrm{RS}_{(0.05)} T_V}{(1.25r + 1.50)}(dr + q), \tag{2}$$

where the random variables d and q are:

$$d = \frac{D}{D_n} \quad q = \frac{Q}{Q_n}$$

Table 2 Summary of the finite element evaluation results on the rolling shear strength

	Rolling shear strength (MPa)		
	Mean	Coefficient of variation (%)	5th percentile
Five-layer CLT	2.02	12.2	1.56
Three-layer CLT	1.62	23.3	1.04

CLT cross laminated timber

Table 3 Summary of the calculated T_V values (in kN/MPa) for cross laminated timber (CLT)

	T_V from layered beam theory	T_V from gamma beam theory	T_V from shear analogy theory
Five-layer CLT	11.24	11.90	11.76
Three-layer CLT	7.46	10.20	7.46

the calculation of the random variables d and q can be found in the literature [11, 17].

With regard to the short-term rolling shear strength design method for the CLT beam under the concentrated load, the snow loads from two sites (in Halifax and Vancouver) were first investigated and included in the following reliability analysis process. The snow load information comes from the statistics on the maximum annual snow depth, the snow duration and the ground-to-roof snow conversion factors provided by the National Research Council of Canada [11].

The objective of this reliability analysis, adopting the first order reliability method (FORM), is to evaluate the relationship between the reliability index β and the performance factor ϕ. Figures 3 and 4 give the results on the relationship between β and ϕ in five-layer CLT products under the different snow load cases; Figs. 5 and 6 give the results on the relationship between β and ϕ in three-layer CLT products.

From the above results from Figs. 3, 4, 5 and 6, under different beam theories, the obtained $\beta-\phi$ relationship is slightly different. This small difference comes from the different interpretations of the defined term T_V in Eq. (2), and this T_V is changing when different beam theories are adopted. The average β from Figs. 3, 4, 5 and 6 is then summarized from the β calculated from the different beam theories to get an average estimation over the error from the different assumptions. The average curve values are also given in Table 4. According to the previous reliability research of timber structures, 2.80 was determined as the target reliability index for the investigation of CLT rolling shear duration-of-load behaviour and it is consistent with the previous research on duration of load of dimensional lumber [11].

From Figs. 3, 4, 5 and 6, it shows that the ϕ factor is close to 0.9 at the target reliability index $\beta = 2.80$ (for five-layer CLT, $\phi = 0.834$ in Fig. 3 and $\phi = 0.855$ in Fig. 4; for three-layer CLT, $\phi = 0.868$ in Fig. 5 and $\phi = 0.776$ in Fig. 6). For the short-term bending strength of lumber in the Canadian design code, the performance factor is $\phi =$ 0.9 [11]. Therefore, the obtained ϕ from Figs. 3, 4, 5 and 6 for CLT is close to the ϕ in the code for lumber.

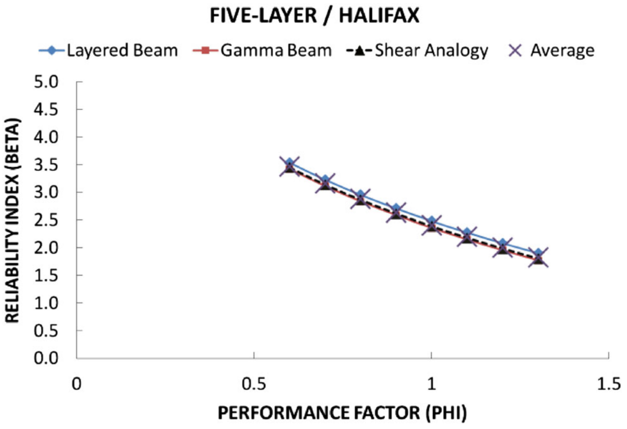

Fig. 3 *Curves* between the reliability index and the performance factor (five-layer/Halifax)

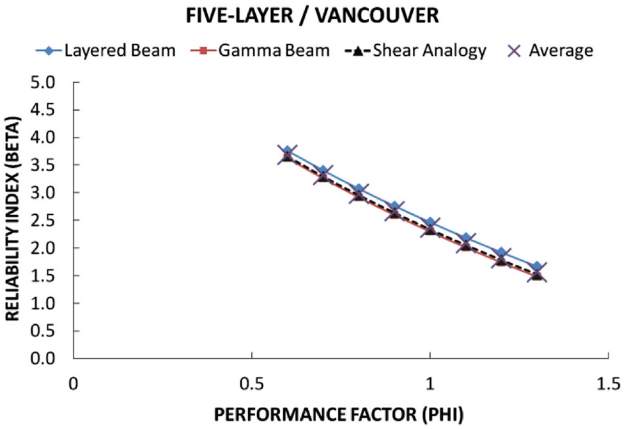

Fig. 4 *Curves* between the reliability index and the performance factor (five-layer/Vancouver)

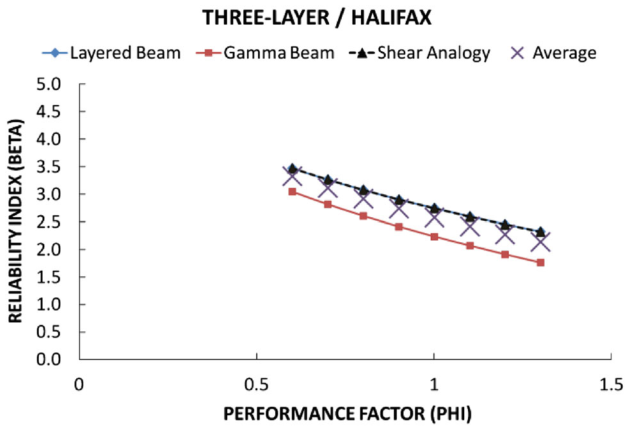

Fig. 5 *Curves* between the reliability index and the performance factor (three-layer/Halifax)

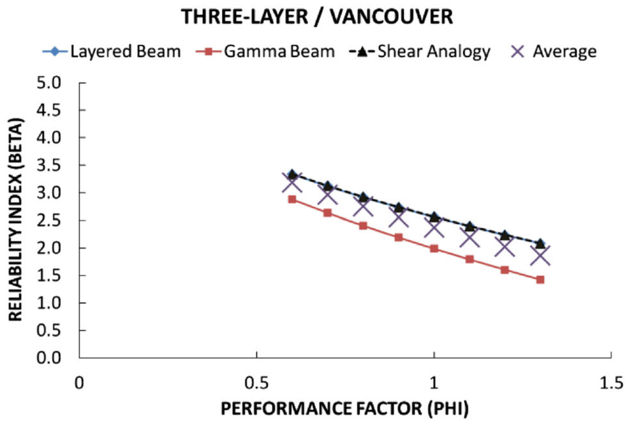

Fig. 6 *Curves* between the reliability index and the performance factor (three-layer/Vancouver)

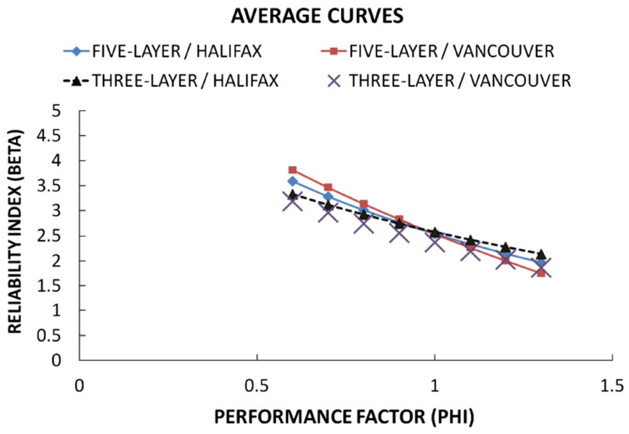

Fig. 7 Average *curves* between the reliability index and the performance factor without considering the duration-of-load effect

From Fig. 7 which shows the average curves between the reliability indices and the performance factors from the previous results under different snow load cases. When the performance factor is less than 0.8, the probability of rolling shear failure in the three-layer CLT is higher than that in the five-layer products. This is consistent with the performed short-term ramp loading test results, where the three-layer CLT products showed the lower rolling shear load-carrying capacity in the tests [10]. It is not clear why the trend is opposite when the performance factor is larger than 0.8 so more research and tests are suggested for further reliability analysis. Also, this reliability analysis on the short-term rolling shear strength will provide necessary information for the following investigation on duration of load.

Table 4 Reliability results for the strength adjustment factors in the five-layer and three-layer cross laminated timber (CLT)

	Reliability results			
	β	ϕ_{I}	ϕ_{II}	K_{D}
Five-layer				
Halifax	3.0	0.758	0.354	0.467
	2.8	0.834	0.388	0.466
	2.5	0.961	0.444	0.463
	2.0	1.205	0.554	0.460
Vancouver	3.0	0.794	0.496	0.625
	2.8	0.855	0.528	0.617
	2.5	0.953	0.580	0.609
	2.0	1.131	0.683	0.604
Three-layer				
Halifax	3.0	0.760	0.346	0.456
	2.8	0.868	0.402	0.462
	2.5	1.050	0.492	0.469
	2.0	1.398	0.670	0.480
Vancouver	3.0	0.682	0.378	0.553
	2.8	0.776	0.440	0.566
	2.5	0.929	0.542	0.583
	2.0	1.216	0.743	0.611

Reliability analysis of CLT rolling shear strength under 30-year snow load

This section introduces the reliability analysis on the limit state of CLT products under a 30-year snow load, with consideration of load duration effect on the rolling shear strength. The objective of this reliability analysis is to evaluate the relationship between the reliability index β and the performance factor ϕ when duration-of-load effect is included. A Monte Carlo simulation procedure, incorporating the verified damage accumulation model in Table 1, was used to determine the probability of the rolling shear failure of a single bending CLT beam specimen under load for a prescribed service life [11]. Then,

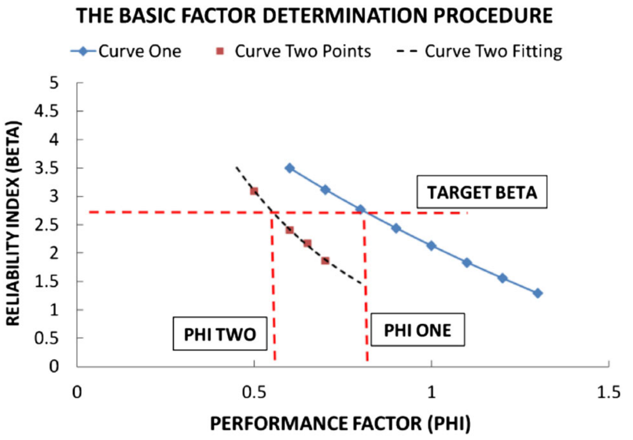

Fig. 8 The basic factor determination procedure (*curve* one-without duration-of-load effect; *curve* two-with duration-of-load effect)

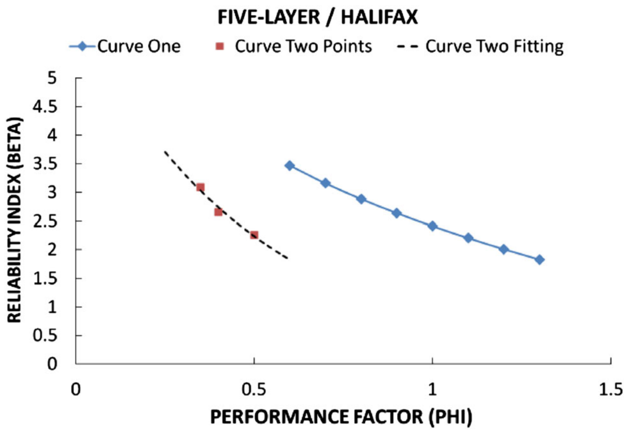

Fig. 9 *Curves* between the reliability index and the performance factor (five-layer/Halifax)

based on the previous results from the short-term rolling shear strength reliability analysis (without considering the duration-of-load effect) as shown from Figs. 3, 4, 5 and 6, the duration-of-load adjustment factor for the rolling shear strength can be obtained with one margin of safety.

The Monte Carlo simulation was used to determine the probability of rolling shear failure for a service life ranging from 1–30 years. Based on the verified damage accumulation model, a sample size of NR $=$ 1000 replications was chosen and these simulated samples were tested under the 30-year snow loading history as introduced in the literature [11, 17]. Consistent with the procedure in reliability analysis of short-term rolling shear strength of CLT, the snow loads from two sites (in Halifax and Vancouver) were considered, and dead load was also included in the service life. Then, the performance function G is:

$$G = 1 - \alpha, \tag{3}$$

where α is the damage parameter from the damage accumulation model. If $G > 0$, the sample will survive. If $G < 0$, the sample will fail.

After performing the Monte Carlo simulation giving the relationship between the reliability index β and the performance factor ϕ, the duration-of-load strength adjustment factor K_{D} can then be derived. The basic determination procedure for the factor K_{D} is shown in Fig. 8. In this figure, two cases are displayed for the relationship between β and ϕ. The first case in the figure is known as curve one, when the duration-of-load effect is not considered and only the short-term rolling shear strength is analyzed. This information comes from the previous reliability analysis on the short-term rolling shear strength of CLT (the results of the average β–ϕ relationship from Figs. 3, 4, 5 and 6). The second curve (curve two) in Fig. 8 includes the performed Monte Carlo simulation results with consideration of the duration-of-load effect. Based on the Monte Carlo simulation results (the points in curve two which are dispersed due to each point represents a calculated β with regard to the probability of failure in a Monte Carlo simulation procedure with a given ϕ value), curve two is calculated from the exponential regression fitting method consistent with the duration-of-load research on dimensional lumber [11]. In Fig. 8, at the same reliability index level β (the target reliability), the performance factor for curve one is defined as ϕ_{I}, and ϕ_{II} is the factor calculated from curve two. Then the strength adjustment factor K_{D} for the rolling shear strength is defined as:

$$K_{\mathrm{D}} = \frac{\phi_{\mathrm{II}}}{\phi_{\mathrm{I}}}. \tag{4}$$

For example, Figs. 9 and 10 show the relationship between the reliability index β and the performance factor ϕ in the five-layer CLT products, for both curve one and curve two; Figs. 11 and 12 show the relationship between the reliability index β and the performance factor ϕ in the three-layer CLT products. The same results from Figs. 9, 10, 11 and 12 are also given in Table 4.

Then, from Eq. (4), the derived duration-of-load rolling shear strength adjustment factor K_{D} is given in Table 4. Take the five-layer CLT under the 30-year Halifax snow load combined with the dead load case as an example, K_{D} is 0.466 when the reliability index $\beta = 2.80$. On the other hand, for the three-layer CLT, Table 4 shows that K_{D} is around 0.462 under the same circumstances.

Based on Eq. (4) and the same reliability analysis procedure, the reliability results for the rolling shear strength adjustment factors are summarized in Table 5 for another three different locations: Quebec City, Ottawa and Saskatoon (The snow load information for these cities and the analysis process are introduced in detail in the literature) [11, 17].

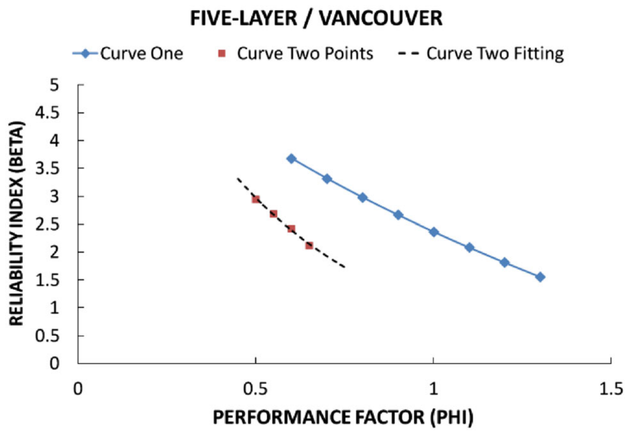

Fig. 10 *Curves* between the reliability index and the performance factor (five-layer/Vancouver)

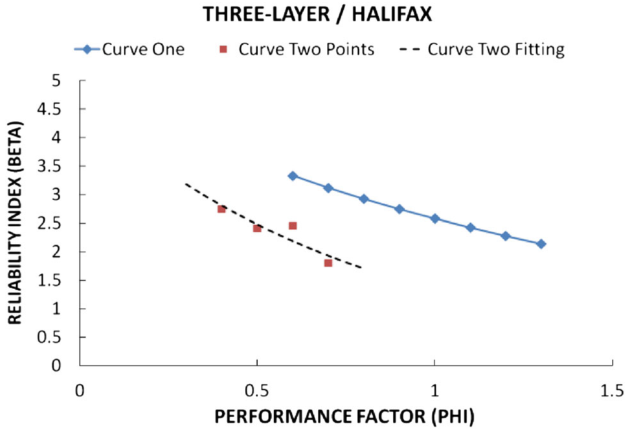

Fig. 11 *Curves* between the reliability index and the performance factor (three-layer/Halifax)

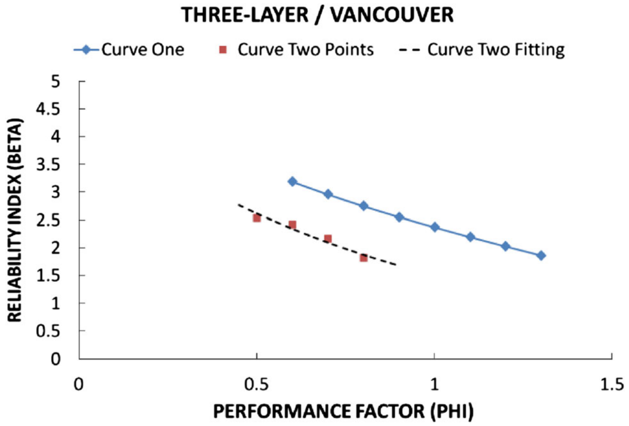

Fig. 12 *Curves* between the reliability index and the performance factor (three-layer/Vancouver)

Take the five-layer CLT under the 30-year snow load combined with the dead load case as an example, K_D is around 0.428–0.617 shown in Table 5 when the reliability index $\beta = 2.80$, i.e., the target reliability in design codes [11, 18]. The factor difference comes from the different snow load in each location, and the average factor from the five cities is 0.481. On the other hand, for the three-layer CLT, Table 5 shows that K_D is around 0.422–0.566 under the same circumstances; the average factor from the five cities is 0.472. In the Canadian design code, for lumber, the factor K_D is 0.8. Therefore, the results suggest that the duration-of-load strength adjustment factor for rolling shear strength in CLT products seems to be very different from that in lumber. Specifically, the rolling shear duration-of-load strength adjustment factor for CLT was found to be more severe compared to the general duration-of-load adjustment factor for lumber.

Reliability analysis of CLT rolling shear strength under 30-year dead load only

One question raised is what the duration-of-load adjustment factor is for the CLT rolling shear strength under a 30-year dead load only case. To answer this question, the rolling shear strength adjustment factor K_D with consideration of the duration-of-load effect for this constant dead loading case was evaluated. The performed procedure for this evaluation was similar to that introduced in the previous sections, except the dead load only case was characterized not only by changing the load factor 1.25 in Eq. (2) to be 1.40 (considering the different load combination factor from the design code for the dead load only loading case) [18], but also by letting r tend to infinity (here chosen to be 1000 consistent with the duration-of-load research on dimensional lumber) leading to the randomness from snow load can be ignored in the following reliability calculation [11].

In the reliability analysis on the short-term rolling shear strength without considering the duration-of-load effect, the performance function G is:

$$G = R - \frac{\phi \mathrm{RS}_{(0.05)} T_{\mathrm{V}}}{(1.40r + 1.50)}(dr + q), \tag{5}$$

where $r = 1000$.

Consistent with the reliability analysis procedure in the previous sections, three beam theories (the layered beam theory, the gamma beam theory and the shear analogy theory) were adopted in the reliability analysis on the short-term rolling shear strength without considering the duration-of-load effect. The Monte Carlo simulation was used to determine the probability of rolling shear failure for a service life ranging from 1–30 years on the limit state of CLT products under a 30-year dead load only case, with the consideration of load duration effect on the rolling shear strength. After performing the Monte Carlo simulation, the simulation results are shown in Figs. 13 and 14.

Table 5 Summary of the reliability results for the strength adjustment factors in cross laminated timber (CLT)

Load case	Factor K_D when $\beta = 2.8$ in the reliability analysis	
	Five-layer	Three-layer
Thirty-year snow load in Quebec City	0.428	0.422
Thirty-year snow load in Ottawa	0.434	0.448
Thirty-year snow load in Saskatoon	0.460	0.464
Thirty-year snow load in Halifax	0.466	0.462
Thirty-year snow load in Vancouver	0.617	0.566
Thirty-year dead load only	0.371	0.445

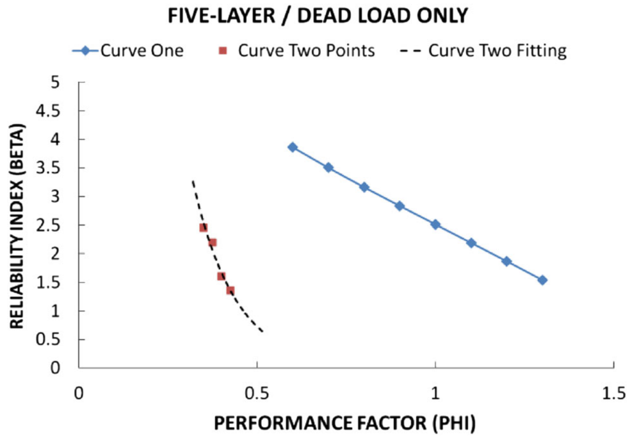

Fig. 13 *Curves* between the reliability index and the performance factor (five-layer/dead load only)

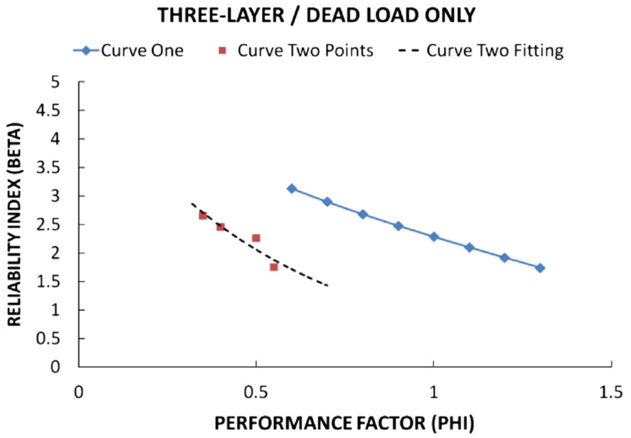

Fig. 14 *Curves* between the reliability index and the performance factor (three-layer/dead load only)

Based on Eq. (4), the rolling shear strength adjustment factor K_D for the 30-year dead load application case is summarized in Table 5. From this table, K_D is from 0.371 to 0.445 at the target reliability level $\beta = 2.80$ for five-layer and three-layer CLT products. This result suggests that there is an approximate 55–63 % strength reduction from the short-term rolling shear strength when duration-of-load effect is considered in the 30-year dead load only case. Based on previous reliability research of the duration-of-load effect on lumber [11], the strength adjustment factor (K_D) for lumber in a 30-year dead load only case is around 0.5. From Table 5, the five-layer and three-layer CLT products show smaller values; K_D is less than 0.5 in a 30-year dead load only case.

Duration-of-load factors based on the stress ratio evaluation approach from model predictions

The previous sections introduced the evaluation of the duration-of-load effect on CLT rolling shear strength using reliability analysis methods. The duration-of-load strength adjustment factor can also be evaluated by another approach, i.e., the stress ratio evaluation approach introduced as follows.

The damage accumulation model has been calibrated and verified by the test data from the short-term ramp and low cycle trapezoidal fatigue loading tests, as given in Table 1; this verified model can be used to predict the duration-of-load behaviour under arbitrary loading history [11].

As shown in Fig. 15, the ramp and constant loading protocol is the combination of the ramp load and the constant load. This loading protocol can simulate the dead load history, and the stress history of the protocol is:

$$\sigma(t) = \begin{cases} K_a t, & 0 \le t \le t_m \\ \sigma_{\max}, & t > t_m \end{cases},$$

where, K_a is the loading rate, and t_m is the duration of uploading segment. $\sigma_{\max} = K_a t_m$ is the constant applied load stress.

According to the damage accumulation theory under the ramp loading protocol as introduced in the literature, when $0 \le t \le t_m$, the damage accumulated at time step $t = t_m$ is [11]:

$$\alpha(t_m) \cong \left[\frac{\sigma_{\max} - \tau_0\sigma_s}{\sigma_s - \tau_0\sigma_s}\right]^{(1+b)}$$

When $t > t_m$, the time to failure T_f under the ramp and constant loading protocol is expressed as follows [11]:

$$T_\mathrm{f} = t_\mathrm{m} + \frac{1}{c(\sigma_{\max} - \tau_0\sigma_\mathrm{s})^n} \times \ln\left[\frac{c + a(\sigma_{\max} - \tau_0\sigma_\mathrm{s})^{b-n}}{\alpha(t_\mathrm{m})c + a(\sigma_{\max} - \tau_0\sigma_\mathrm{s})^{b-n}}\right]$$

However, when the applied maximum stress exceeds the short-term capacity ($\sigma_{\max} > \sigma_\mathrm{s}$), the time to failure T_f will be:

$$T_\mathrm{f} = \sigma_\mathrm{s}/K_\mathrm{a}$$

When the applied maximum stress does not exceed the threshold ($\sigma_{\max} < \tau_0\sigma_\mathrm{s}$), there will be no damage accumulated.

By modeling duration-of-load behaviour under the long-term constant loading protocol simulating the dead load shown in Fig. 15, the rolling shear duration-of-load effect of CLT can also be quantified in terms of the relationship between the time to failure and the applied stress ratio. Using the verified model in Table 1, a sample size of NR = 500 replications was chosen (consistent with the duration-of-load research method on dimensional lumber) [11], and these simulated samples were tested under the ramp and constant loading protocol.

Based on the stress ratio evaluation approach, Fig. 16 shows the predicted relationship between the time to failure and the stress ratio applied in the verified five-layer CLT model (denoted as SPF5-0.4) [10]. By analyzing the prediction in the figure, the stress ratio corresponding to different load duration cases can be quantified; assuming that the factor in a short-term case (10-min) is equal to one, factors can be derived for each load duration case by calculating the ratio between the quantified stress ratio values, as given in Table 6. For example, the stress ratio values are 0.3942 and 0.7967 in the short-term and standard-term cases (3-month); then, the factor in standard-term case is calculated as 0.3942/0.7967 ≈ 0.49. Similarly, the predicted results for three-layer CLT specimens (denoted as SPF3-0.4) are shown in Fig. 16 and Table 6.

In Table 6, based on the factor calculated from the verified models, the ratio of the 30-year long-term rolling shear strength to the 10-min short-term strength is 37 % for five-layer CLT and is 48 % for three-layer CLT, which agreed well with the reliability analysis results in Table 5 (between 37 and 44 % when $\beta = 2.8$).

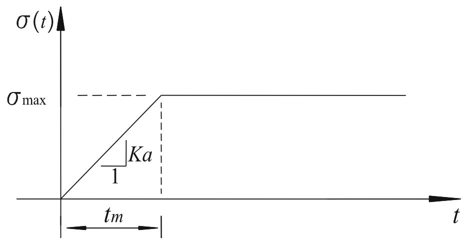

Fig. 15 Ramp and constant loading protocol

Discussion of the duration-of-load rolling shear strength adjustment factors

Based on the previous reliability research of the duration-of-load effect on dimensional lumber, the strength adjustment factor (K_D) for lumber in a 30-year snow load case is around 0.7–0.8, and in a 30-year dead load only case is around 0.5 [11]. From Table 5, five-layer CLT shows smaller values, e.g., K_D in a 30-year snow load case is around 0.428–0.617 (the average factor of the five cities is 0.481), and K_D is 0.371 which is less than 0.5 in a 30-year dead load only case. The decreasing trend in lumber K_D from snow to dead load cases in the reliability analysis (0.7–0.8 to 0.5) is consistent with that of five-layer CLT

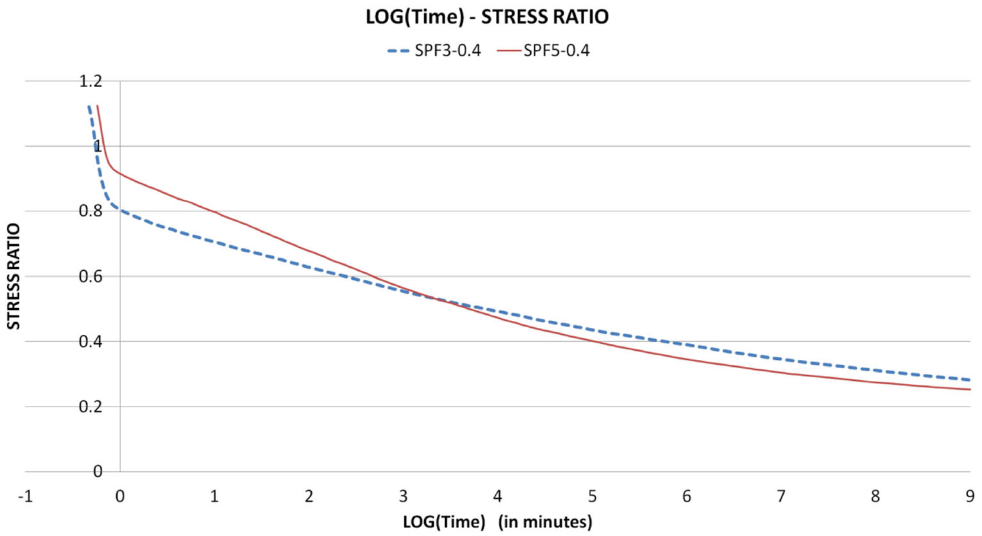

Fig. 16 Time to failure prediction (minutes in the logarithm to base 10) under the ramp and constant loading protocol (five-layer CLT is denoted as SPF5-0.4; three-layer CLT is denoted as SPF3-0.4)

Table 6 Summary of the factor calculation in cross laminated timber (CLT)

Loading	Duration	Factor between the quantified stress ratio	
		Five-layer	Three-layer
Short term	10 min	1.00	1.00
Standard term	3 months	0.49	0.61
Long term	30 years	0.37	0.48

(0.428–0.617 to 0.371). However, the specific values and the decreasing magnitudes of five-layer CLT are different from those of lumber. The five-layer CLT specimens also exhibited similar results in another approach (0.49 to 0.37) through the evaluation of the factors between the different load duration cases as presented in Table 6.

Three-layer CLT specimens exhibited the similar results as five-layer CLT. Factor K_D in the 30-year snow load case is around 0.422–0.566 (the average factor of the five cities is 0.472). K_D in the 30-year dead load only case is 0.445 and is also lower than the average factor of the five cities (0.472). These factors in three-layer CLT are also different from those of lumber.

In the stress ratio investigation approach for three-layer CLT in Table 6, the factors between the different load duration cases had similar results as those from the reliability analysis in Table 5. For example, the factor for the long-term constant loading case is 0.48 in Table 6, and it is also lower than 0.5 (in Table 5 it is 0.445 which is lower than 0.5).

Based on the reliability-based approach (shown in Table 5), the load duration adjustment factor from short-term test duration (10 min for short-term test specimen failure) to 30-year return period snow loads is approximately between 0.4 and 0.6 for the five-layer CLT, and is also approximately between 0.4 and 0.6 for the three-layer CLT. Considering the stress ratio investigation approach (based on the rolling shear failure result at different load levels as shown in Table 6), the load duration adjustment factor from short-term test duration (10 min) to standard term (3 months) is approximately 0.5 for the five-layer CLT, and is 0.6 for the three-layer CLT. The evaluated adjustment factor from the stress ratio investigation approach is approximately in the range of the calculated factors from the reliability-based approach.

For code implementation, further adjustments are needed to convert the values from short-term test duration (10 min) to the short-term seven-day duration (7 days); typically, an adjustment factor of $1.25/1.15 = 1.087$ for such load-case conversion can be assumed [18].

In summary, the five-layer and three-layer CLT results in Tables 5 and 6 are different from those of lumber, but the five-layer and three-layer products gave similar results in both the reliability analysis and the stress ratio evaluation approach. This stress ratio evaluation approach presented very close output to that of the reliability theory based method. The CLT rolling shear duration-of-load strength adjustment factor was found to be more severe compared to the general duration-of-load adjustment factor for lumber.

Figure 16 shows the relationship of the model predictions between the three-layer and five-layer CLT specimens under ramp and constant loading protocol as given in Fig. 15. It is suggested that, under the same stress ratio, the three-layer CLT product will fail sooner than five-layer CLT when the duration is between 10 min and 2 days (the short-term duration when $1.0 < \mathrm{LOG(Time)} < 3.5$ in Fig. 16). This may be due to the single middle layer in three-layer CLT takes almost all the high shear stress (as shown in the stress evaluation results in the previous study), which is consistent with the short-term ramp loading test results [10]. Also, in the long-term duration, five-layer CLT and three-layer CLT show similar long-term behaviour with small difference, as suggested in Fig. 16. Compared to three-layer CLT products, the five-layer CLT includes more pieces of laminated boards in the cross layer. This difference might increase the probability of the rolling shear failure in the long-term behaviour of five-layer CLT considering more pieces of boards under rolling shear stress, as suggested in Fig. 16.

Figure 16 also shows that the curves of the five-layer and three-layer CLT group do not have the same shape as lumber based on previous research of the duration-of-load effect on lumber [11]. This result suggests that the duration-of-load behaviour of rolling shear strength in CLT is different from that of lumber. This duration-of-load test was performed under concentrated loading on the CLT short-span beam, which may be different from other cases, such as the uniformly distributed loading pattern on a two-dimensional CLT panel. Future research is recommended on the load protocol influence on the duration-of-load effect on the rolling shear strength of CLT.

In this study, the rolling shear failure was defined when the first rolling shear crack was observed [10]. After the first crack occurred, the specimen could still carry a further but limited load. However, under long-term sustained loads, the rolling shear cracks, although small, may reduce the long-term panel stiffness of CLT. The reduced stiffness issue should raise concerns about the overall structural performance in CLT systems, such as the system influence from floor panels with the soften stiffness. Therefore, the choice of first observable rolling shear crack as the failure criteria is conservative; future research is needed for the analysis of the rolling shear behaviour in terms of different failure criteria and its impact on the CLT system performance.

Conclusions

The stress-based damage accumulation model theory was adopted to evaluate the duration-of-load effect on the rolling shear strength of CLT. This model has been calibrated and verified based on the collected test results. As the developed duration-of-load model is a probabilistic model, a time-reliability study of the CLT products was performed. The reliability results provided further information about the duration-of-load effect on the rolling shear behaviour of CLT. The predictions of the time to failure from this model and this investigation process elucidated the duration-of-load effect and provided guidance for the evaluation of the CLT duration-of-load effect.

The verified damage accumulation model is also able to predict the duration-of-load behaviour of wood-based products under arbitrary loading history, including the long-term dead load case; then, the predictions of time to failure from the model under dead load can evaluate duration of load using the stress ratio evaluation approach.

The duration-of-load adjustment factors on the rolling shear strength of CLT were discussed, and it is suggested that this adjustment factor for CLT is more severe than the general duration-of-load adjustment factor for lumber. Therefore, when CLT is introduced into the building codes for engineered wood design, the duration-of-load adjustment factor on the rolling shear strength should be considered.

This study considered the duration-of-load effect only for CLT beam specimens under concentrated load cases; therefore, different loading patterns, such as uniformly distributed loading on CLT two-dimensional panels, may influence CLT duration-of-load behaviour. This influence needs more investigation in the future research.

Since the rolling shear failure was defined at the time point when the first rolling shear crack was observed, the derived adjustment factor for CLT could be relatively conservative based on this failure definition. Therefore, further research on the rolling shear failure mechanism and its impact on the structural performance of CLT systems are suggested.

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