J Wood Sci (2016) 62:251–262
DOI 10.1007/s10086-016-1547-6

ORIGINAL ARTICLE

Low cycle fatigue tests and damage accumulation models on the rolling shear strength of cross-laminated timber

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Received: 22 October 2015 / Accepted: 12 February 2016 / Published online: 14 March 2016

Abstract This paper presents a study on rolling shear damage accumulation and duration of load of cross-laminated timber (CLT) with low cycle fatigue tests. The study of the duration-of-load (DOL) effect on strength properties of wood products is typically challenging; it may be more challenging for non-edge-glued CLT considering crosswise layups of wood boards, existing gaps, and non-uniform stress distributions in cross layers. In experimental studies, short-term ramp loading tests and low cycle trapezoidal fatigue loading tests were used to study the DOL behaviour of the CLT rolling shear. The ramp tests were performed to establish the short-term CLT rolling shear strength properties. The low cycle trapezoidal fatigue tests were performed to evaluate the damage accumulation process for the matched specimens under controlled rolling shear stress levels. A stress-based damage accumulation model was further used to investigate the rolling shear DOL effect with model parameters treated as random variables calibrated against one set of the test data. The calibrated model predicted well comparing with the other set of the test data. This verified model provides a robust tool to quantify the DOL effect on rolling shear strength in the core layers of CLT that can be used in future studies of DOL behaviour in CLT under arbitrary loading histories.

Keywords Cross-laminated timber · Rolling shear · Low cycle fatigue test · Duration-of-load effect · Damage accumulation model

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Introduction

Cross-laminated timber (CLT) is a wood composite panel product suitable for floor, roof and wall applications in timber buildings [1]. The layup of CLT panel is similar to that of plywood with crosswise oriented laminae; however, the notable difference is that CLT panels are composed of dimensional lumber laminations instead of thin veneers. The CLT panel usually includes three to eleven layers of wood boards, as shown in Fig. 1 [2]. Rolling shear stress in wood 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 [3–5]. Under out-of-plane bending loads, for example, the CLT panel capacity can sometimes be governed by the rolling shear strength of the cross layers, as shown in Fig. 2 [6].

Rolling shear strength and stiffness of wood are much lower than its longitudinal shear strength and stiffness [4]. According to the literature [3–5, 7–9], rolling shear strength normally varies between 18 and 28 % of parallel-to-grain shear strength based on limited test data. In Eurocode 5 [10], a characteristic rolling shear strength value of 1.0 MPa is used for wood independent of its strength class. Therefore, in timber design, high rolling

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)

shear stresses should always be avoided due to the low rolling shear strength of wood.

In general, wood is stronger under short-term loads and is weaker under sustained loads. This phenomenon is called duration of load; and, the primary relationship between the stress ratio (i.e., 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 (DOL) effect. In fact, the DOL effect is not introduced by material deterioration or decaying; rather, it is a distinctive characteristic of wood. Previous researches to study the DOL effect on wood strength properties were mainly focused on bending properties of solid sawn materials [11–15]. No research has been reported on studying the DOL effect on the rolling shear strength in wood, since CLT is a relatively new engineered wood product, and before its emergence rolling shear in wood was not considered a technical characteristic of primary importance. It is a challenging task to study the DOL effect on the rolling shear strength of CLT considering the complicated features such as the crosswise arrangement of wood boards, gaps between laminates in one layer, glue bonding properties between different layers and strength variability in timber material [16, 17]. However, it is necessary to conduct such a research to develop fundamental understanding of the long-term structural performance of CLT in the support of code and standard development activities.

The objective of the paper is to investigate the CLT rolling shear damage accumulation and DOL behaviour, by performing DOL tests (low cycle fatigue tests) and the damage accumulation modeling process.

Methods

Theories

In this study, two matched specimen groups were tested by short-term ramp loading and low cycle trapezoidal fatigue loading, respectively. To limit the influence of environmental variables on the damage accumulation process, the low cycle trapezoidal fatigue loading tests were chosen since the time duration of these tests is relatively short [18, 19]. The cyclic load levels for the trapezoidal fatigue loading tests were determined based on the short-term ramp loading test data. Compared with the long-term constant loading method, more damage will be accumulated in the same period of time during the trapezoidal fatigue loading test, so the total test time of the trapezoidal loading can be reduced.

The short-term rolling shear strengths of the CLT beam specimens were evaluated by three composite beam theories: (1) Layered beam method [20]; (2) Gamma beam method [10] and (3) Shear analogy method [21]. The rolling shear strength was also evaluated by finite element models [9, 17].

The theory of the damage accumulation model is one of the key tools to understand the DOL behaviour in wood-based products [13, 22, 23]. A stress-based damage accumulation model was developed by Foschi and Yao [24] to consider the DOL effect on the strength properties of dimensional lumber [12, 22]. The Foschi and Yao model considers the damage accumulation rate as a function of stress history and the already accumulated damage state as follows:

$$\begin{cases} \mathrm{d}\alpha/\mathrm{d}t = a(\sigma(t)-\tau_0\sigma_s)^b + c(\sigma(t)-\tau_0\sigma_s)^n\alpha & \text{if } \sigma(t) > \tau_0\sigma_s \\ \mathrm{d}\alpha/\mathrm{d}t = 0 & \text{if } \sigma(t) \le \tau_0\sigma_s \end{cases} \quad (1)$$

where α is the damage state variable ($\alpha = 0$ represents the undamaged state and $\alpha = 1$ represents the failure state); t is the time; $\sigma(t)$ is the applied stress history; σ_s is the short-term strength; τ_0 is a fraction to be applied to 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 and a, b, c, τ_0 and n are random model parameters.

The Foschi and Yao model was adopted in this study. The short-term rolling shear strength distribution was first established by the short-term ramp loading; the time to failure data from the trapezoidal fatigue loading tests was obtained to understand the development of damage accumulation process. Rolling shear strength properties of CLT beam specimens were calculated by different beam theories (Layered beam, Gamma beam and Shear analogy methods) and finite element models as well, based on the results from the short-term ramp loading tests. By analysing the data from the trapezoidal fatigue loading tests, the stress-based damage accumulation model was calibrated and verified. This calibrated model is available to elucidate the DOL effect on the CLT rolling shear strength under various loading conditions in the future research.

Test specimens

As shown in Fig. 3, two categories of the non-edge-glued CLT plates laminated with polyurethane adhesive, i.e., 5-layer Spruce-Pine-Fir (SPF5) plates and 3-layer Spruce-Pine-Fir (SPF3) plates, were studied. The clamping pressure of 0.4 MPa to cure the adhesive was applied by a mechanical press [25]. 38 mm × 140 mm No. 2 grade dimensional lumber was used for the top and bottom layers of the 3-layer and 5-layer plates as well as in the middle core layer of the 5-layer plates, whereas 38 mm × 140 mm stud grade lumber was used for all the cross layers. The wood boards were planed into a cross section of 34 mm × 140 mm for the cross layers in the 3-layer plates and 19 mm × 140 mm for the cross layers in the 5-layer CLT panels. For convenience, a 5-layer Spruce-Pine-Fir plate is simply denoted as a SPF5 plate. Considering the 0.4 MPa clamping pressure, this plate is further denoted as SPF5-0.4. Similarly, a 3-layer Spruce-Pine-Fir plate pressed under 0.4 MPa is denoted as a SPF3-0.4 plate. Table 1 shows the detailed configurations of the plates including the board grades, the lamination thickness and width, and the plate dimensions [26].

Fig. 3 CLT panels

Then, small beam specimens in a span-depth ratio of 6.0 (to encourage the rolling shear failure in the cross layers) were sampled from the full size plates, as shown in Fig. 4. These specimens were prepared for the ramp loading tests and the trapezoidal fatigue loading tests. The pair sampling method was adopted in the specimens' preparation to assure random matching formula. Specimens, of similar depth, were generated from a single source CLT panel and were side matched; in one plate replicate, specimens were selected in a staggered way for the ramp tests, and the corresponding specimens for the trapezoidal tests were cut from the same panel [17]. Test matrix of these specimens is given in Table 2.

Experimental tests

The test setup for the short-term ramp loading and the low cycle trapezoidal fatigue loading tests is shown in Fig. 5. The ramp loading tests were displacement controlled [27]. The loading rate was 2 mm/min (0.08 inch/min) for the 5-layer specimens and 1.5 mm/min (0.06 inch/min) for the 3-layer specimens; the centre-point load was applied on the top of the beam. In general, the average time to failure in the ramp loading tests was about 5 min. Both the time-history of the applied load and the mid-span deflections were recorded for each specimen. The rolling shear failure load was recorded when the first rolling shear crack in the cross layers was visually observed by technician.

The low cycle trapezoidal fatigue loading tests were force controlled, as shown in Fig. 6. First, the load increased from zero to a target value, i.e., the load level in the plateau loading part. Then, the load was sustained for a

Table 1 Grades and configurations of the cross laminated timber (CLT) plates

CLT category	Lamination grade	Lamination thickness (mm)	Lamination board width (mm)	Plate dimension length × width × height (mm)
SPF5-0.4	No. 2/Stud/No. 2/Stud/No. 2	34/19/34/19/34	140	3658 × 1219 × 140
SPF3-0.4	No. 2/Stud/No. 2	34/34/34	140	3658 × 1219 × 102

Fig. 4 CLT beam specimens

Table 2 Test matrix of CLT specimens

Group	SPF5-0.4	SPF3-0.4
Layers	5	3
Test span (mm)	840	612
Depth (mm)	140	102
Width (mm)	50.8	50.8
Sample size in ramp loading tests	60	60
Sample size in trapezoidal loading (short-plateau test)	30	30
Sample size in trapezoidal loading (long-plateau test)	30	33

Fig. 5 Loading setup

certain period of time before the load decreased to zero. The loading cycles were then repeated periodically.

The uploading and unloading rate was 37.5 kN/min for the 5-layer specimens and 27.0 kN/min for the 3-layer specimens; this loading rate was higher than the loading rate used in the short-term ramp loading tests (around 3.9 kN/min for the 5-layer specimens and 2.3 kN/min for the 3-layer specimens). It should be noted that the short-term ramp tests adopted the displacement control method (with a constant deformation rate), so the actual stress rate is different from one specimen to another due to the different force levels, while the stress rate in the trapezoidal test specimens is controlled.

The constant load level in the plateau part was chosen as the 25th percentile of the short-term rolling shear capacity obtained from the short-term ramp loading tests. The load cycles were applied until the first rolling shear crack was observed in the cross layers, defined as rolling shear failure. Meanwhile, the number of cycles to the rolling shear failure (i.e., time to failure) and the deflection history at the mid-span of the specimens were recorded.

Two types of the low cycle trapezoidal fatigue loading tests were performed; these two tests had different load duration in the plateau part. The first one, so called the short-plateau test, includes the constant loading part with a duration of 0.5 t_m, where t_m is the duration in the uploading segment shown in Fig. 6. The second type was the long-plateau tests with a longer plateau part of 2.0 t_m. Sample sizes for these two different CLT trapezoidal fatigue loading tests have also been given in Table 2.

Test results and data analysis

Test results

In the short-term ramp loading tests, rolling shear failure was the major failure mode. The failure process typically started with rolling shear cracks in the cross layers at an inclined angle as shown in Fig. 7, followed by horizontal cracks in the timber material near the glue lines between adjacent layers. Finally the capacity-reduced specimens experienced tension parallel to the grain failure in the bottom layers of CLT.

In the low cycle trapezoidal fatigue loading tests, the number of cycles to rolling shear failure N_f was recorded when the first rolling shear crack was observed within that N_fth cycle. The shape of these rolling shear cracks in the cross layer was typically very similar to those in the short-term ramp loading tests. There are different types of rolling shear cracks observed in the cross layer, as shown in Fig. 8.

The ramp loading test results and the low cycle trapezoidal fatigue loading test results are shown in Table 3.

In the ramp loading tests, 55 5-layer specimens and 59 3-layer specimens had rolling shear failure. Due to the different layering of the specimens, the rolling shear capacity of the 3-layer CLT was lower than that of the 5-layer CLT. The short-term 5th and 25th percentile rolling shear capacities in Table 3 were obtained using lognormal fitting.

In the trapezoidal long-plateau tests, since more damages were accumulated during the plateau part, the specimens generally had less loading cycles to rolling shear

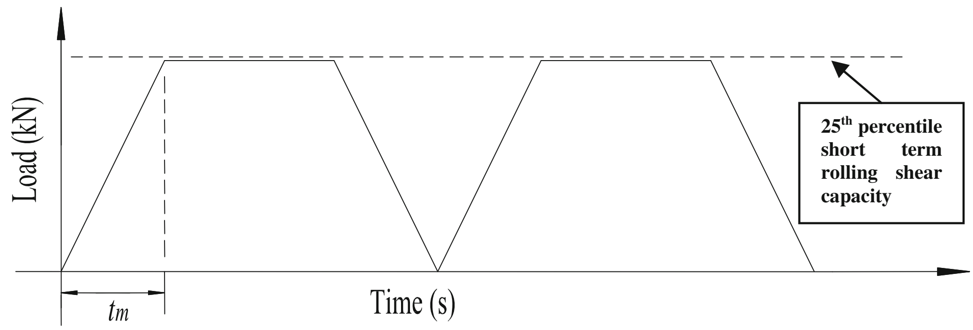

Fig. 6 Low cycle trapezoidal fatigue loading protocol

Fig. 7 Failure mode in the ramp loading test

failure compared with the specimens tested in the trapezoidal short-plateau tests.

The 25th percentile rolling shear failure loads from the ramp loading tests, given in Table 3, were applied in the trapezoidal fatigue tests; however, less than 25 % of the specimens failed in the first uploading process, as given in Table 3. This difference was attributed to the use of a significantly higher loading rate (the uploading rate) in the trapezoidal fatigue test. It is well recognised that a higher loading rate tends to increase apparent short-term strength of wood. Previous research has reported that about 15 % shear strength increase was observed when the loading rate was increased by ten times [15]. Therefore, in this study, it is reasonable to observe less than 25 % of specimens failed in the first cycle of the trapezoidal fatigue tests. Therefore, the development of the damage accumulation model and its verification process should take into account such a relationship between the loading rate and strength properties.

Rolling shear strength evaluation

The test results in Table 3 show the mean capacity value of the 3-layer specimens was 65 % of the 5-layer specimens' mean capacity value. The reason is that the 3-layer specimens had a much smaller cross section and the cross layer is located in the mid-height experiences highest shear stresses. It may be better explained by evaluating the sectional shear stress distribution, which will be introduced in the next paragraph.

To investigate shear stress levels in the cross layers, different beam theories (i.e., the layered beam theory, the gamma beam theory and the shear analogy theory) were used to evaluate the shear stress distribution along the beam cross sections. Figure 9 shows the calculated shear stress values in the 3-layer and the 5-layer specimens, under the same point load, i.e., the mean of the rolling shear failure loads of the 3-layer specimens (12.51 kN from

Fig. 8 Rolling shear cracks in the low cycle trapezoidal fatigue loading test (*black marker line in the circle* is next to the crack)

Table 3 Tests results

Group	SPF5-0.4	SPF3-0.4
Ramp loading		
No. of specimens with rolling shear failure	55	59
Rolling shear failure load (kN)		
Mean	19.39	12.51
Coefficient of variation	12.6 %	24.3 %
25th % tile	17.79	10.33
5th % tile	14.75	7.97
Low cycle trapezoidal short-plateau test		
No. of specimens with rolling shear failure	28	30
No. of specimens with rolling shear failure in the first cycle	2	0
No. of cycles to rolling shear failure (N_f)		
Mean	66.1	38.5
Standard deviation	76.5	50.3
Maximum cycles	281	212
Low cycle trapezoidal long-plateau test		
No. of specimens with rolling shear failure	29	32
No. of specimens with rolling shear failure in the first cycle	0	4
No. of cycles to rolling shear failure (N_f)		
Mean	15.2	12.8
Standard deviation	18.5	23.2
Maximum cycles	88	92

Table 3). Detailed examples of calculations based on the different beam theories were given in the literature [10, 17, 20, 21].

The results in Fig. 9 suggest that the mean rolling shear strength for the 3-layer CLT, which was evaluated from the different beam theories, ranges from 1.23 to 1.68 MPa. Similarly, Fig. 10 shows the calculated shear stress values in the cross section of 5-layer CLT beams, under the average rolling shear failure load of the 5-layer CLT (19.39 kN from Table 3). The results in Fig. 10 suggest that the mean rolling shear strength for 5-layer CLT ranges from 1.63 to 1.73 MPa. The results suggest that there is underestimation in the Gamma beam calculation for 3-layer CLT; however, the results are close in 5-layer CLT group.

In Fig. 9, using the same beam theory, shear stress in the cross layer is lower in the 5-layer specimens (1.05–1.11 MPa) than that in the 3-layer specimens. The cross layer in the 3-layer CLT is under higher shear stress; this can explain why the cross layer in the 3-layer CLT has all the high shear stress at the mid-height of the cross section, leading to the lower load-carrying capacity of the specimens.

Finite element modeling was further adopted for the simulation of the specimens, as shown in Fig. 11. Dimensions of the finite element model are the same as those in the experimental 3-layer and 5-layer CLT beam specimens. This modeling work was performed on the ANSYS v14.0 platform, and SOLID185 elements (based on the orthotropic volume modeling in Cartesian coordinate system) were used to model CLT wood boards with rectangular section [17]. Small gaps, with an average value of 1 mm, were also simulated in the cross layers of finite element models. A linear elastic analysis was performed to evaluate the rolling shear stress distribution with consideration of the orthotropic wood material property. The finite element models can give detailed rolling shear stress distribution at different locations in the beam specimens.

Figures 12 and 13 show the results about the rolling shear stress distribution in the cross layers of the 3-layer and the 5-layer CLT specimens subjected to the mean rolling shear failure load of the 3-layer CLT (12.51 kN from Table 3). The maximum rolling shear stress occurs near the one-third of span in the lamination boards. Under the same applied load, the maximum rolling shear stress in the cross layers of the 5-layer CLT (1.13 MPa) is lower than that in the 3-layer CLT (1.41 MPa). This result further explains why the rolling shear load-carrying capacity of the 3-layer specimens is lower. The mean rolling shear strength (1.41 MPa) in 3-layer CLT is also in the range of the results from Fig. 9 (1.23–1.68 MPa).

Similarly, when the applied load is the mean rolling shear failure load of the 5-layer specimens (19.39 kN from Table 3), the maximum rolling shear stress in the cross layers of 5-layer specimens is 1.76 MPa, which is close to the results from Fig. 10 (1.63–1.73 MPa).

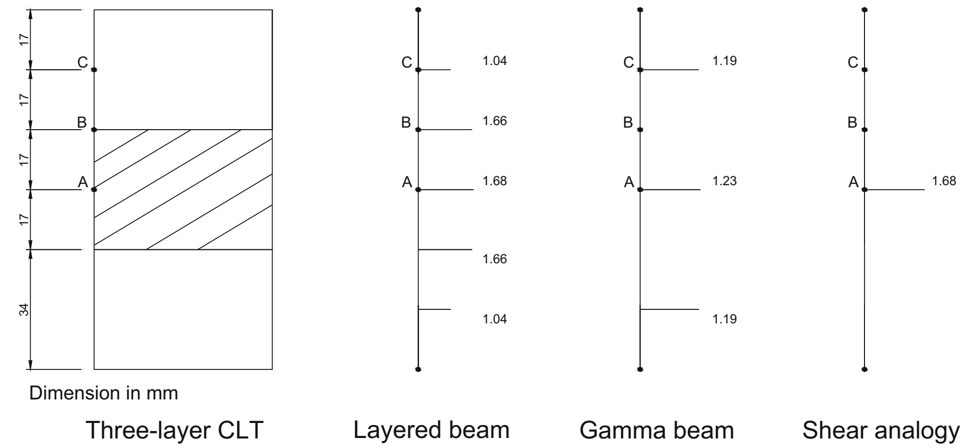

Fig. 9 Shear stress evaluated in the cross section of the CLT beam (in N/mm^2 under 12.51 kN centre-point load)

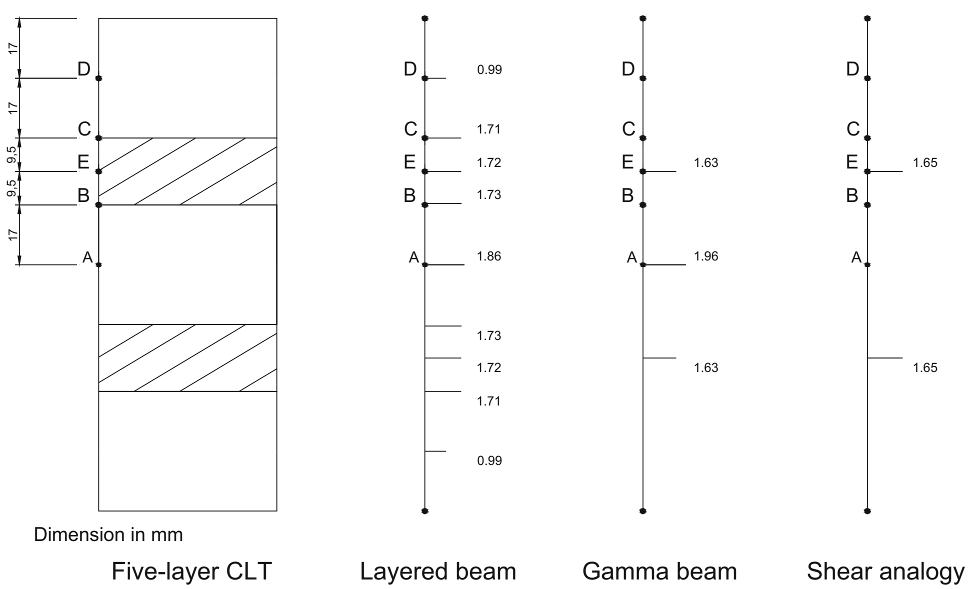

Fig. 10 Shear stress evaluated in the cross section of the CLT beam (in N/mm^2 under 19.39 kN centre-point load)

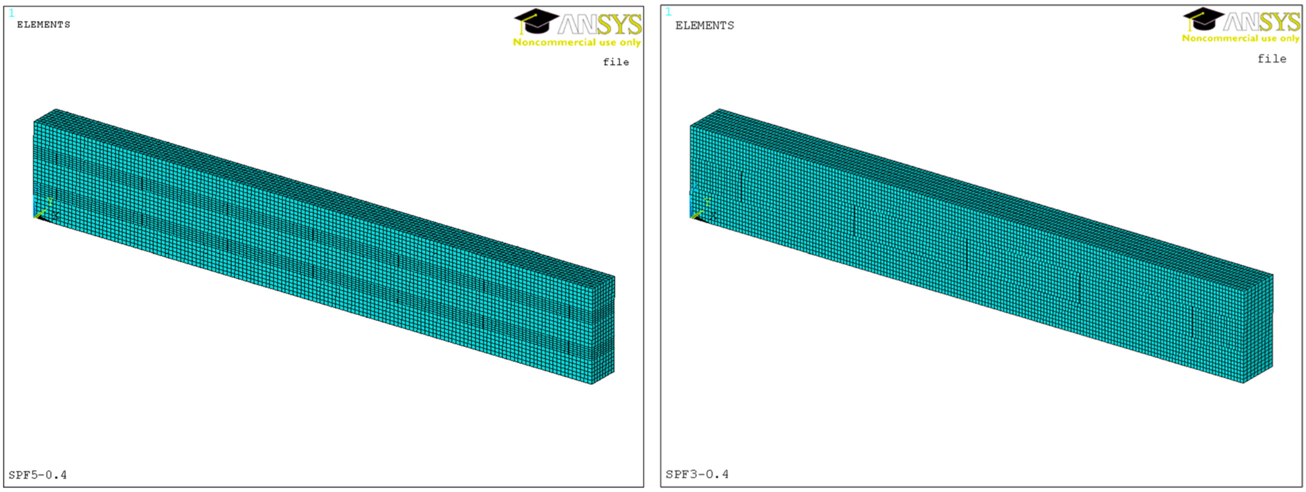

Fig. 11 Finite element modeling of the CLT beam test specimens

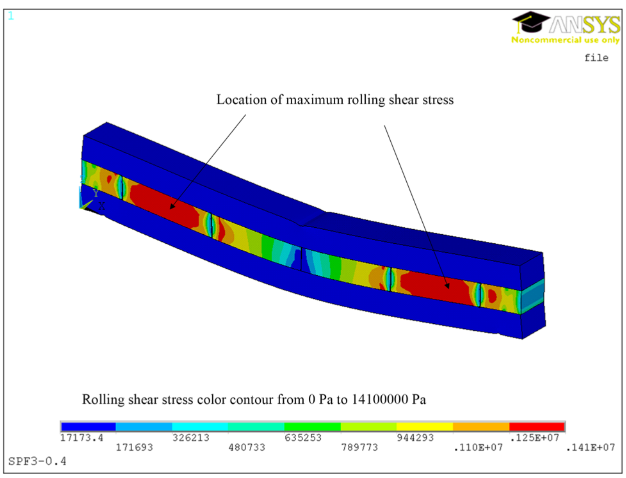

Fig. 12 Rolling shear stress distribution in 3-layer CLT specimen under 12.51 kN load (stress in Pa)

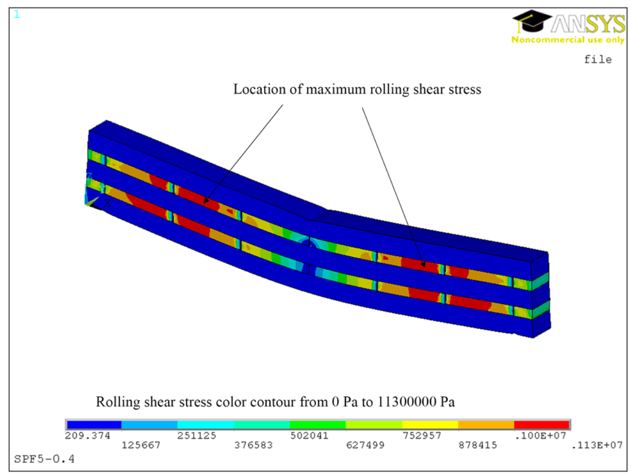

Fig. 13 Rolling shear stress distribution in 5-layer CLT specimen under 12.51 kN load (stress in Pa)

Future research is recommended to be investigated in the ramp tests with the same cross layer thickness or the same width to thickness ratio for both the 5-layer and 3-layer plates, to check the stress distribution and load capacity differences. Also, considering the large-dimensional CLT members typically used in application, larger specimen width (larger than 50.8 mm) is recommended to be investigated in tests, to give a better picture regarding the large-scale structural application of CLT.

The summary of the rolling shear strength σ_s evaluated by the finite element models is given in Table 4. These values were based on the maximum cross layer rolling shear stresses using the short-term rolling shear failure loads (from Table 3) as the load input [17]. The short-term 5th and 25th percentile rolling shear strengths in Table 4 were obtained using lognormal fitting.

Damage accumulation model

The theory for the damage accumulation model is one of the key tools to investigate the DOL behaviour of wood-based products. The Foschi and Yao model, Eq. (1), has been successfully applied to study the DOL effect on the strength properties of Canadian dimensional lumber. Therefore, in this study, this model was also adopted. Considering a ramp loading case, the model parameter a is calculated by [22]:

$$a \cong \frac{K_s(1+b)}{[\sigma_s - \tau_0\sigma_s]^{(1+b)}} \tag{2}$$

where K_s is the ramp loading rate; other parameters are the same as given in Eq. (1).

Table 4 Summary of the finite element evaluation results on the rolling shear strength

CLT type	Rolling shear strength (MPa)			
	Mean	Coefficient of variation (%)	25th percentile	5th percentile
SPF5-0.4	1.76	12.2	1.61	1.34
SPF3-0.4	1.41	23.3	1.16	0.90

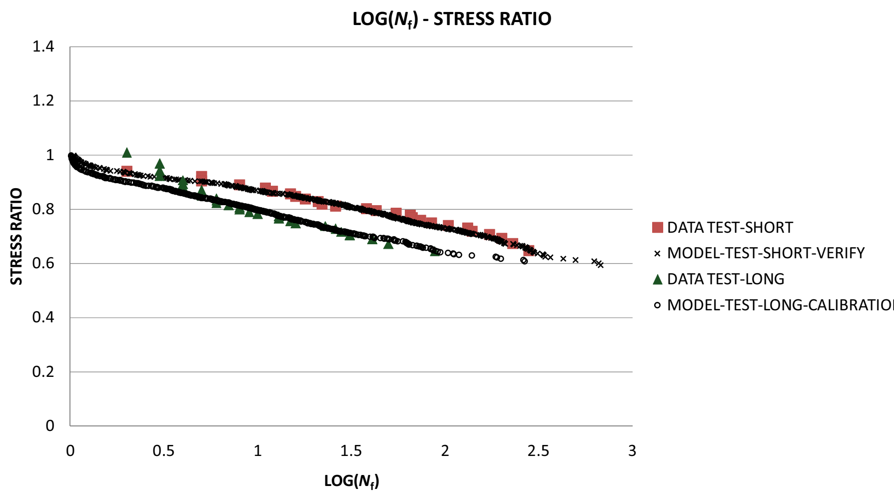

Fig. 14 Relationships between the number of cycles to failure (in the logarithm to base 10) and the stress ratio from test and model in 5-layer CLT

The number of cycles to rolling shear failure in the trapezoidal fatigue loading tests can be predicted by [17]:

$$N_f = \frac{\log\left(\frac{K_1+K_0-1}{K_1}\right)}{\log(K_0)} + 1 \tag{3}$$

where K_0 and K_1 are determined by analysing the damage accumulated in the first two cycles of the trapezoidal fatigue loading,

$$K_0 = \frac{\alpha_2}{K_1} - 1$$

$$K_1 = \alpha_1$$

where α_1 and α_2 are the damage accumulated in the first cycle and in the first two intact cycles, respectively.

Considering the fact that one specimen cannot be broken twice to evaluate its short-term strength and its response under fatigue loading, so-called equal ranking assumption can be used to estimate this specimen's short-term rolling shear strength [17, 28]. The short-term rolling shear strength distribution was first established based on the ramp loading test results. If one group of specimens was subjected to a ramp uploading to a constant stress level A, some specimens with short-term strength lower than A would fail upon uploading while other specimens would fail under cyclic long-term loading; therefore, under the constant stress level A, the numbers of cycles to failure can be estimated.

Since long-term strength of wood is positively correlated with its short-term strength, the specimens with high short-term strength would take more loading cycles to failure. Therefore, based on the long-term test data, the corresponding short-term strength of the individual specimens can be estimated by the matched control group's short-term strength distribution.

Based on the equal rank assumption, the relationship between the number of cycles to rolling shear failure (N_f from Table 3 in the logarithm scale) and the stress ratio applied in the SPF5-0.4 group is shown in Fig. 14, where the data points are related to the test results in Table 3. The figure shows that, under the same stress ratio, the time to failure was shorter in the trapezoidal long-plateau test, since more damage was accumulated within each loading cycle. The cumulative distribution of the measured number of cycles to rolling shear failure (N_f from Table 3 in the logarithm scale) is shown as data points in Fig. 15. The same information in the SPF3-0.4 group is included in Figs. 16 and 17, where the data points are related to the test results in Table 3.

The model calibration procedure was based on the algorithm developed by Foschi [22]. The random model parameters, i.e., b, c, n and τ_0 in this damage accumulation model, and the developed ramp rolling shear strength σ_s were assumed to be lognormally distributed. The lognormal distributed rolling shear strength σ_s was based on the maximum cross layer rolling shear stresses evaluated from the finite element models with consideration of the influence of higher loading rate, which used each individual ramp rolling shear failure load (from Table 3) as the load

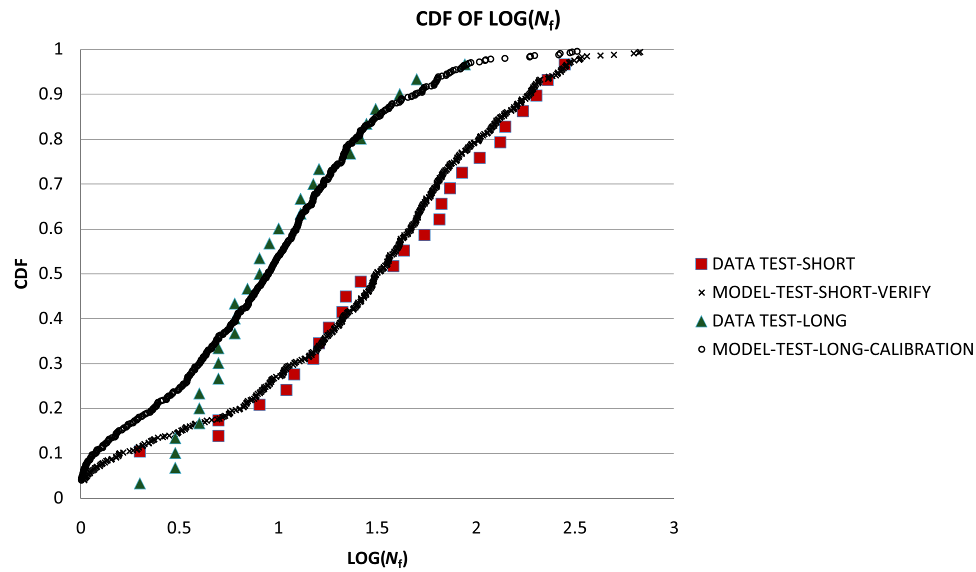

Fig. 15 Cumulative distributions (CDF) of the experimental and simulated number of cycles to failure (in the logarithm to base 10) in 5-layer CLT

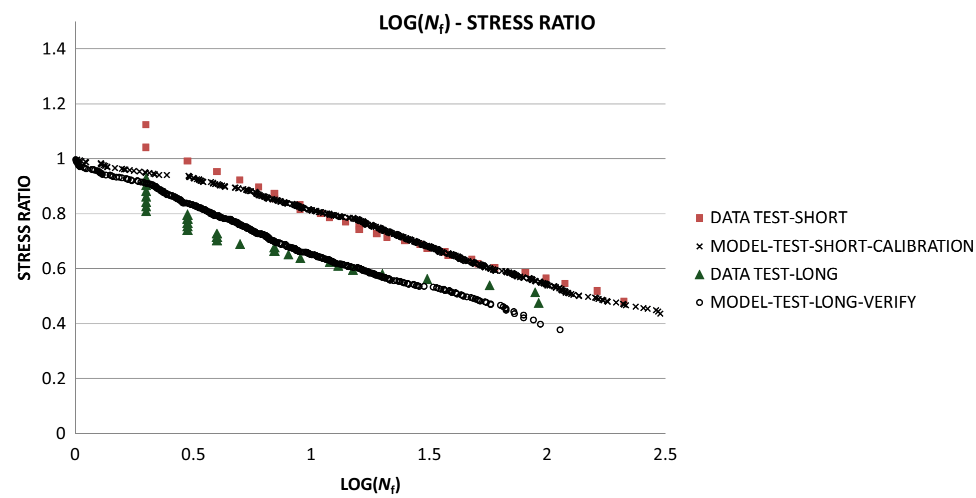

Fig. 16 Relationships between the number of cycles to failure (in the logarithm to base 10) and the stress ratio from test and model in 3-layer CLT

input. The short-term rolling shear strength (from Table 4) was adjusted with a 15 % increase due to the higher uploading rate (in trapezoidal tests) [17]. The applied stress history $\sigma(t)$ was evaluated by the finite element models as well.

Then, by employing a nonlinear function minimisation procedure using the quasi-Newton method, the mean and standard deviation of the lognormal distribution for each random model parameter were estimated. This damage accumulation model was calibrated against the trapezoidal long-plateau test data for the SPF5-0.4 group, as shown in Figs. 14 and 15. For the SPF3-0.4 group, this model was calibrated against the trapezoidal short-plateau test data, as shown in Figs. 16 and 17. Table 5 shows the model calibration results.

In Figs. 15 and 17, at the lower tail when N_f is small, the model output in calibration (i.e., the fitting) and test results seemed to be different; this difference might have been magnified by the logarithm scale [17]. Also, the other reason for such a difference is that, in the lower tail of the distribution where the number of cycles to failure is small, the specific time to failure point was approximated by a round number N_f, leading to some error. However, as the N_f increases, this error becomes trivial. For example when $N_f = 100$, this error should be less than $1/100 = 1$ %.

The fitting was also generally acceptable in the upper tail as shown in Figs. 15 and 17; therefore, it is a viable option to investigate the DOL behaviour based on the measured number of cycles to failure, which is also in time scale basis.

After calibrating the damage accumulation model by the trapezoidal rolling shear data, the relationship between the stress ratio and the number of cycles to rolling shear failure can be predicted. For example, with the calibrated model

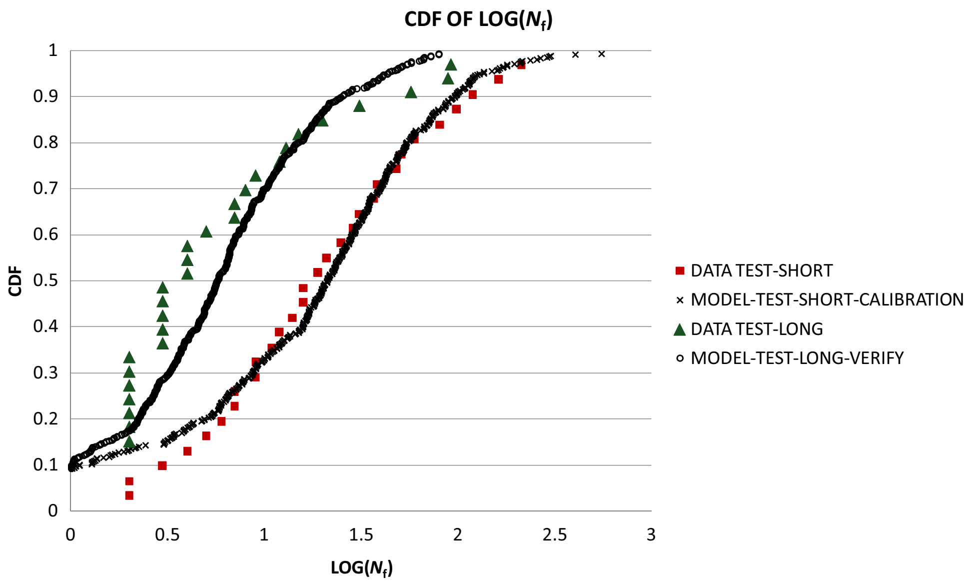

Fig. 17 Cumulative distributions (CDF) of the experimental and simulated number of cycles to failure (in the logarithm to base 10) in 3-layer CLT

Table 5 Calibration results

	Mean	Standard Deviation
Model parameters for SPF5-0.4		
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 SPF3-0.4		
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

parameters for the SPF5-0.4 group in Table 5, simulated N_f values were produced and compared to the other set of the experimental measurements obtained from the trapezoidal short-plateau tests. These model calibration and verification results are shown in Fig. 14, including the relationships between the stress ratio and the predicted Log(N_f) values. Figure 15 shows the cumulative distributions of the experimental and the simulated Log(N_f) values based on the model calibration and verification for the SPF5-0.4 group. The results from Figs. 14 and 15 show that the model predictions agreed well with the test data.

With the calibrated model parameters for the SPF3-0.4 group in Table 5, simulated N_f values were produced and compared to the other set of the test results from the trapezoidal long-plateau test data. These model calibration and verification results are shown in Figs. 16 and 17; the figures show the experimental and the simulated Log(N_f) values based on the model calibration and verification for the SPF3-0.4 group. The results from Figs. 16 and 17 also show that the model fitting agreed well with the test results.

The long-term rolling shear behaviour of the CLT specimens can be further evaluated using this verified model; as the damage accumulation model is a probabilistic model, it can be incorporated into a time-reliability study as well. Therefore, this model allows one to gain a deeper insight into the reliability assessment of the long-term rolling shear behaviour of CLT products.

Conclusions

Based on the ramp loading test data and the low cycle trapezoidal fatigue loading test data, the damage accumulation and the DOL effect on the rolling shear strength of CLT was investigated. Based on the results from the short-term ramp loading tests, rolling shear strength properties of CLT beam specimens were evaluated. In the ramp loading test, the 3-layer CLT had lower maximum rolling shear stress (strength) at failure when compared to the 5-layer CLT. In addition, the rolling shear failure mechanism and strength failure are suggested to be further investigated in the future. A stress-based damage accumulation theory was used to investigate the DOL effect of CLT rolling shear behaviour. This model included the evaluated rolling shear strength from the ramp loading tests. This model was calibrated and verified by the low cycle trapezoidal fatigue loading test data. The results show that the model predictions fit well with the test measurements. The characteristic of this modelling theory lies in that the verified model is able to predict the DOL behaviour of wood-based products under arbitrary loading history, such as long-term dead load case; then, these predictions of time to failure from this damage accumulation model can elucidate duration of load in the future research.

Acknowledgments The authors would like to thank NSERC strategic network for engineered wood-based building systems for supporting this research. Special thanks also go to Dr. Ricardo O. Foschi for his advice and guidance in the research. Dr. Minghao Li is acknowledged for his assistance in the finite element modeling work.

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