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DURATION-OF-LOAD EFFECT ON THE ROLLING SHEAR STRENGTH OF CROSS LAMINATED TIMBER: DURATION-OF-LOAD TESTS AND DAMAGE ACCUMULATION MODEL

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ABSTRACT: In this study, the duration-of-load (DOL) effect on the rolling shear strength of cross laminated timber (CLT) were evaluated. The study of the DOL effect on the strength properties of wood products is typically challenging; and, additional complexity exists with the DOL effect on the rolling shear strength of CLT, given the necessary consideration of crosswise layups of wood boards, existing gaps, non-uniform stress distributions in the cross layers, glue bonding between layers, and strength and stiffness variability of timber materials. In this study, short-term ramp loading tests and long-term trapezoidal fatigue loading tests (damage accumulation tests) were used to study the DOL behaviour of the rolling shear strength of CLT. A stress-based damage accumulation model was used to investigate the DOL effect on CLT rolling shear. The model was calibrated with the test data. The test results show that the model predictions agree well with the test data. This calibrated model can be used to quantify the rolling shear DOL effect of CLT under other loading conditions in future research.

KEYWORDS: Duration-of-load effect, damage accumulation model, trapezoidal fatigue loading, cross laminated timber, rolling shear, mountain pine beetle

1 INTRODUCTION

Cross laminated timber (CLT) is a wood composite product suitable for floor, roof and wall applications. The layering of CLT is similar to that of plywood; however, the notable difference is that CLT panels are composed of wood laminates or boards instead of thin veneers. The CLT panel usually includes three to eleven layers of wood boards [1]. Meanwhile, rolling shear stress is defined as shear stress leading to shear strains in a plane perpendicular to the grain [2]. 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 Figure 1 [3].

Figure 1: Rolling shear behaviour in CLT

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

Although it is well known that the strength properties of wood products are influenced by the DOL effect [4], there is very little research reported on studying the DOL effect

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on the rolling shear strength of CLT. This topic is difficult as the rolling shear strength of CLT can be influenced by the crosswise arrangement of wood boards, gaps between different laminates in one layer, glue bonding properties between different layers, and strength variability in timber material [5]. Therefore, there is a need to conduct CLT rolling shear DOL research to develop fundamental understanding of the long-term structural performance of CLT for the support of code and standard development activities.

In the beginning of the twenty-first century, the largest mountain pine beetle (MPB) outbreak ever recorded struck western Canada. Technologies to convert MPB-afflicted lumber into engineering wood products are urgently required. The manufacture of CLT using MPB wood as a value added product is one available option. In Canada, commercial production of MPB CLT products has recently been established available. However, little research has been undertaken on the DOL effect for this product. The objective of this work is the investigation and evaluation of the DOL effect on the rolling shear strength of these CLT products.

In this study, short-term ramp loading protocol and long-term trapezoidal fatigue loading protocol to accumulate damage have been considered in the research of the rolling shear DOL behaviour of CLT under uncontrolled laboratory climatic conditions, where temperature and relative humidity remained fairly constant. To limit the influence of environment variables on the damage accumulation, low cycle trapezoidal fatigue loading protocol was adopted. The applied cyclic load intensities for the trapezoidal fatigue load tests were based on the short-term ramp loading test data. Compared with the constant loading method, there is more damage accumulated in the same period of time in the trapezoidal fatigue loading test, so the total test time of the trapezoidal loading is reduced.

A stress based damage accumulation model was developed by Foschi and Yao [6] to consider the DOL effect on the strength properties of dimension lumber [7]. The Foschi and Yao model considers the damage accumulation rate as a function of stress history and the already accumulated damage state as follows:

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

where α is the damage state variable ($\alpha = 0$ in an undamaged state and $\alpha = 1$ in a failure state); t is the time history; τ is the stress ratio, defined as the applied stress history $\sigma(t)$ divided by the short-term strength σ_s, i.e., $\tau = \sigma(t) \,/\, \sigma_s$; τ_0 is the stress threshold below which damage will not accumulate; and, τ_0, a, b, c and n are random model parameters.

In this study, basic short-term rolling shear strength distribution can be first established by short-term ramp loading, and the time to failure data from the trapezoidal fatigue loading tests can be obtained to understand the development of deflection and damage accumulation process [8]. By analysing the measured data from the trapezoidal fatigue loading tests, this stress based damage accumulation model can be calibrated, with consideration of the DOL effect on rolling shear strength. Then, the calibrated model can be used to quantify the rolling shear DOL effect of CLT under other loading conditions.

2 METHODS

2.1 SPECIMENS

As shown in Figure 2, two categories of CLT plates glued with polyurethane adhesive, i.e., five-layer Spruce-Pine-Fir (SPF5) plates and three-layer Spruce-Pine-Fir (SPF3) plates, were studied. The CLT plates were manufactured by 0.4 *MPa* clamping pressure using a mechanical press. For convenience, the five-layer Spruce-Pine-Fir plate is denoted as SPF5-0.4, and the three-layer Spruce-Pine-Fir plate is denoted as SPF3-0.4. Then, the CLT beam specimens in a short span-depth ratio of 6.0 were sampled from the full size CLT panels, as shown in Figure 3. These specimens were intended for the ramp loading tests and the trapezoidal fatigue loading tests. The pair sampling method was adopted in the specimens' preparation, and test matrix of these specimens is given in Table 1.

Figure 2: *CLT panels*

Figure 3: *CLT beam specimens*

Table 1: *Test Matrix of CLT specimens*

Group	SPF5-0.4	SPF3-0.4
Species	SPF	SPF
Press pressure (*MPa*)	0.4	0.4
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

2.2 EXPERIMENTAL STUDIES

The ramp loading and recording devices setup, which was the same as that of the following trapezoidal fatigue loading tests, is shown in Figure 4. The short-term ramp loading tests were displacement controlled until specimen failure. The loading speed was 2 *mm/min* (0.08 *inch/min*) for five-layer CLT specimens and 1.5 *mm/min* (0.06 *inch/min*) for three-layer CLT specimens, and the centre-point load was applied to the top of the CLT beam. In general, the average time to failure in the ramp loading tests was about 5 *min*. Both the time-dependent applied load value and the deformation were recorded for each test specimen. The rolling shear failure load was collected when the first rolling shear crack occurred in the cross layer of CLT.

Figure 4: *Loading setup*

For the trapezoidal fatigue loading test with the load control method, as shown in Figure 5, first, the jack applied the load from zero to one target value, i.e., the load level in the plateau loading part. Then, the jack held the load which equalled this target load value in the plateau loading process. Finally, the jack released the load level to zero. The loading proceeded periodically. With regard to the constant load level in the plateau part, the load value was chosen as the 25th percentile of the rolling shear capacity obtained from the rolling shear failure loads in the short-term ramp loading tests. The uploading rates, which are equal to the unloading rates, were 37.5 *kN/min* for five-layer CLT specimens and 27.0 *kN/min* for three-layer CLT specimens. The load was cyclically applied until the first rolling shear crack was observed with careful examination in the cross layer, defined as rolling shear failure.

Two types of the trapezoidal fatigue loading tests were performed, and these two tests had different load duration in the plateau part when the constant loading was applied. The first one, i.e., the trapezoidal short-plateau test, includes the constant loading part with a duration of $0.5t_m$, where t_m is the duration in the uploading segment shown in Figure 5. The second type has a longer plateau part, which is equal to $2.0t_m$. Table 1 above shows the sample size for these two different CLT trapezoidal fatigue loading tests.

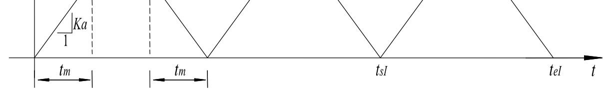

Figure 5: *Trapezoidal fatigue loading protocol*

3 RESULTS

3.1 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, followed by horizontal cracks in the timber material near the glue lines between the different layers. Finally the capacity-reduced specimens experienced tension failure in the bottom layers of the CLT specimens. The failure mode in the test is shown in Figure 6.

Figure 6: *Failure mode in the ramp loading test*

In the trapezoidal fatigue loading tests, the number of cycles to rolling shear failure N_f was recorded when first rolling shear crack was observed. 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 occurred in the cross layer, as shown in Figure 7.

The ramp loading test results and the trapezoidal fatigue loading test results are shown in Table 2. Due to the cross sectional layout difference in the CLT products, the rolling shear capacity is relatively lower in the three-layer CLT in comparison to the five-layer CLT. Also, in Table 2, with longer duration in the plateau part, the trapezoidal long-plateau test shows smaller number of cycles to rolling shear failure compared to the number of cycles to failure in the trapezoidal short-plateau test.

Figure 7: *Rolling shear cracks in the trapezoidal fatigue loading test (black marker line in the circle is next to the crack)*

Table 2: *Test results*

Group		SPF5-0.4	SPF3-0.4
Ramp loading rolling shear failure load (*kN*)	Mean	19.39	12.51
	COV	12.6%	24.3%
	25th%	17.79	10.33
	5th%	14.75	7.97
No. of cycles to rolling shear failure (*Nf*) in trapezoidal short-plateau test	Mean	66.1	38.5
	STDV	76.5	50.3
	Maximum cycles	281	212
No. of cycles to rolling shear failure (*Nf*) in trapezoidal long-plateau test	Mean	15.2	12.8
	STDV	18.5	23.2
	Maximum cycles	88	92

3.2 MODEL CALIBRATION

The theory for the damage accumulation model is one of the key tools to investigate the DOL behaviour in wood-based products. The Foschi and Yao model [9] was applied in the DOL investigation on the strength property of dimensional lumber. This model was adopted in the current DOL research of CLT rolling shear capacity. Considering this model in a ramp loading case, the model parameter a, is expressed approximately by the ramp rate K_s, the short-term rolling shear strength σ_s, and two other model parameters, τ_0 and b. This model parameter a is shown as follows [10]:

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

Then, the predicted number of cycles to rolling shear failure in the trapezoidal fatigue loading tests could be expressed as follows:

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

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.

The model calibration procedure was based on the algorithm developed by Foschi [10]. The random parameters, i.e., b, c, n and τ_0 in this damage accumulation model, and the developed ramp rolling shear strength, were assumed to be lognormally distributed. Then, by employing a nonlinear function minimization procedure using the quasi-Newton method, the mean and standard deviation of the lognormal distribution for each model parameter were estimated. Specifically, this damage accumulation model was calibrated with the trapezoidal short-plateau test data for the SPF5-0.4 group. But, for the SPF3-0.4 group, this model was calibrated with the trapezoidal long-plateau test data. Table 3 shows the model calibration results.

Table 3: *Calibration results*

Model parameters in SPF5-0.4	Mean	STDV
b	69.961	6.000
c	3.483×10^{-8}	2.466×10^{-8}
n	0.925	0.104
τ_0	0.157	0.450
Model parameters in SPF3-0.4	**Mean**	**STDV**
b	16.810	1.601
c	3.326×10^{-8}	4.203×10^{-9}
n	1.233	0.138
τ_0	0.320	0.130

After calibrating the damage accumulation model with the different trapezoidal rolling shear data sets for the SPF5-0.4 group and the SPF3-0.4 group, the relationship between the stress ratio and the number of cycles to rolling shear failure can be predicted. For example, with the calibrated model parameters in the SPF5-0.4 group in Table 3, simulated N_f values were produced and compared to the other set of the experimental measurement, i.e., the trapezoidal long-plateau test data, as shown in Figure 8. Similarly, for the SPF3-0.4 group, the verification was against the trapezoidal short-plateau test data. These model calibration and verification results are shown in Figure 8 and Figure 9, which include the relationships between the stress ratio and the number of cycles to failure in a logarithm scale.

Figure 10 and Figure 11 show the cumulative distributions of the experimental and the simulated N_f values based on the model calibration and verification for those two different CLT groups (i.e., SPF5-0.4 and SPF3-0.4). From Figures 10 and 11, it can be seen that there are differences between the model prediction and the collected test data in the cumulative distribution fitting results. Figures 8 and 9 show however good agreement between model predicted and experimental results in the stress ratio basis. Since the key concern in this research is to understand the relationship between the time to failure and the stress ratio; therefore, the results from Figure 8 and Figure 9 show that the model predictions agree well with the test data.

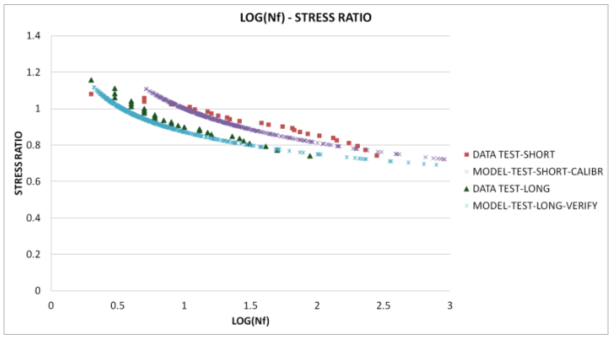

Figure 8: *Relationship between the stress ratio and the number of cycle to failure in SPF5-0.4*

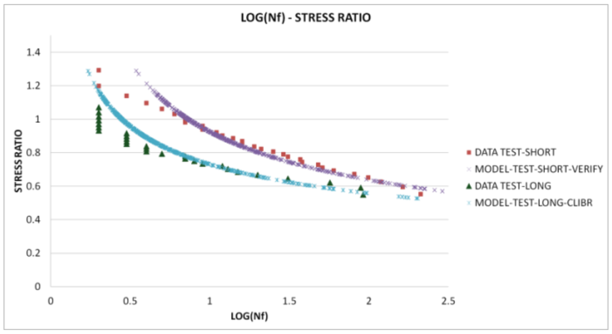

Figure 9: *Relationship between the stress ratio and the number of cycle to failure in SPF3-0.4*

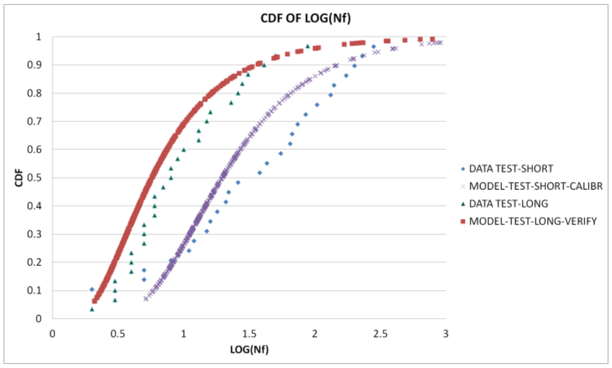

Figure 10: *Cumulative distributions of the number of cycle to failure in SPF5-0.4*

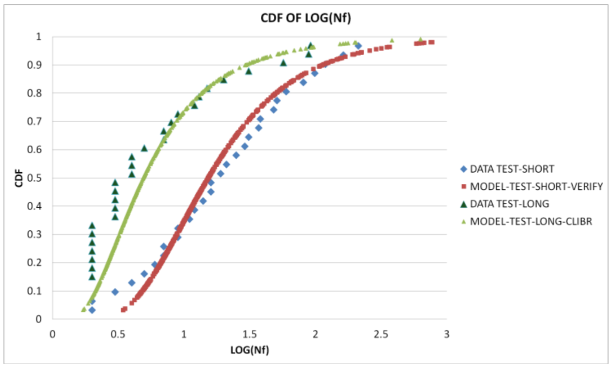

Figure 11: *Cumulative distributions of the number of cycle to failure in SPF3-0.4*

4 CONCLUSIONS

Based on the ramp loading test data and the trapezoidal fatigue loading test data, the DOL effect on the rolling shear strength of MPB lumber based CLT was investigated. A stress-based damage accumulation theory was used to investigate the DOL effect of CLT rolling shear behaviour. This model included the evaluation of rolling shear capacity from ramp loading tests. This model was calibrated and verified with the trapezoidal fatigue loading test data. The results show that the model predictions fit well with the test measurements. This calibrated model is available to elucidate the DOL effect on the CLT rolling shear strength under various loading conditions.

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