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Duration-of-Load Effect on the Rolling Shear Strength of Cross Laminated Timber: Reliability Analysis and Duration-of-Load Strength Adjustment Factor

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ABSTRACT: In this study, the duration-of-load (DOL) effect on the rolling shear strength of cross laminated timber (CLT) was evaluated. A stress-based damage accumulation model is chosen to evaluate the DOL effect on 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 was calibrated and verified based on the test data from low cycle trapezoidal fatigue tests (the damage accumulation tests). 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-reliability study. Therefore, a reliability assessment of the CLT products was performed considering short-term and snow loading cases. The reliability analysis results and factors reflecting the DOL effect on the rolling shear strength of CLT are compared and discussed. The results suggest that the DOL rolling shear strength adjustment factor for CLT is more severe than the general DOL adjustment factor for lumber; and, this difference should be considered in the introduction of CLT into the building codes for engineered wood design.

1. INTRODUCTION

Cross laminated timber (CLT) is a wood composite product suitable for floor 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. The CLT panel usually includes three to eleven layers, as shown in Figure 1.

Figure 1: Layering of CLT

Rolling shear stress is defined as the shear stress leading to shear strains in a radial-tangential plane perpendicular to the grain (Fellmoser and Blaß, 2004). 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 (Blaß and Görlacher, 2003). 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 Figure 2 (Jöbstl and Schickhofer, 2007). Therefore, there is a need to evaluate the rolling shear strength properties for 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; 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 to as the duration-of-load (DOL) effect. In fact, the DOL effect is not introduced by material deterioration, such as biological rot; rather, it is an inherent characteristic of wood.

Figure 2: Rolling shear behaviour in cross layers

Although it is well known that the strength properties of wood products are influenced by the DOL effect (Barrett and Foschi, 1978; Foschi and Barrett, 1982; Gerhards and Link, 1987; Laufenberg et al., 1999; Madsen, 1992), there is very little research reported on studying the DOL effect on the rolling shear strength of CLT. Therefore, more research work is needed to quantify the DOL effect and reduce the possibility of CLT rupture under long-term loading throughout its intended service life.

Li et al. (2014) performed short-term ramp loading tests and low cycle trapezoidal fatigue loading tests to accumulate damage in the research of the rolling shear DOL behaviour of CLT. 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 theory of the damage accumulation model is one of the key tools to investigate the DOL behaviour in wood-based products (Foschi, 1989; Gerhards and Link, 1987). A stress-based damage accumulation model was developed by Foschi and Yao (1986) to consider the DOL effect on the strength properties of dimensional lumber (Foschi and Barrett, 1982; Foschi, 1989). The Foschi and Yao model considers the damage accumulation rate as a function of stress history and the already accumulated damage state as follows:

$if\ \sigma(t) > \tau_0\sigma_s$

$$\frac{d\alpha}{dt} = a(\sigma(t) - \tau_0\sigma_s)^b + c(\sigma(t) - \tau_0\sigma_s)^n\alpha$$

$$if\ \sigma(t) \leq \tau_0\sigma_s \qquad \frac{d\alpha}{dt} = 0$$

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 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; and, a, b, c, τ_0 and n are random model parameters.

The Foschi and Yao model was adopted in the current DOL research of CLT rolling shear capacity. In this study, by analysing the measured data from the trapezoidal fatigue loading tests (Li et al., 2014), the stress-based damage accumulation model was calibrated and verified. This verified model can then be used to quantify the rolling shear DOL 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 was performed considering short-term and snow loading cases. The reliability analysis results and factors reflecting the DOL effect on the rolling shear strength of CLT are compared and discussed.

2. EXPERIMENTAL TESTS AND DAMAGE ACCUMULATION MODEL

2.1. Introduction of Specimens and Test Results

The detailed information in this section can be found in the literature (Li et al., 2014). Five-layer Spruce-Pine-Fir (SPF5) CLT plates were studied; they were denoted as SPF5-0.4 for convenience. The CLT beam specimens in a short span-depth ratio of 6.0 were sampled for the short-term ramp tests and the trapezoidal fatigue loading tests. The pair sampling method was adopted to assure random matching formula; 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 (Li, 2015).

Figure 3: Loading setup

The ramp loading setup, the same as that of the trapezoidal tests, is shown in Figure 3. The ramp tests were displacement controlled until specimens' failure; the speed was 2 *mm/min* (around 3.9 *kN/min*). The short-term rolling shear failure load was recorded, when the first rolling shear crack occurred in the cross layer at an inclined angle, as shown in Figure 5.

In the trapezoidal fatigue loading protocol using load control method as shown in Figure 4, the uploading and unloading rate was 37.5 *kN/min*; this was higher than the short-term ramp loading rate. Furthermore, the ramp tests adopted the displacement control method with a constant deformation rate, so the stress rate was different from one beam to another, while the loading rate for trapezoidal cases is given in terms of stress.

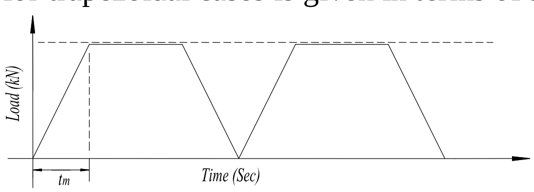

Figure 4: Trapezoidal fatigue loading protocol

The constant load level in the plateau part was chosen as the 25th percentile of the short-term ramp rolling shear failure loads. 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 with different load duration in the plateau part. 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 4. The second type, i.e., the trapezoidal long-plateau test, has a longer plateau part which is equal to $2.0t_m$. The number of cycles to rolling shear failure N_f was recorded when the first rolling shear crack was observed within that $N_f^{\,th}$ cycle.

The basic short-term rolling shear strength distribution can be established by the ramp tests. The time to failure data from the trapezoidal tests can be obtained to understand the development of deflection and damage accumulation process, and it can be adopted in the damage accumulation modeling process.

Less than 25% of the specimens failed in the first uploading although the 25th percentile failure load was applied, due to the use of a significantly higher rate of uploading resulting in the increase of apparent short-term strength. In the modeling process, past research has shown that short-term strength property of wood increases under higher loading rate. Madsen (1992) observed a 15% increase in shear strength when the loading rate was increased by a factor of ten. Based on this information, a 15% increase in short-term rolling shear strength was assumed in the damage accumulation modeling process to account for the difference between the loading rates used in ramp and fatigue tests (Li, 2015).

Table 1: Test results

Group	*SPF5-0.4*	
Ramp loading rolling shear failure load (kN)	*Mean*	*19.39*
	COV	*12.6%*
	25th% tile	*17.79*
	5th% tile	*14.75*
No. of cycles to rolling shear failure (Nf) in trapezoidal short-plateau test	*Mean*	*66.1*
	STDV	*76.5*
	Maximum cycles	*281*
No. of cycles to rolling shear failure (Nf) in trapezoidal long-plateau test	*Mean*	*15.2*
	STDV	*18.5*
	Maximum cycles	*88*

Figure 5: Failure mode in the ramp loading test

The ramp and the trapezoidal test results are shown in Table 1. In the short-term ramp loading tests, rolling shear failure was the major failure mode, as shown in Figure 5. The short-term 5th and 25th percentile rolling shear capacities in Table 1 were obtained based on fitted Lognormal distributions. In the trapezoidal fatigue loading tests, the trapezoidal long-plateau test showed smaller number of cycles to rolling shear failure compared to the N_f in the short-plateau test.

2.2. The Damage Accumulation Model

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 has been applied in the DOL investigation on the strength property of dimensional lumber (Foschi, 1989); this model was adopted in the current DOL research of CLT rolling shear capacity. In a ramp loading case, the model parameter a, is expressed approximately by the ramp rate $\mathrm{K_s}$, the strength σ_s and model parameters, τ_0 and b.

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

then, the predicted number of cycles to failure in the trapezoidal tests can be expressed as follows:

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

where $\mathrm{K_0}$ and $\mathrm{K_1}$ are determined by analysing the damage accumulated in the first two cycles of the trapezoidal fatigue loading:

$$\mathrm{K_0} = \frac{\alpha_2}{\mathrm{K_1}} - 1 \qquad \mathrm{K_1} = \alpha_1$$

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

Based on the equal rank assumption (Barrett, 1996), the relationship between the number of cycles to rolling shear failure (N_f from Table 1 in the logarithm scale) and the stress ratio applied is shown in Figure 6, where the data points are related to the results in Table 1. The figure shows that, under the same stress ratio, the time to failure was shorter in the trapezoidal long-plateau test, since more damage is accumulated in this test category for each loading cycle. The cumulative distribution of the measured number of cycles to rolling shear failure (N_f from Table 1 in the logarithm scale) is shown as data points in Figure 7.

The model calibration procedure was based on the algorithm developed by Foschi (1989). The random parameters (i.e., $\mathrm{b, c, n}$ and τ_0) and the developed ramp rolling shear strength 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 model with consideration of the influence of higher loading rate, which used each individual ramp rolling shear failure load (from Table 1) as the load input; the short-term rolling shear strength was then corrected with a 15% strength increase due to the higher uploading rate (in trapezoidal tests) for modeling purpose, as given in Table 2. The applied stress history $\sigma(t)$ was evaluated by finite element models as well.

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

Five-layer CLT	*Rolling shear strength (MPa)*		
	Mean	*COV*	*5th percentile*
	2.02	*12.2%*	*1.56*

Table 3: Calibration results

Model parameters in SPF5-0.4	*Mean*	*STDV*
b	*39.857*	*2.219*
c	3.483×10^{-8}	2.466×10^{-8}
n	*6.754*	*0.117*
τ_0	*0.194*	*0.247*

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. The damage accumulation model was calibrated against the trapezoidal long-plateau test data, as shown in Figure 6 and Figure 7. Table 3 shows the model calibration results.

In Figure 6 and Figure 7, at the lower tail when N_f is small, the model output in calibration and test results seemed to be slightly different; however, this is due to the small difference has been magnified by the logarithm scale.

Also, the other reason for the small difference between the fitting and the test data at the lower tail is that, in the lower tail of the distribution when the calibration was performed at the time basis, there was uncertainty of how to define the specific time to failure point within that N_f th cycle, because only N_f value as whole number (in Table 1) with rolling shear failure was measured in the tests. However, as the N_f increases, this error becomes trivial because the N_f value is much larger. For example when $N_f = 100$, this error is only less than 1/100=1%.

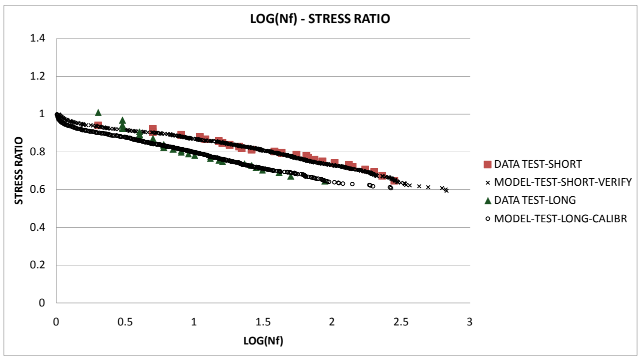

Figure 6: Relationship between stress ratio and number of cycles to failure (in logarithm to base 10)

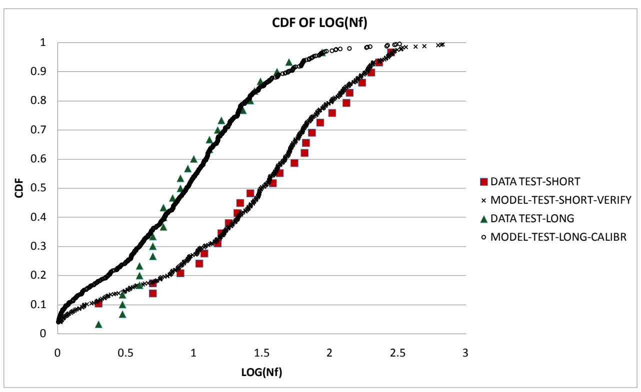

Figure 7: Cumulative distributions of number of cycles to failure (in logarithm to base 10)

In general, the fitting was also quite acceptable in the upper tail; 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 model by the trapezoidal data, the relationship between the stress ratio and the number of cycles to failure can be predicted. For example, with the calibrated parameters in Table 3, simulated N_f values were produced and compared to the trapezoidal short-plateau test data. These model calibration and verification results are shown in Figure 6, giving the relationships between the stress ratio and the predicted $Log(N_f)$ values. Figure 7 shows the cumulative distributions of the experimental and the simulated $Log(N_f)$ values. In Figure 6 and Figure 7, the model verifications agreed well with the test data.

3. RELIABILITY ANALYSIS

3.1. Reliability Analysis of Short-Term Rolling Shear Strength of CLT

This section introduces the reliability analysis on the limit state of the short-term rolling shear strength of CLT products, without considering the DOL effect. The objective of this analysis is to evaluate the relationship between the reliability index and the performance factor in the design codes. To clarify, the reliability analysis with consideration of the DOL effect will be addressed in the next section.

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

$$1.25D_n + 1.50Q_n = \phi RS_{(0.05)}T_V \qquad (1)$$

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 (i.e., 30 years return); and, ϕ is the performance factor applied to the characteristic strength (i.e., $RS_{(0.05)}$).

This characteristic rolling shear strength is chosen to be the parametric 5th percentile rolling shear stress value evaluated by Lognormal fitting (Foschi, 1989); the $RS_{(0.05)}$ is calculated with consideration of the influence of higher loading rate (consistent with the model calibration process in Section 2.2), 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, $RS_{(0.05)}$ is not dependent on the ratio T_V used.

T_V in Equation (1) is defined as the ratio between the sectional rolling shear load capacity calculated from different beam theories (i.e., the layered beam, the gamma beam and the shear analogy theory) and the shear stress value. For each theory, the relationship between the sectional capacity and the shear stress is introduced in the literature (Bodig and Jayne, 1982; Eurocode 5, 2004; Kreuzinger, 1999); the calculated T_V values are shown in Table 4.

Table 4: Summary of the calculated T_V values (in kN/MPa) for five-layer CLT

Five-layer CLT	*T_V from layered beam theory*	*T_V from gamma beam theory*	*T_V from shear analogy theory*
	11.24	*11.90*	*11.76*

From Equation (1), the performance factor ϕ will affect the reliability index β; 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 Table 1) corrected with the expected strength increase due to the higher loading rate for modeling purpose, which is consistent with the term $RS_{(0.05)}$ in Equation (1); D is the random dead load; and, Q is the random live load. Then, the ratio of the design dead load to the design live load is defined as:

$$r = \frac{D_n}{Q_n} = 0.25$$

therefore, the performance function G is:

$$G = R - \frac{\phi RS_{(0.05)} T_V}{(1.25r + 1.50)}(dr + q) \qquad (2)$$

where the random variables d and q are:

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

the calculation of the random variables d and q can be found in the literature (Foschi, 1989).

Two site snow loads from Halifax and Vancouver were investigated in the reliability analysis. The snow load information comes from the statistics on the maximum annual snow depth, the snow duration and the ground-to-roof conversion factors provided by the National Research Council of Canada (Foschi, 1989; Li, 2015).

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. Figure 8 gives the results under the Halifax snow load case.

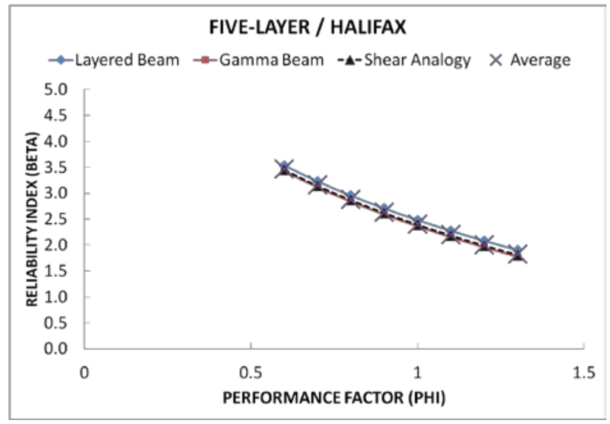

Figure 8: Curves between the reliability index and the performance factor (Five-layer/Halifax)

From the above results in Figure 8, under different beam theories, the obtained $\beta - \phi$ relationship is slightly different; this small difference comes from the different term T_V in Equation (2), and this T_V is changing when different beam theories are adopted.

The average β in Figure 8 is then calculated from the β values in the three beam theories, to get an average estimation over the error from the different assumptions; it is also given in Table 5.

In Figure 8, it shows that the $\phi = 0.834$ which is around 0.9 at a target reliability index $\beta = 2.80$. For the short-term bending strength of lumber in the Canadian design code, the performance factor is $\phi = 0.9$. Therefore, the obtained ϕ in Figure 8 for CLT is close to the ϕ in the code for lumber.

3.2. Reliability Analysis of CLT Rolling Shear Strength under Thirty-Year Snow Load

This section will introduce the reliability analysis on the limit state of CLT products under a thirty-year snow load, considering the DOL effect on the rolling shear strength to evaluate the $\beta - \phi$ relationship. A Monte Carlo simulation procedure, incorporating the verified damage accumulation model in Section 2.2, 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 (Foschi, 1989). Then, based on the previous results from the short-term rolling shear strength reliability analysis (without considering the DOL effect), the DOL adjustment factor for rolling shear strength can be obtained with one safety margin.

The Monte Carlo simulation was used to determine the probability of rolling shear failure for a service life ranging from one year to thirty years. Based on the verified model, a sample size of *NR=1000* replications was chosen. Then, these simulated samples were tested under the thirty-year snow loading history as introduced in the literature (Foschi, 1989). Consistent with the procedure in Section 3.1, the snow loads from Halifax and Vancouver were considered. Dead load was also included in the service life. Then, the performance function G is:

$$G = 1 - \alpha \qquad (3)$$

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.

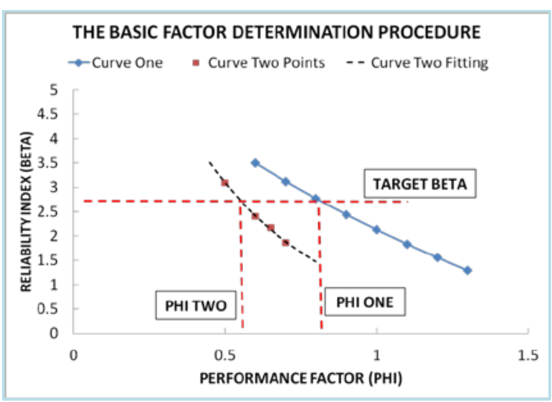

Figure 9: The factor determination procedure (curve one-without DOL effect; curve two-with DOL effect)

The DOL strength adjustment factor K_D can then be derived, after performing the Monte Carlo simulation. The basic determination procedure for this factor is shown in Figure 9, with two cases displayed for the $\beta - \phi$ relationship. The first case is curve one without considering the DOL effect, based on the average $\beta - \phi$ relationship in Figure 8. The second curve in Figure 9 includes the performed Monte Carlo simulation results with the DOL effect taken into account. With the Monte Carlo simulation results (the dots in curve two), curve two is calculated using the exponential regression fitting method.

In Figure 9, at the target reliability index level $\beta = 2.8$ (consistent with the literature) (Foschi, 1989), the performance factor for curve one is defined as ϕ_I, and ϕ_{II} is the factor from curve two. Then the strength adjustment factor K_D for the rolling shear strength is defined as:

$$K_D = \frac{\phi_{II}}{\phi_I} \qquad (4)$$

For example, Table 5 shows 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.

Table 5: Reliability results for the strength adjustment factors in the five-layer CLT

Five-layer	*Reliability results*			
	β	ϕ_I	ϕ_{II}	K_D
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*
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*

Then, from Equation (4), the derived DOL rolling shear strength adjustment factor K_D is shown in Table 5. K_D is around 0.466 to 0.617 when the reliability index $\beta = 2.80$. The factor difference comes from the different snow load in each location, and the average factor from the two cities is 0.541. In the Canadian design code, for lumber, the factor K_D is 0.8. Therefore, the results suggest that the DOL strength adjustment factor for rolling shear strength in CLT products seems to be very different from that in lumber. Specifically, the CLT rolling shear DOL strength adjustment factor was found to be more severe compared to the general DOL factor for lumber.

4. CONCLUSIONS

The stress-based damage accumulation model theory was adopted to evaluate the DOL effect on the rolling shear strength of CLT. This model was calibrated and verified based on the collected test results; the model predictions fitted the measured data well.

As the developed DOL model is a probabilistic model, a time-reliability study of the CLT products was performed. The reliability results provided further information about the DOL effect on the rolling shear behaviour of CLT. The predictions of the time to failure from this model and this investigation process elucidated the DOL effect and provided guidance for the evaluation of the CLT DOL effect.

The DOL 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 DOL adjustment factor for lumber. Therefore, when CLT is introduced into the building codes for engineered wood design, the DOL adjustment factor on the rolling shear strength should be considered.

This study considered the DOL 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 DOL 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.

5. ACKNOWLEDGEMENT

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