WCTE 2014
Quebec City
Canada
August 10-14
World Conference on Timber Engineering

DESIGN EQUATIONS FOR DOWEL EMBEDMENT STRENGTH AND WITHDRAWAL RESISTANCE FOR THREADED FASTENERS IN CLT

Shawn Kennedy[1], Alexander Salenikovich[2], Williams Munoz[3], Mohammad Mohammad[4]

ABSTRACT: Cross-laminated timber (CLT), which was developed in Europe in the early 1990's, has a growing success in timber construction. Unfortunately, development of CLT in Canada is lagging behind Europe. Lack of experience and methods for design with CLT is partly the reason. The CLT design properties are different from those of sawn timber and glued-laminated timber because of the orthogonal laminations, which may particularly have influence on the design of connections. The purpose of this project is to determine predictive models for embedment strength and withdrawal resistance for threaded fasteners in CLT. Based on test results on lag screws and self-drilling screws, design equations are proposed for implementation in the CSA O86 standard for design of connections in Canadian-made CLT.

KEYWORDS: Dowel bearing strength, Canadian timber design code

1 INTRODUCTION

Cross-laminated timber (CLT), which was developed in Europe in the early 1990's, has a growing success in timber construction. This product is lifting timber high-rise buildings to new heights. Unfortunately, development of CLT in Canada is lagging behind Europe. Lack of experience and methods for design with CLT is partly the reason. The CLT design properties are different from those of sawn timber and glued-laminated timber because laminations with orthogonal grain directions are combined in the same cross-section. This alternation of layers in CLT panels may particularly have influence on the design of connections. The purpose of this project is to determine the predictive equations for embedment strength and withdrawal resistance for threaded fasteners in Canadian-made CLT.

2 BACKGROUND

As part of a large research project on basic mechanical properties of CLT, Uibel and Blaβ [1], [2] studied the load carrying capacity of fasteners and proposed design equations for CLT panels produced in Europe. Follesa *et al.* [3], Munoz *et al.* [4] and Joyce and Smith [5] studied lap and spline connections between floor and/or wall elements. Recently, major efforts in Canada and US have been brought forward for the development of CLT engineering design guidelines, which resulted in publication of the CLT Handbook (Canadian Edition [6] and US Edition [7]). However, these past studies lack experimental validation of proposed design equations for fastenings in Canadian-made CLT. The research project described in this paper was conducted jointly at FPInnovations and Université Laval [8] aiming at filling the gap and putting forward proposals for the adoption in the Canadian timber design standard CSA O86 [9].

3 MATERIALS

3.1 FASTENERS

Fasteners evaluated in this research are traditional lag screws and self-drilling screws.

3.1.1 Withdrawal

The experimental program included 360 tests on lag screws and 120 tests on self-drilling screws loaded in withdrawal. Lag screws of six diameters (from 6.35 mm to 19.1 mm) were commodity off-shelf products, while self-drilling screws of three diameters (6, 8 and 12 mm) were supplied by European manufacturers. Two lengths of penetration were examined for each diameter of fastener. Dimensions of lag screws and self-drilling screws are presented in Tables 1 and 2, respectively.

3.1.2 Embedment

Same type and diameter of fasteners were used for the dowel embedment tests. Approximately 720 embedment tests were performed with lag screws and 360 tests with self-drilling screws. Two embedment lengths were examined depending on the fastener diameter. For the three smaller diameters, tests were performed using a length of 76.2 mm, while for the three larger diameters a length of 152 mm was used, as shown in Table 3. Another approach was used for self-drilling screws: they penetrated the full thickness of a three or five-ply CLT panel. Since

---

[1] Shawn Kennedy, Université Laval, 2425 rue de la Terrasse, Quebec, Canada. Email: shawn.kennedy.1@ulaval.ca
[2] Alexander Salenikovich, Université Laval, Quebec, Canada
[3] Williams Munoz, Nordic Structures Bois, Montreal, Canada
[4] Mohammad Mohammad, FPInnovations, Ottawa, Canada

the thickness of layers varies between the producers, the actual embedment length shown in Table 4 for producers A and B is slightly different.

Table 1: *Dimensions of lag screws (withdrawal)*

Fastener diameter (mm/in.)	Fastener length (mm)	Penetration length (mm)	Lead hole diameter (mm)
6.35	50.8	32	4.39
1/4	127	82	
7.94	76.2	51	5.56
5/16	152	100	
9.53	102	55	6.75
3/8	203	131	
12.7	127	70	9.13
1/2	254	170	
15.9	152	100	11.9
5/8	305	155	
19.1	152	102	14.3
3/4	305	146	

Table 2: *Dimensions of self-drilling screws (withdrawal)*

Fastener diameter (mm)	Fastener length* (mm)	Penetration length (mm)	Lead hole diameter (mm)
6	100/64	36 64	N/A
8	160/100	48 96	N/A
12	380/145	72 144	9.13

*Total length/threaded length

Table 3: *Dimensions of lag screws (embedment)*

Fastener diameter (mm/in.)	Threaded (T) or Non-threaded (NT) portion	Penetration length (mm)	Lead hole diameter (mm)
6.35	NT	76.2	6.35
1/4	T	76.2	4.39
7.94	NT	76.2	7.94
5/16	T	76.2	5.56
9.53	NT	76.2	9.53
3/8	T	76.2	6.75
12.7	NT	152	12.7
1/2	T	152	9.13
15.9	NT	152	15.9
5/8	T	152	11.9
19.1	NT	152	19.1
3/4	T	152	14.3

Table 4: *Dimensions of self-drilling screws (embedment)*

Fastener diameter (mm)	Penetration length (mm)		Lead hole diameter (mm)
	CLT “A”	CLT “B”	
6	105	99	N/A
8	105 175	99 169	N/A
12	105 175	99 169	9.13

3.2 WOOD PRODUCTS

Withdrawal and embedment tests were conducted on 3-ply and 5-ply CLT manufactured in Quebec and British Columbia using Spruce-pine-fir species group. The test pieces were conditioned in the standard environment with 65 ± 5% of relative humidity and 20 ± 2°C temperature prior to testing. The oven-dry relative density of wood in these products ranged between 0.35 and 0.55.

4 TEST PROCEDURES

4.1 WITHDRAWAL

Axial withdrawal tests were performed in accordance with European standard EN 1382 [10] with fastener insertion perpendicular to the face of the panel. Minimum end and edge distances of 5d and 10d were applied in lateral and longitudinal directions, same as used in [11]. Installation of lag screws required lead holes equal to 70% of the nominal fastener diameter as per CSA O86 [9]. Same requirement was applied to self-drilling screws with 12-mm diameter.

The withdrawal force was applied using a hydraulic actuator at a constant crosshead speed of 1 mm/min and 0.5 mm/min for lag screws and self-drilling screws, respectively. Test stopped after the resistance decreased to 80% of the peak load. After the test, a small sample was cut from each specimen to determine relative density and moisture content of wood in the vicinity of the tested area.

4.2 EMBEDMENT

Embedment tests were performed in accordance with ASTM D5764 [11] half-hole test method with the fasteners inserted perpendicular to the face of the panel and loaded at 0°, 45° or 90° angle to the grain direction of the face layer of CLT panel. The specimen width and depth were 5 and 6 times the fastener diameter, respectively, but not less than 50 mm (same as in [13]). The tests were conducted separately on the unthreaded and on the threaded portions of lag screws. In the case of self-drilling screws, evaluation of the dowel embedment strength was performed only on the threaded portion of the shank.

Load was applied using a fastener welded to a steel plate attached to the loading head of a hydraulic actuator. The specimen was loaded at a constant speed of 1.0 mm/min. The test was stopped when the resistance decreased to 80% of the peak load unless the displacement first reached the lesser of 7.0 mm or half the diameter of the fastener. The displacement was calculated as the average of measurements recorded using two laser sensors measuring the movement of the fastener relative to the ends of the specimen. After the test, a small sample was cut from each specimen to determine the relative density and moisture content in the vicinity of the tested area.

5 ANALYSIS OF RESULTS: WITHDRAWAL

To propose a design equation for withdrawal resistance of threaded fasteners in CLT, the following models were considered:

1. CSA O86 [9] equation for wood screws,
2. NDS [14] equation for lag screws,
3. NDS [14] equation for wood screws, and
4. EN [2] equation for self-drilling screws in CLT.

The evaluation of the models was made in two steps. First, individual experimental data (P_i) were compared against the values predicted for the average withdrawal resistance ($P_{rw,\text{ avg}}$) at 5-min load duration using the measured oven-dry relative density. Then, the 5th percentile estimates of experimental values ($P_{i,std}$) obtained per test series were adjusted for the standard load duration (multiplied by 0.8 according to the CSA O86 Commentary [15]) and compared with design values (P_{rw}) predicted by the design equations (5th percentile values at standard load duration) using the mean oven-dry relative density for the species group as per CSA O86. To estimate the 5th percentile values, the normal distribution was assumed.

The following subsections discuss results of comparisons using the following notation:

$P_{rw,\text{ avg}}$ = average withdrawal resistance (N);
P_{rw} = specified withdrawal resistance (N);
d_F = fastener nominal diameter (mm);
ρ_{12} = measured density based on mass and volume at12% moisture content (g/cm^3);
G_0 = measured relative density based on oven-dry mass and volume of wood;
G = mean relative density for the species or species group based on oven-dry mass and volume;
L_t = length of penetration in wood specimen (mm).

The statistical parameters estimated for each model are presented in section 5.1.6.

5.1 CSA O86 EQUATION FOR WOOD SCREWS

Equation for wood screw average withdrawal resistance in CSA O86-09 [9] originates from McLain [16]:

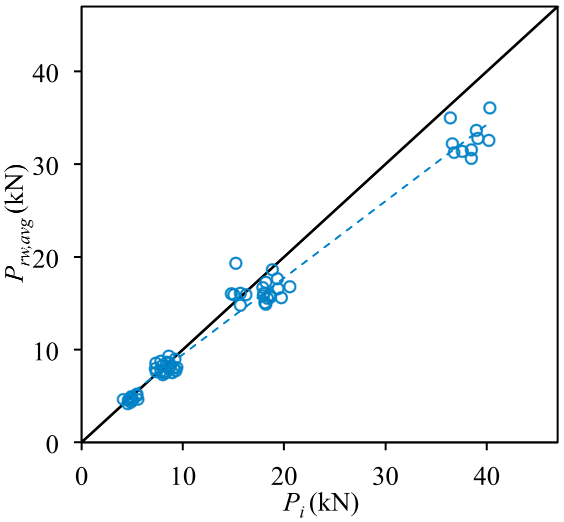
$$P_{rw,\,avg} = 112\, d_F^{0.82}\, G_0^{1.77}\, L_t \qquad (1)$$

The corresponding equation for the design withdrawal resistance (standard load duration) is as follows:

$$P_{rw} = 59\, d_F^{0.82}\, G^{1.77}\, L_t \qquad (2)$$

Figure 1 illustrates the comparison of equations (1) and (2) with experimental values. In general, this model presents conservative predictions for the tested fasteners.

a) Equation (1)



b) Equation (2)

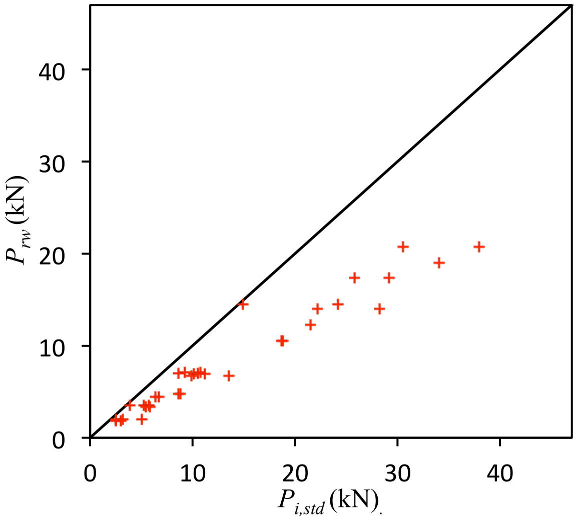


Figure 1: *Comparison of (a) Equation (1) vs. average test results and (b) Equation (2) vs. adjusted test results (kN)*

5.2 NDS EQUATION FOR LAG SCREWS

The NDS [14] has separate equations for different types of threaded fasteners. The equation for average withdrawal resistance for lag screws is:

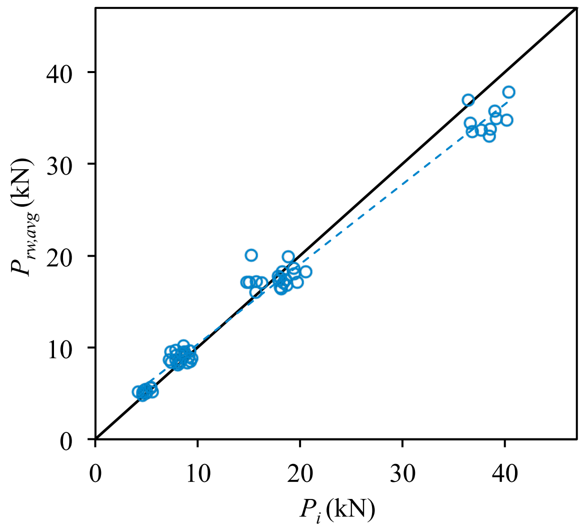
$$P_{rw,\,\mathrm{avg}} = 116\, d_F^{0.75}\, G_0^{1.5}\, L_t \tag{3}$$

The design withdrawal resistance in the CSA O86 design format would be expressed as follows:

$$P_{rw} = 62\, d_F^{0.75}\, G^{1.5}\, L_t \tag{4}$$

As can be seen in Figure 2, this model also presents conservative predictions.

a) Equation (3)



b) Equation (4)

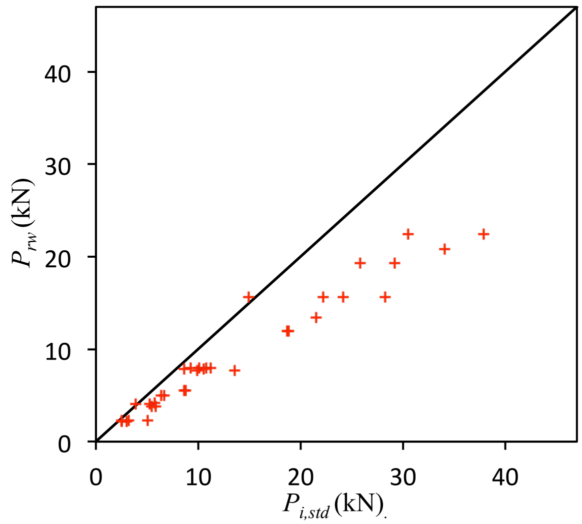


Figure 2: *Comparison of (a) Equation (3) vs. average test results and (b) Equation (4) vs. adjusted test results (kN)*

5.3 NDS EQUATION FOR WOOD SCREWS

The NDS [14] equation for average withdrawal resistance for wood screws is:

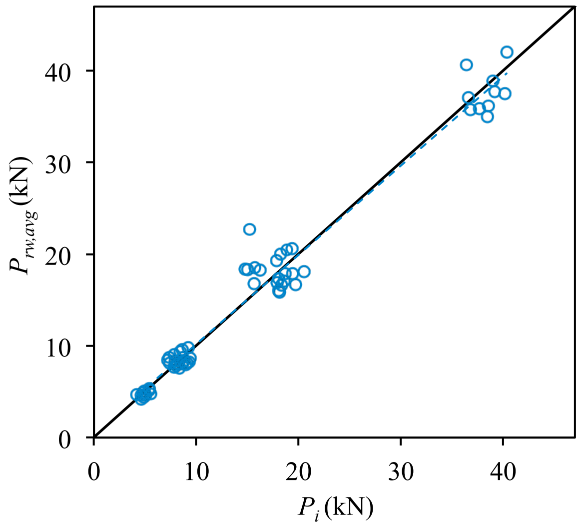
$$P_{rw,\,avg} = 98\, d_F\, G_0^{2}\, L_t \tag{5}$$

The design withdrawal resistance in the CSA O86 design format would be expressed as follows:

$$P_{rw} = 52\, d_F\, G^{2}\, L_t \tag{6}$$

Equation (5) provides the best goodness-of-fit with the measured peak loads on Canadian CLT (Figure 3a). As can be seen in Figure 3b, the design withdrawal resistance values are also predicted very well by Equation (6).

a) Equation (5)



b) Equation (6)

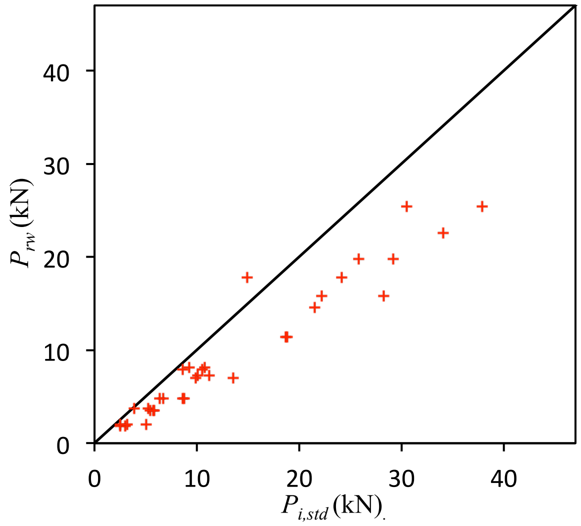


Figure 3: *Comparison of (a) Equation (5) vs. average test results and (b) Equation (6) vs. adjusted test results (kN)*

5.4 EN EQUATION FOR SCREWS IN CLT

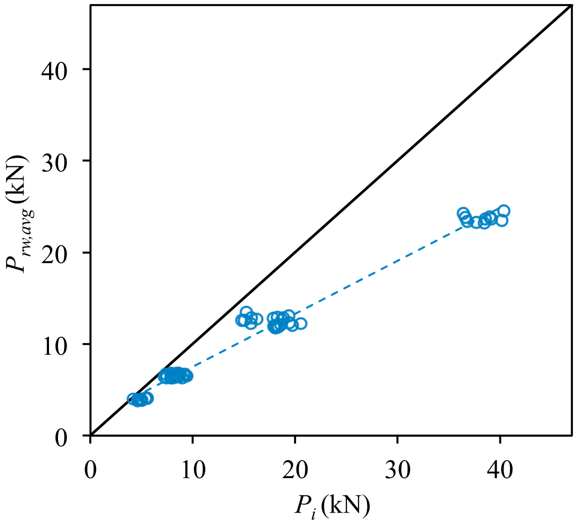
The following equation for the average withdrawal resistance for self-drilling screws in CLT was developed by Uibel and Blaβ [2]:

$$P_{rw,\,avg} = 62\, d_F^{0.8}\, \rho_{12}^{0.75}\, L_t^{0.9} \tag{7}$$

The design withdrawal resistance in the CSA O86 design format would be expressed as follows:

$$P_{rw} = 37\, d_F^{\,0.8}\, G^{0.75}\, L_t^{\,0.9} \tag{8}$$

Equation (7) doesn't appear to match withdrawal resistance of fasteners observed in our tests on Canadian CLT (Figure 4a). Equation (8) seems to underestimate the design withdrawal resistance especially of larger fasteners and longer penetration length (Figure 4b).


a) Equation (7)

b) Equation (8)

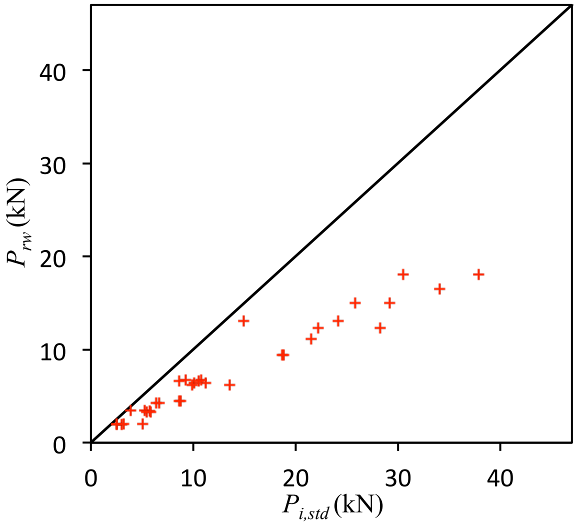


Figure 4: *Comparison of (a) Equation (7) vs. average test results and (b) Equation (8) vs. adjusted test results (kN)*

5.5 COMPARISON OF DESIGN EQUATIONS

Non-linear regression analysis was performed for the average predicted values using the formulas described in [11] to determine the following parameters: mean error, root mean square error (RMSE), absolute percentage error and pseudo R^2. Table 5 summarises the results of statistical comparison. Equation (5) appears to perform the best. It should be noted that Equations (1) and (3) could also be considered as acceptable. Equation (7) appears to be the least accurate.

Table 5: *Statistics for average CLT withdrawal resistance*

Design Method Equations	Mean Error	RMSE	Abs. % Error	Pseudo R²
(1)	1.54	2.82	11.4%	93.6%
(3)	0.379	1.97	8.48%	96.9%
(5)	-0.039	1.84	8.61%	97.3%
(7)	4.96	6.90	37.9%	61.9%

6 ANALYSIS OF RESULTS: EMBEDEMENT

Unlike sawn timber and glued-laminated timber, CLT products present orthogonal grain orientations between adjacent layers. Therefore, existing design equations for the embedment strength of wood under large diameter fasteners may not be valid for CLT. This section evaluates the applicability of different design models to the dowel embedment strength of Canadian CLT products.

First, the design approach presented in the US edition of the CLT Handbook [7] is studied. According to this approach, the embedment (dowel bearing) strength of the face layer is associated with the "effective" bearing length of the fastener, which is adjusted in proportion between the embedment strengths of the cross layer and the parallel layer. If applied directly to the embedment strength of CLT, this model can be expressed as follows:|

$$f_{\theta,CLT} = \left(l_{\parallel} f_\theta + l_\perp f_{90-\theta}\right) l_p^{-1} \tag{9}$$

where,

$l_{\parallel}$ = fastener bearing length in parallel layer(s);
$l_\perp$ = fastener bearing length in cross layer(s);
l_p = total bearing length of fastener in CLT panel;
f_θ = embedment strength of parallel layer(s);
$f_{90-\theta}$ = embedment strength of cross layer(s); and
θ = angle of load to the grain of the face layer.

The embedment strength of an individual layer loaded at an angle to the grain is calculated using the Hankinson formula:

$$f_\theta = \frac{f_0 \cdot f_{90}}{f_0 \sin^2\theta + f_{90}\cos^2\theta} = \frac{f_0}{\dfrac{f_0}{f_{90}}\sin^2\theta + \cos^2\theta} \tag{10}$$

where,

f_0 = embedment strength parallel to grain;
f_{90} = embedment strength perpendicular to grain;
θ = angle of load to the grain of a layer.

Such approach may be too complex for the designer, because the calculation depends on the thickness of individual layers in the panel. Equations proposed by Uibel and Blaβ [1] provide values of the embedment strength for parallel and perpendicular layers, which are independent of the panel layup and thickness of layers. In this case, Equation (10) is used directly to calculate the embedment strength of CLT under the loads applied at an angle θ to the grain of the face layer where f_0 and f_{90} are the values of embedment strength of CLT parallel and perpendicular to grain of the face layer, respectively.

In the following paragraphs, the US CLT Handbook approach is examined using the embedment (dowel bearing) strength equations found in CSA O86 [9], NDS [14] and those proposed by Kennedy et al. [13]. Then, the European approach is studied using equations from Uibel and Blaβ [1] and those obtained from regression analysis of our own test data on Canadian CLT. The following notation is used (see also notation in 5.1):

$f_{\theta,avg}$ = average embedment strength (MPa);
$f_{\theta,k}$ = specified embedment strength (MPa);
θ = loading angle relative to the specimen face grain (°).

In the comparisons of design models, the experimental data present the measured stress (f_i) as the 5% diameter offset load (P_y) divided by the embedded length (l) and the nominal diameter (d_F) of the fastener:

$$f_i = \frac{P_y}{l \cdot d_F} \tag{11}$$

For each model, non-linear regression analysis was performed and the statistics were evaluated using equations presented in [11].

6.1 CSA O86 EQUATIONS (US CLT APPROACH)

6.1.1 Average values

The model for the average embedment strength for parallel and perpendicular loading angle is expressed as follows:

$$f_{0,avg} = 82\rho_{12}(1-0.01d_F) \tag{12a}$$

$$f_{90,avg} = 36\rho_{12}(1-0.01d_F) \tag{12b}$$

The CSA average dowel embedment equations (Eq. 12) appear to predict the embedment strength of Canadian CLT reasonably well when using the US CLT Handbook approach (Eq. 9, 10). In fact, the statistical analysis reveals the best goodness-of-fit with observations:

- Pseudo $R^2 = 35.8\%$,
- Mean Error = -0.48,
- Root Means Square Error (RMSE) = 3.59, and
- Absolute Percent Error = 12.2%.

Figure 5 shows the comparison between predictions and observations.

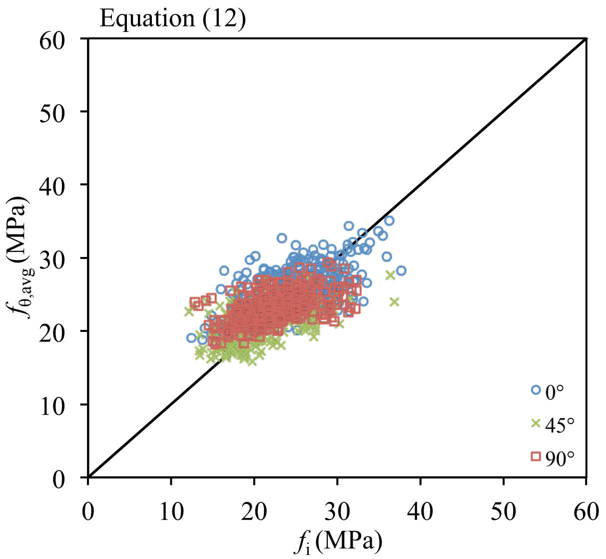


Figure 5: *Comparison of Equation (12) vs. test data (MPa)*

6.1.2 Design values

CSA O86 [9] design embedment strength for parallel and perpendicular loading angles can be presented as follows:

$$f_{0,k} = 50G(1-0.01d_F) \tag{13a}$$

$$f_{90,k} = 22G(1-0.01d_F) \tag{13b}$$

Although the average CSA design model performs fairly well, the equation adjusted to design values present a weak level of safety with over 36% of predictions above the experimental data adjusted to the standard load duration (Figure 6). Similar lack of safety was previously observed by Kennedy *et al.* [13].

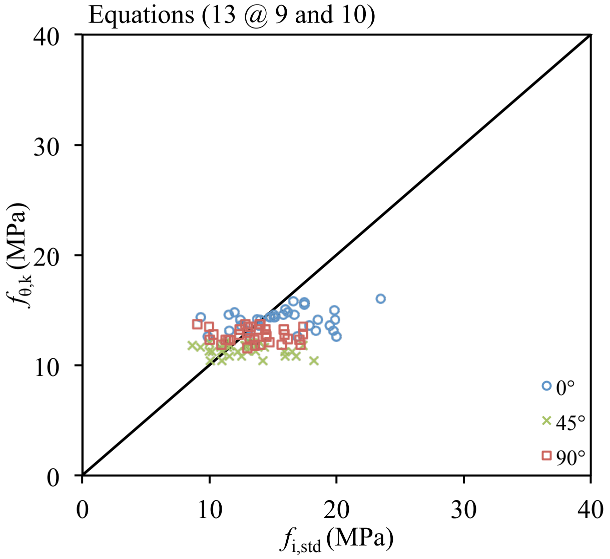


Figure 6: *Comparison of Equation (13) vs. test data adjusted to standard load duration (MPa)*

6.2 NDS EQUATIONS (US CLT APPROACH)

6.2.1 Average values

NDS equations for dowel bearing strength parallel and perpendicular to grain represent the average values in Inch-Pound units as follows:

$$f_{\theta,avg} = 12000 G_0 \tag{14a}$$

$$f_{\theta,avg} = 6100 G_0^{1.45} d_F^{-0.5} \tag{14b}$$

where,
$f_{\theta,avg}$ = average dowel bearing strength (psi);
d_F = fastener nominal diameter (in.);

In SI units, the same equations are expressed as follows:

$$f_{\theta,avg} = 77 G_0 \tag{15a}$$

$$f_{\theta,avg} = 212 G_0^{1.45} d_F^{-0.5} \tag{15b}$$

where,
$f_{\theta,avg}$ = average dowel bearing strength (MPa);
d_F = fastener nominal diameter (mm).

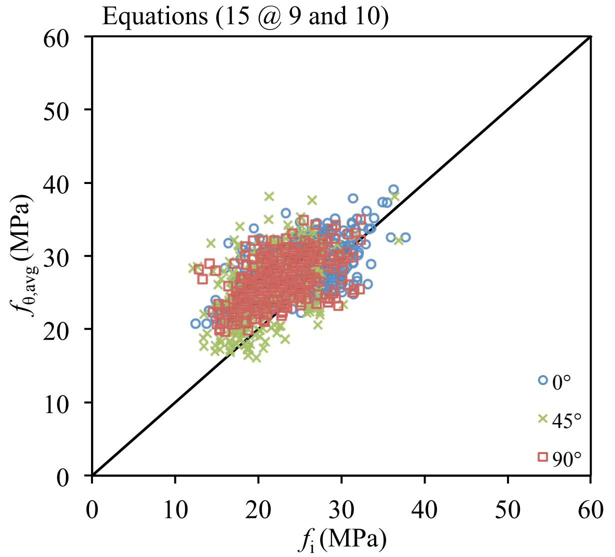


Figure 7: *Comparison of Equation (15) vs. test data (MPa)*

Figure 7 illustrates comparison of values predicted with Eq. 15 using the US CLT Handbook approach (Eq. 9, 10) vs. test results. Non-linear regression analysis performed on Equation (15) presents the following statistics:

- Pseudo R² = -0.54%,
- Mean Error = -3.90,
- Root Means Square Error (RMSE) = 5.56, and
- Absolute Percent Error = 16.9%.

6.2.2 Design values

To convert the NDS average dowel bearing strength to the design values in the CSA O86 format, a factor of 0.574 would be used to adjust the average values at 12% MC to the characteristic values at 15% MC and to the standard load duration and the following expression would be used:

$$f_{\theta,k} = 44G \tag{16a}$$

$$f_{\theta,k} = 105 G^{1.45} d_F^{-0.5} \tag{16b}$$

Figure 8 illustrates comparison of the design values vs. test results adjusted to standard load duration. A poor level of safety is achieved with 45% of predicted values being non-conservative.

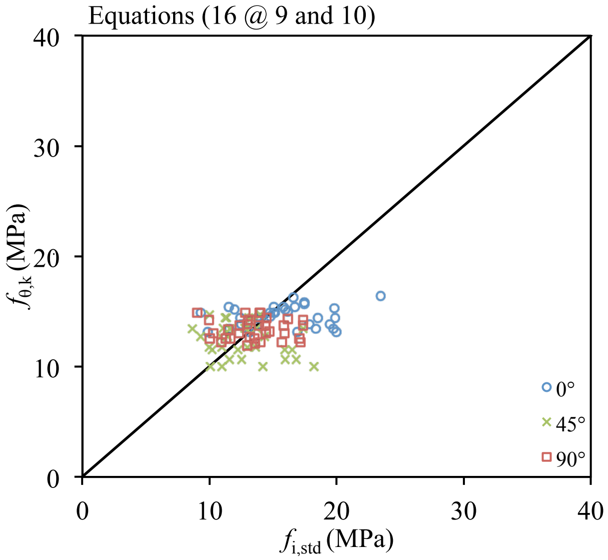


Figure 8: *Comparison of Equation (16) vs. test data adjusted to standard load duration (MPa)*

6.3 KENNEDY *ET AL.* [13] PROPOSED EMBEDMENT EQUATIONS (US CLT APPROACH)

6.3.1 Average values

It was shown by Kennedy *et al.* [13] that the fastener diameter greater than 6 mm was not significantly related to the embedment strength of sawn timber and glued-laminated timber. Similar observations were made from the tests on CLT. Based on the work of Kennedy *et al.* [13] the average embedment strength for loading parallel and perpendicular to grain is expressed as follows:

$$f_{0,avg} = 108 \rho_{12}^{1.7} \tag{17a}$$

$$f_{90,avg} = 70 \rho_{12}^{2.2} \tag{17b}$$

This model presents a fair level of prediction (Figure 9), although, it tends to underestimate the embedment strength of Canadian CLT, as reflected in the statistical errors:

- Pseudo R² = 13.3%%,
- Mean Error = 2.23,
- Root Means Square Error (RMSE) = 4.17, and
- Absolute Percent Error = 16.9%.

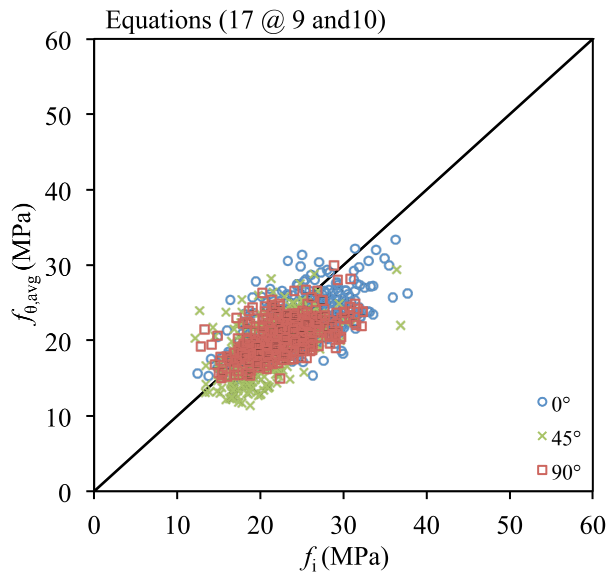


Figure 9: *Comparison of Equation (17) vs. test data (MPa)*

6.3.2 Design values

The model for the design embedment strength can be expressed as follows:

$$f_{0,k} = 42G^{1.7} \tag{18a}$$

$$f_{90,k} = 27G^{2.2} \tag{18b}$$

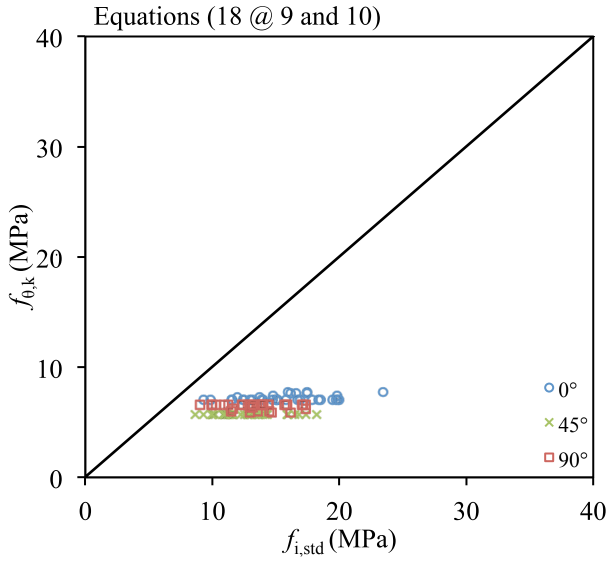


Figure 10: *Comparison of Equation (18) vs. test data adjusted to standard load duration (MPa)*

Comparison of the design values vs. test results adjusted to standard load duration (Figure 10) also shows that the predictions underestimate considerably the dowel embedment strength in Canadian CLT, but it can be improved by applying an appropriate adjustment coefficient.

6.4 EUROPEAN [1] CLT DOWEL EMBEDMENT EQUATIONS

6.4.1 Average values

Average embedment strength equation originates from the studies of Uibel and Blaβ [1]:

$$f_{\theta,avg} = \frac{105.7\rho_{12}^{1.16}\left(1-0.015d\right)}{1.1\sin^2\theta+\cos^2\theta} \tag{19}$$

Comparison of the values predicted with Equation (19) shows a better trend than the other design models; however, the values are overpredicted by 13 MPa, on average, as can be seen in Figure 11 and confirmed with the non-linear regression analysis statistics:

- Pseudo R² = -712%,
- Mean Error = -12.1,
- Root Means Square Error (RMSE) = 13.0 and
- Absolute Percent Error = 34.3%.

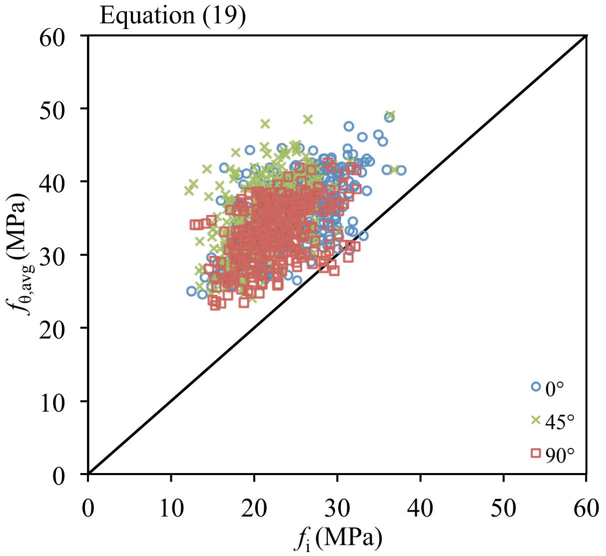


Figure 11: *Comparison of Equation (19) vs. test data (MPa)*

6.4.2 Design values

To convert the European model to the CSA O86 design format the following adjustments were made:

1. Conversion from characteristic density at 12% MC to characteristic density at 15% MC (0.89);
2. Conversion from characteristic density at 15% moisture content to oven-dry characteristic density (1.075);
3. Conversion from characteristic density to mean specific gravity (0.8);
4. Conversion from short term to standard term (0.8).

The European design embedment equation converted to CSA O86 format becomes:

$$f_{\theta,k} = \frac{55G^{1.16}\left(1-0.015d\right)}{1.1\sin^2\theta+\cos^2\theta} \tag{20}$$

Equation (20) over-predicts over 75% of the calculated values relative to the measured ones (Figure 12).

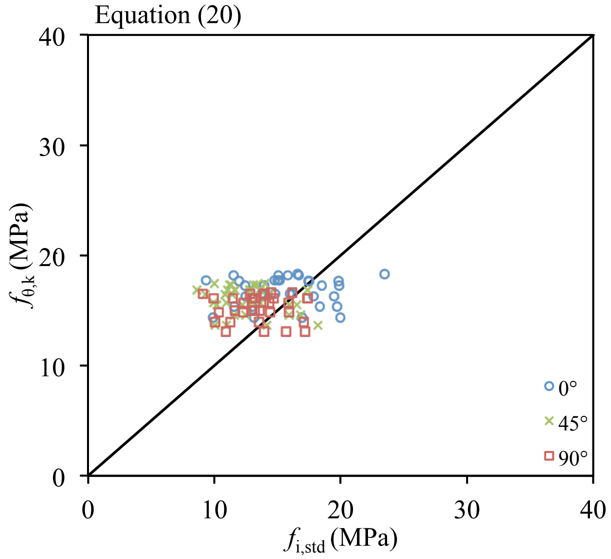


Figure 12: *Comparison of Equation (20) vs. test data adjusted to standard load duration (MPa)*

6.5 NEW CLT DOWEL EMBEDMENT EQUATION

Nonlinear regression analyses were performed to develop an equation for the average dowel embedment strength independent of the panel layup and on the fastener diameter for Canadian CLT. Following that, the model for the design value was derived to represent the 5th percentile value at standard load duration.

6.5.1 Average values

The following model expressed in the format of the Hankinson equation was investigated:

$$f_{\theta,avg} = \frac{\beta_1(\rho_{12}+\beta_2)^{\beta_3}}{\frac{\beta_1}{\beta_4}(\rho_{12}+\beta_2)^{\beta_5-\beta_3}\cdot\sin^2\theta+\cos^2\theta} \tag{21}$$

The optimum coefficients obtained from the statistical analysis are shown in Table 6 and the model can be expressed as follows:

$$f_{\theta,avg} = \frac{80(\rho_{12}-0.12)^{1.11}}{1.07(\rho_{12}-0.12)^{-0.07}\cdot\sin^2\theta+\cos^2\theta} \tag{22}$$

Table 6: *Parameter estimation resulting from nonlinear regression analysis*

Coefficient	Estimate	Std. Error	*t*-value	*p*-value
β_1	80	N/A	N/A	N/A
β_2	-0.12	0.19	-0.67	0.50
β_3	1.11	0.59	1.89	0.06
β_4	75	N/A	N/A	N/A
β_5	1.18	0.93	1.26	0.21

This model provides fair predictions for the average embedment strength of the Canadian CLT products tested. As shown in Figure 12, predictions with Equation (22) present a better fit than Equation (19):

- Pseudo $R^2 = 27.1\%$
- Mean Error = -0.78,
- Root Means Square Error (RMSE) = 3.83, and
- Absolute Percent Error = 12.6%.

However, the CLT specimens present higher variability in mechanical properties than glued-laminated timber.

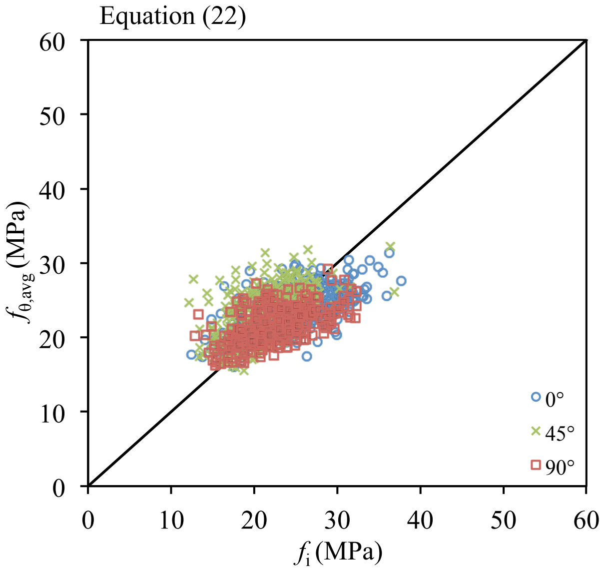


Figure 12: *Comparison of Equation (22) vs. test data (MPa)*

6.5.2 Design values

The design equation for the new embedment strength model was determined by calibrating Equation (22) using the same reduction ratio to the perpendicular and parallel to grain components until the percentage of non-conservative values would not exceed 5% limit. This design equation can be written as follows:

$$f_{\theta,avg} = \frac{41(\rho_{12}-0.12)^{1.11}}{1.07(\rho_{12}-0.12)^{-0.07}\cdot\sin^2\theta+\cos^2\theta} \tag{23}$$

As shown in Figure 13, this equation predicts the embedment strength conservatively with no more than 5%

of calculated values exceeding the test results adjusted to standard load duration. The large dispersion of the test values is explained by the large dispersion of the relative density of the tested products (from 0.35 to 0.55) while the calculation was done using G = 0.42 (according to CSA O86 for Spruce-pine-fir species group).

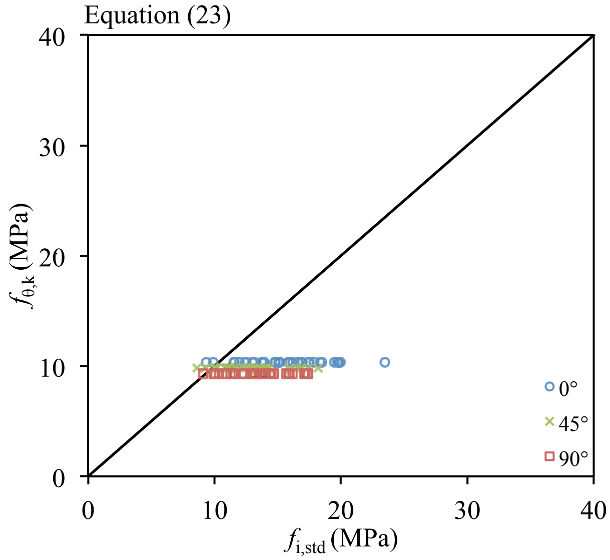


Figure 13: *Comparison of Equation (23) vs. test data adjusted to standard load duration (MPa)*

7 CONCLUSIONS

The advancement of CLT structural panels on the Canadian market requires studies on the mechanical performance of connections with Canadian made CLT. This research project was focussed on the withdrawal resistance and the dowel embedment strength of threaded fasteners in CLT from two Canadian suppliers.

The withdrawal experiments included 360 tests with lag screws and 120 tests with self-drilling screws with diameters ranging from 6.0 mm to 19.1 mm. Four design equations from Canada, US and Europe were compared with the measured peak withdrawal loads. Based on statistics, the NDS wood screw withdrawal equation showed the best fit. However, for more conservative predictions, harmonization and convenience of design for threaded fasteners of all sizes, CSA O86 wood screw withdrawal equation may also be considered.

To determine the dowel embedment strength of CLT, approximately 720 embedment tests were performed with lag screws and 360 tests with self-drilling screws with diameters ranging from 6.0 mm to 19.1 mm. The test data were used to verify the US CLT Handbook [7] approach, which takes into account bearing length of the fastener in the cross layer. Three design models (Canadian, American, and Kennedy *et al.* [13]) were used to describe the embedment strength of parallel and perpendicular layers. An alternative approach, independent of the panel layup was also verified using a European [1] equation and those developed in this study. The two approaches have their advantages and disadvantages and show various levels of fitness with the test data. However, the precision of the design equations is jeopardized by the high level of variability of the relative density of the products (0.35 to 0.55). In this situation, the choice of the design equation would rather depend on the strategy chosen by the CSA O86 technical committee. Equation (18) would be suitable for adoption with the US CLT Handbook approach (Eq. 9 and 10). Alternatively, Equation (23) may be suitable, as it is independent of the panel layup and the fastener diameter.

Both dowel embedment and withdrawal design models for CLT will be proposed to the CSA O86 technical committee for potential inclusion in the next edition of the standard.

ACKNOWLEDGEMENT

Acknowledgements are gratefully made to FPInnovations, and all suppliers of wood products. The authors also express their gratitude to all interns and technicians who participated to the project including l'École Supérieur du Bois, Université Paris-Est Marne-la-Vallée, Université Laval and FPInnovations.

REFERENCES

[1] Uibel, T. and H. J. Blaβ. 2006. Load carrying capacity of joints with dowel type fasteners in solid wood panels. Proceedings of the CIB Working Commission W18–Timber Structures. 39th meeting, Florence, Italy, August 2006.

[2] Uibel, T. and H. J. Blaβ. 2007. Edge joints with dowel type fasteners in cross-laminated timber. Proceedings of the CIB Working Commission W18–Timber Structures. 40th meeting, Bled, Slovenia, August 2007.

[3] Follesa M., M. Brunetti, and R. Cornacchini. 2010. Mechanical in-plane joints between cross-laminated timber panels. WCTE 2010 Proceedings. Riva del Garda, Italy.

[4] Muñoz W., M. Mohammad and S. Gagnon. 2010. Lateral and withdrawal resistance of typical CLT connections. WCTE 2010 Proceedings. Riva del Garda, Italy.

[5] Joyce T. and I. Smith. 2011. Mechanical behaviour of in-plane shear connections between CLT wall panels. Proceedings of the CIB Working Commission W18–Timber Structures. 44th meeting, Alghero.

[6] FPInnovations. 2011. *CLT Handbook: Cross-laminated timber*. Canadian Edition. Special Publication SP-528E. Edited by S. Gagnon and C. Privu. FPInnovations, Quebec, QC, Canada.

[7] FPInnovations and BSLC. 2013. *CLT Handbook: Cross-laminated timber*. US Edition. Special Publication SP-529E. Edited by E. Karacabeyli and B. Douglas. FPInnovations, Pointe-Claire, QC, Canada.

[8] Kennedy, S. 2014. Withdrawal and embedding resistance of fasteners in timber and CLT panels. Master's Thesis. Université Laval, Quebec, CA.

[9] CSA Standards. 2009. CSA O86-09 Engineering design in wood, Canadian Standards Association. Mississauga, ON, Canada.

[10] EN 1382: 1999. Timber structures – Test methods – Withdrawal capacity of timber fasteners.

[11] Kennedy, S., A. Salenikovich, W. Munoz, and M. Mohammad. 2014. Design equation for withdrawal resistance of threaded fasteners in the Canadian timber design code. WCTE 2014 Proceedings, Québec, QC, Canada.

[12] American Society for Testing and Materials (ASTM). 2007. D5764-97a (2007). Standard test method for evaluating dowel-bearing strength of wood and wood-based products. ASTM, West Conshohocken, PA.

[13] Kennedy, S., A. Salenikovich, W. Munoz, M. Mohammad, and D. Sattler. 2014. Design equation for embedment strength of wood for threaded fasteners in the Canadian timber design code. WCTE 2014 Proceedings, Québec, QC, Canada.

[14] ANSI/AWC. 2012. National design specification for wood construction. NDS-2012. American Wood Council. Washington, D.C., USA.

[15] Canadian Wood Council (CWC). 2010. Wood design manual: The complete reference for wood design in Canada. CWC. Ottawa, ON, Canada.

[16] McLain, T.E. 1997. Design axial withdrawal strength from wood: I. Wood screws and lag screws. Forest Prod. J. Vol. 47, No. 5, pp. 77-84.

[17] Schabengerber, O. and F.J. Pierce. 2002. Contemporary statistical models for the plant and soil sciences. USA: CRC Press LLC, 520p.