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DESIGN EQUATION FOR WITHDRAWAL RESISTANCE OF THREADED FASTENERS IN THE CANADIAN TIMBER DESIGN CODE

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ABSTRACT: The 2009 edition of Canadian standard for engineering design in wood (CSA O86) [1] provides two different design equations for wood screws and lag screws, which are, in turn, different from those in the American "National Design Specification for Wood Construction" (NDS) [2] and from other overseas codes. The purpose of this study was to evaluate the withdrawal resistance of various types of threaded fasteners in timber and to propose a harmonized/unified design equation for the Canadian timber design code.

KEYWORDS: Lag screws, wood screws, self-drilling screws, glued laminated timber, sawn timber

1 INTRODUCTION

Threaded type fasteners used in structural wood connections are chosen in different fields for their pull out resistance, among other advantages such as the ease of installation. Withdrawal resistance for lag screws, and wood screws has been studied and codified in various ways in the past. However, the advancement of wood engineered products, such as glue-laminated timber (glulam) and cross-laminated timber (CLT), and the introduction of new threaded fasteners, such as self-drilling screws, required revisiting the formulas for traditional fasteners and additional testing with those new products.

The 2009 version of the Canadian standard for engineering design in wood (CSA O86) [1] provides two different design equations for wood screws and lag screws, which are, in turn, different from those in the American "National Design Specification for Wood Construction" (NDS) [2] and from the overseas codes. Although the unit withdrawal resistance is usually associated with the fastener diameter and density (or relative density) of the wood product in a form of empirical equations, CSA O86-09 does not provide such equation for lag screws in explicit form. Instead, it provides a table for the four major wood species groups of visually graded lumber produced in Canada. Since the relative density of glulam and other engineered wood products may be different from that used in derivation of the table, it is assumed that withdrawal resistance would differ. For high capacity connections with large diameter fasteners, the errors in estimation of the withdrawal resistance may become significant. Another motivation for this study is also driven by the discrepancy in the predictions of the withdrawal resistance for fasteners of the same diameter obtained using different equations.

The purpose of this project is to verify the existing withdrawal resistance equations for threaded fasteners using the newly obtained test data combined with those previously published and to offer a single design equation for withdrawal resistance of all threaded fasteners used with Canadian wood engineered products.

2 BACKGROUND

The NDS design values for withdrawal of wood screws originate from the data collected by Fairchild [3] as early as 1926 when over 10,000 wood screws were tested in wood of seven species. Effect of lead holes, screw lubrication and shape and dimensions were considered in that study. In 1960, Johnson [4] extended studies on wood screws and reported the impact of lead holes, test speed and size of screws on withdrawal strength of various western wood species. Later, Wilkinson & Laatsch [5] reported a better performance of tapping screws compared to common wood screws.

The NDS design equation for lag screws originates from the work of Newlin and Gahagan [6] in 1938. They tested 233 fasteners of different diameters in five wood species to evaluate the impact of lead hole and fastener diameter, and penetration length on withdrawal strength of lag screws. In the 1980s, the CSA O86 technical committee adopted a modified version of the NDS [2] design model for the withdrawal strength of lag screws and presented it in a form of a table of values for visually graded lumber. In 1997, McLain [7] expanded the database using tests conducted by various American researchers and proposed

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new equations based on nonlinear regression analysis for wood screws and lag screws. In 2009, the McLain's equation for wood screws was adopted in CSA O86 [1].

More recently, Gehloff [8], Abukari *et al.* [9], and Baek *et al.* [10] conducted independent investigations on the withdrawal resistance of self-drilling screws.

3 MATERIALS

3.1 FASTENERS

The experimental program conducted jointly at FPInnovations, Laval University [11] and at McGill University ([9], [12]), included withdrawal tests on 360 lag screws and 1760 self-drilling screws. 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 producers. 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.

Table 1: *Dimensions of lag screws*

Fastener diameter (mm/in.)	Length / threaded length (mm)	Lead hole diameter (mm)	Penetration: Sawn timber (mm)	Penetration: Glulam (mm)
6.35	55/35	4.39	32	32
1/4	125/90		82	51
7.94	75/55	5.56	51	51
5/16	155/105		100	62
9.53	100/55	6.75	55	55
3/8	205/135		131	79
12.7	130/75	9.13	70	70
1/2	255/175		170	133
15.9	155/110	11.9	100	100
5/8	305/165		155	155
19.1	155/110	14.3	102	102
3/4	305/155		146	146

Table 2: *Dimensions of self-drilling screws*

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

3.2 WOOD PRODUCTS

Sawn timber and glulam products manufactured in Quebec and British Columbia provinces were used in this project. These are sawn Douglas-fir timber, Black spruce (*Picea mariana*) glulam, Spruce-pine-fir glulam, and Douglas-fir glulam. All specimens were conditioned at standard ambient environment (65 ± 5% of relative humidity and 20 ± 2°C temperature) prior to testing.

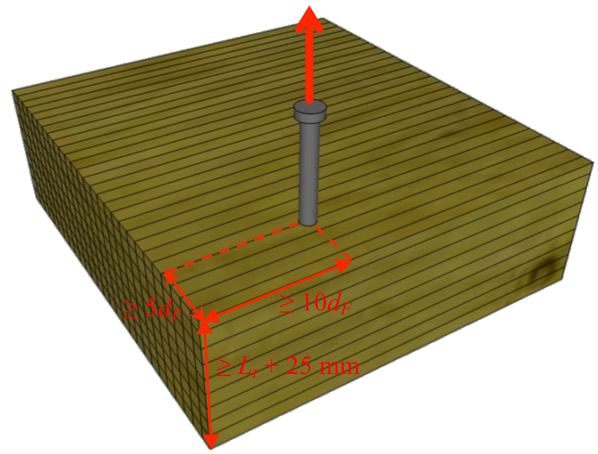

Figure 2: *Specimen for withdrawal of threaded fasteners*

4 METHODOLOGY

The fasteners were inserted in wood specimens for perpendicular to grain withdrawal, in accordance with the minimum end and edge distance requirements of the European standard EN 1382 [13], i.e., at $5d_F$ and $10d_F$ in transverse and longitudinal directions, respectively (see Figure 2). The lag screws and 12-mm diameter self-drilling screws were installed into lead holes, which were predrilled to 70% of the nominal fastener diameter (d_F) in accordance with the CSA O86 requirements. Newlin and Gahagan [6] also recommended the lead holes with 70% of d_F to achieve the optimum withdrawal resistance.

Baek *et al.* [10] demonstrated that withdrawal resistance of a threaded fastener was greater when the smooth shank portion or a part of it was inserted into wood. Therefore for conservatism, only the threaded portion of fasteners was inserted into specimens in our study. The penetration depth of lag screws in glulam of higher density was less than in sawn timber (see Table 1) to avoid rupture of the fastener shank in tension. As illustrated in Figure 1, a wood cushion of at least one inch was maintained between the tip of the fastener and the bottom surface of the wood block. The insertion of the fasteners was performed using pneumatic tools and all tests were performed within 24 hours after the insertion.

Each specimen was clamped to the base of the test machine, and fasteners were pulled out with a hydraulic actuator at a constant cross head speed of 1 mm/min and 0.5 mm/min for lag screws and self-drilling screws, respectively. The test was stopped after the resistance decreased to 80% of the peak load. After testing, small samples were cut out to determine local relative density and moisture content of each specimen.

5 DATABASE

5.1 SAWN TIMBER

The database collected for sawn timber is composed of experimental results from the following studies:

1. Kennedy (2013) [11],
2. Newlin and Gahagan (1938) [6], and
3. Baek (2012) [10].

As discussed in Section 3, Kennedy [11] studied lag screws of six diameters in Douglas-fir. Newlin and Gahagan [6] tested lag screws of seven diameters in five wood species. Baek *et al*. [10] tested three types of self-drilling screws of 6.25mm diameter in sugi wood from Japan. The number of tests in each study is given in Table 3.

Table 3: *Fasteners under study in sawn timber database*

Fastener	Source	Diameter mm(in.)	Species	*G*	Number of tests
LS	Kennedy (2014)[1]	6.4(1/4) 7.9(5/16) 9.5(3/8) 12.7(1/2) 15.9(5/8) 19.1(3/4)	D-Fir	0.46 to 0.52	120
LS	Newlin and Gahagan (1938)[2]	7.9(5/16) 9.5(3/8) 12.7(1/2) 15.9(5/8) 19.1(3/4) 22.2(7/8) 25.4(1)	N. white pine, redwood, Douglas-fir, yellow pine, white oak	0.36 to 0.68	233
SDS	Baek *et al.* (2012)[2]	6.25	Sugi	0.40 to 0.42	200
					553

5.2 GLULAM PRODUCTS

The database for glulam is composed of experimental results from the following studies:

1. Kennedy (2014) [11],
2. Abukari *et al*. (2012) [9],
3. Abukari (2012) [12],
4. Gehloff (2011) [8], and
5. Simpson Strong Tie (2006) [14].

Kennedy [11] and Abukari *et al.* [12] covered lag screws tested in three Canadian glulam products (see Section 3). Abukari [9] examined self-drilling screws of 6, 8, 10 and 12-mm diameters in the same three Canadian glulam products. Gehloff [8] investigated self-drilling screws of 6, 8, and 10-mm diameters in three glulam products: Douglas-fir, Spruce-pine and Hem-fir. Simpson strong-Tie [14] tested 6.4-mm self-drilling lag screws in Douglas-fir. The number of tests in each study is given in Table 4.

Table 4: *Fasteners under study in glulam database*

Fastener	Source	Diameter mm (in.)	Specie	*G*	Number of tests
LS	Kennedy (2014)[1] and Abukari (2012)[1]	6.4(1/4) 7.9(5/16) 9.5(3/8) 12.7(1/2) 15.9(5/8) 19.1(3/4)	Spruce-Pine-Fir glulam Spruce-Pine glulam D-Fir glulam	0.42 to 0.52	360
SDS	Abukari *et al.* (2012)[1]	6 8 10 12	D-Fir glulam Spruce-Pine glulam	0.42 to 0.52	1740
SDS	Gehloff (2011)[1]	6 8 10	D-Fir glulam Spruce-pine glulam Hem-fir glulam	0.42 to 0.49	360
SDS	Simpson Strong-Tie (2006)[1,3]	6.4(1/4)	D-Fir glulam	0.45 to 0.48	130
					2590

Notes to Tables 3 and 4:
[1] All test values and statistics are available
[2] Only average values and statistics are available
[3] Same data set is used in both comparisons, because SDS1/4" screws may be assigned to either category of fasteners.

6 RESULTS

Experimental data on withdrawal resistance of threaded fasteners compiled in the database were compared with five models:

1. CSA O86-09 equation for wood-screw;
2. NDS-2012 equation for lag-screws;
3. NDS-2012 equation for wood-screws;
4. McLain (1997) [7] equation for lag-screws; and
5. MHBH (1982) [15] equation for lag screws (basis for CSA O86-09 lag screw basic withdrawal resistance values).

The evaluation of the models was made in two steps. First, individual experimental data were compared against the values predicted for the average withdrawal resistance at 5-min load duration using the measured oven-dry relative density. Then, the 5th percentile values at 75% confidence (assuming normal distribution, according to ASTM D2915 [17]) obtained per test series were adjusted for the standard load duration (multiplied by 0.8 according to the CSA O86 Commentary [16]) and compared with the withdrawal resistance values predicted by various design equations (characteristic values at standard load duration) using the mean oven-dry relative density for the species or species group as per CSA O86. It should be noted that the American design equations were adjusted to represent the 5th percentile lower tolerance limit. Measured variation was applied to the design values from this research, while a variation of 15% was assumed for the experimental values for which the variability data were not available.

The following subsections discuss results of comparisons for each model using the following notation:

- $P_{rw,\,\mathrm{avg}}$ = average withdrawal resistance (N);
- P_{rw} = specific withdrawal resistance (N);
- d_F = fastener nominal diameter (mm);
- 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 and the percentage of non-conservative values for each design equation are presented in Section 6.6.

6.1 CSA O86-09 equation for wood-screws

6.1.1 Average values

Withdrawal resistance equation for wood screws in CSA O86-09 standard originates from the model proposed by McLain [7]:

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

Figure 3 shows relatively good correlation between the values predicted with equation (1) and experimental data for both types of products. However, glulam products show higher experimental values than those of sawn timber, especially for larger diameter fasteners. In general, the McLain's model for wood screws predicts very well the withdrawal resistance for small diameter fasteners and tends to slightly underestimate glulam values as the diameter increases.

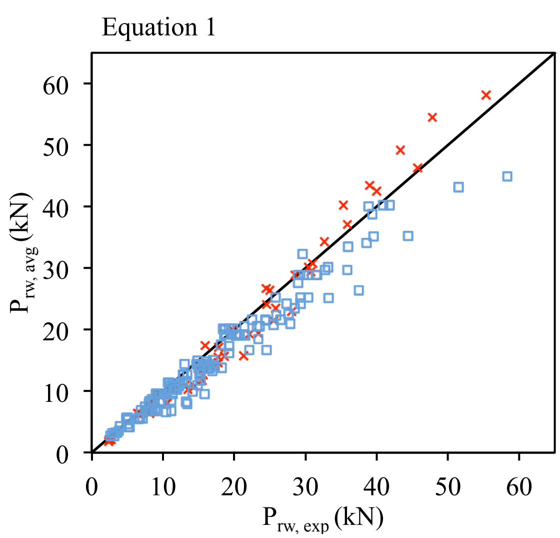

Figure 3: *Comparison of Equation (1) predicted values with mean test values for sawn timber (×) and glulam (□)*

6.1.2 Design withdrawal resistance values

Basic withdrawal resistance values for wood screws in CSA O86-09 are based on the McLain's model [7] (Equation 1), and after adjustment to standard load duration are calculated as follows:

$$P_{rw} = 59\ d_F^{0.82}\ G^{1.77}\ L_t \tag{2}$$

As shown in Figure 4, Equation (2) predicts the specified values within acceptable safety limit.

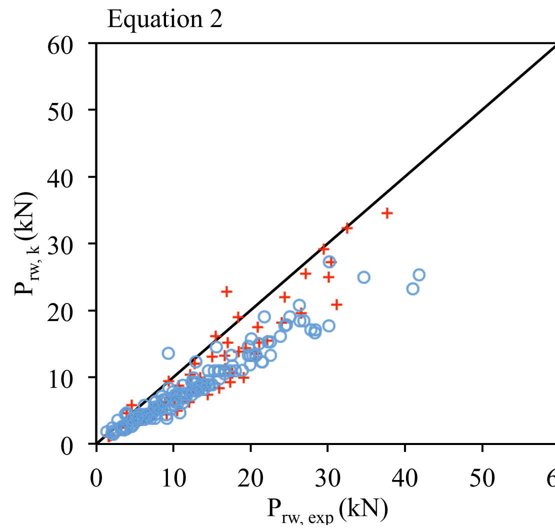

Figure 4: *Comparison of Equation (2) predicted values with 5th%-tile test values for sawn timber (+) and glulam (o) adjusted to standard load duration*

6.2 NDS-2012 equation for lag screws

6.2.1 Average values

The NDS [2] equation for withdrawal of lag screws is based on the work of Newlin and Gahagan [6] who determined the equation for the average withdrawal strength as follows (in SI units):

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

As shown in Figure 5 and Section 6.6, the predictions from Equation (3) produce the best fit with the mean test values. It can be seen that this equation seems to predict equally well the withdrawal resistance for fasteners of all tested diameters, from 6 to 19 mm.

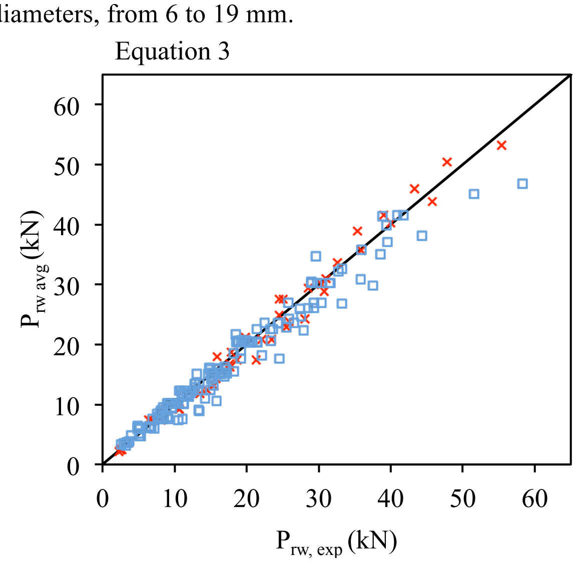

Figure 5: *Comparison of Equation (3) predicted values with mean test values for sawn timber (×) and glulam (□)*

6.2.2 Design withdrawal resistance values

Equation (3) can be converted to determine design withdrawal resistance values for fasteners in the CSA O86 format at standard load duration as follows:

$$P_{rw} = 57\ d_F^{\,0.75}\ G^{1.5}\ L_t \qquad (4)$$

Figure 6 presents the comparison between predicted values from Equation (4) and the experimental data.

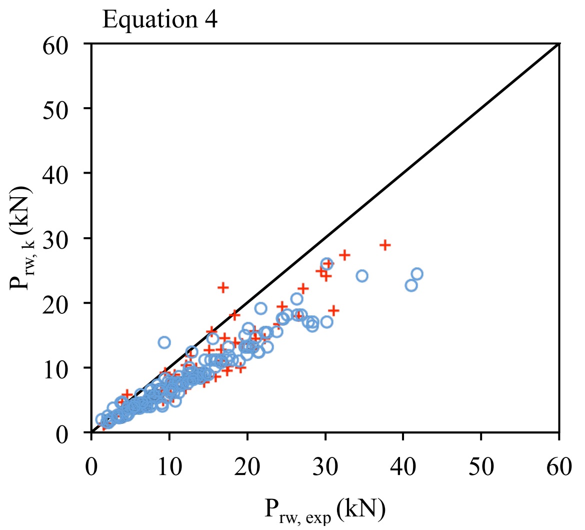

Figure 6: *Comparison of Equation (4) predicted values with 5th%-tile test values for sawn timber (+) and glulam (o) adjusted to standard load duration*

6.3 NDS-2012 equation for wood screws

6.3.1 Average values

The NDS [2] equation for withdrawal of wood screws is based on the work of Fairchild [3] who determined the equation for the average withdrawal strength as follows (in SI units):

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

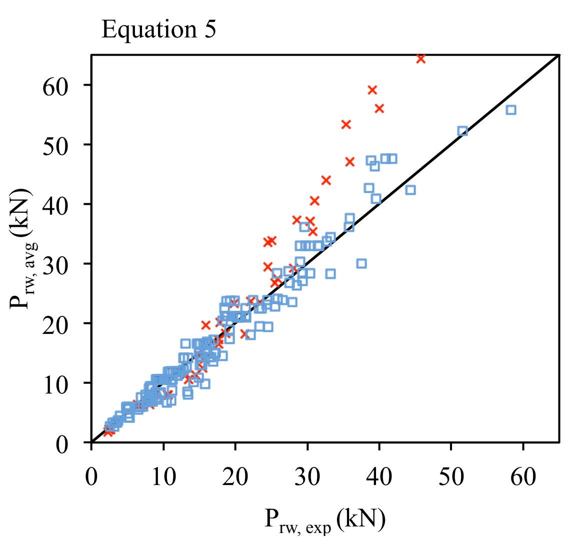

Figure 7: *Comparison of Equation (5) predicted values with mean test values for sawn timber (x) and glulam (□)*

6.3.2 Design withdrawal resistance values

Equation (5) can be converted to determine design withdrawal resistance values for fasteners in the CSA O86 format at standard load duration as follows:

$$P_{rw} = 40\ d_F\ G^2\ L_t \qquad (6)$$

Figure 8 presents the comparison between predicted values from Equation (6) and the experimental data. It tends to be less accurate with predictions often too high for large diameter fasteners, especially in sawn timber products.

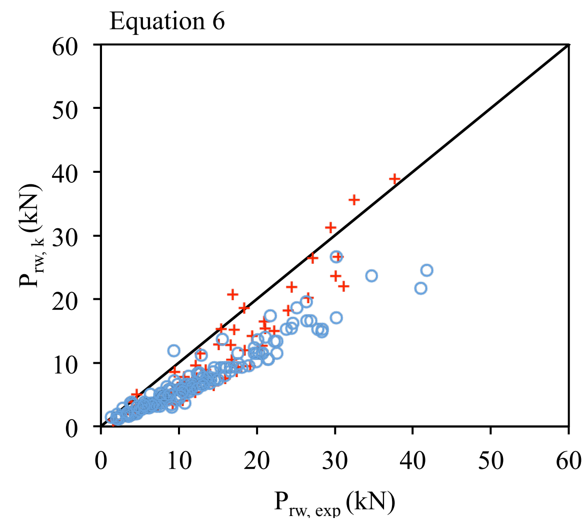

Figure 8: *Comparison of Equation (6) predicted values with 5th%-tile test values for sawn timber (+) and glulam (o) adjusted to standard load duration*

6.4 McLain [7] equation for lag-screws

6.4.1 Average values

The following equation was proposed by McLain [7] for the average withdrawal strength of lag screws (in SI units):

$$P_{rw,avg} = 165\ d_F^{\,0.61}\ G_0^{\,1.35}\ L_t \qquad (7)$$

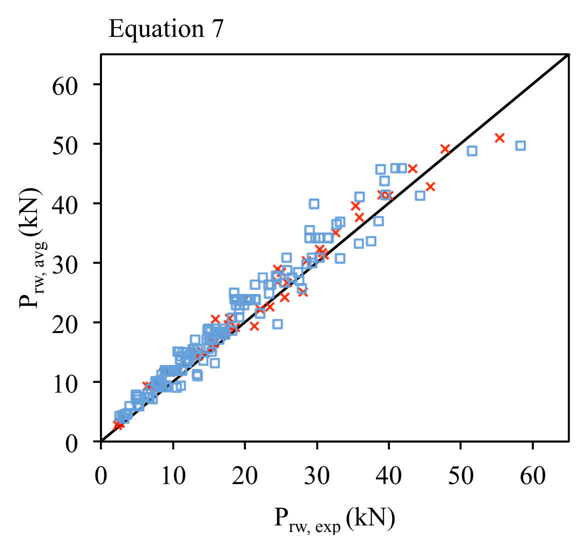

Figure 9: *Comparison Equation (7) predicted values with mean test values for sawn timber (x) and glulam (□)*

Figure 9 shows that Equation (7) has a good correlation when compared to measured resistance. The individual regressions of either sawn timber or glulam products present almost the same slope.

6.4.2 Design withdrawal resistance values

Equation (7) can be converted to determine basic withdrawal resistance values for fasteners in the CSA O86 format at standard load duration as follows:

$$P_{rw} = 74\ d_F^{0.61}\ G^{1.35}\ L_t \qquad (8)$$

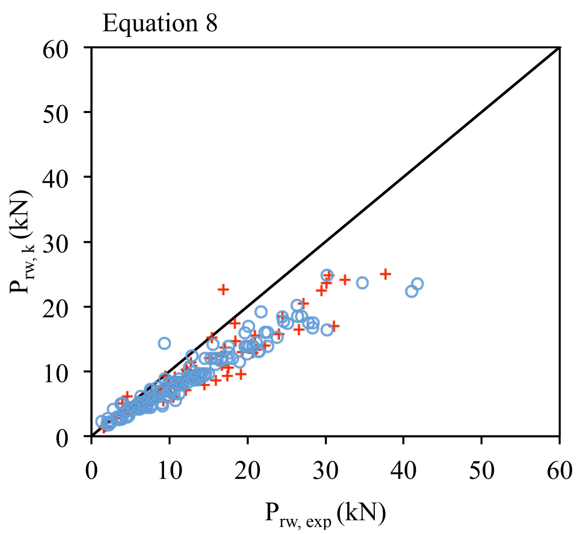

Figure 10: *Comparison of Equation (8) predicted values with 5th%-tile test values for sawn timber (+) and glulam (o) adjusted to standard load duration*

As shown in Figure 11, Equation (10) predictions are the less accurate from a safety point of view. More than one third of the predictions are non-conservative and most are associated with small diameter fasteners.

6.5 MHBH [15] equation for lag screws

6.5.1 Average values

When the CSA O86 design rules were developed for lag screw withdrawal, MHBH [15] considered equation proposed by Newlin and Gahagan [6] (in SI units):

$$P_{rw,\ avg} = 110\ d_F^{0.75}\ G_0^{1.5}\ L_t \qquad (9)$$

Figure 12 shows that this equation performs adequately when predicted values are compared to experimental data, same as for Equation (3).

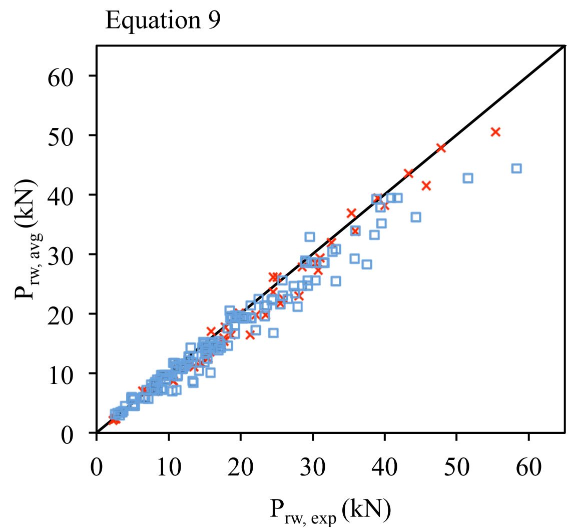

Figure 11: *Comparison of Equation (9) predicted values with mean test values for sawn timber (x) and glulam (□)*

6.5.2 Design withdrawal resistance values

Equation (9) was converted by Morrison *et al.* [15] to determine basic withdrawal resistance values for lag screws in the CSA O86 format at standard load duration as follows:

$$P_{rw} = (82\ d_F^{0.75}\ G^{1.5} - 56)\ L_t \qquad (10)$$

In 1984, results predicted by this equation were included in the CSA O86 standard in the form of a table using the values of relative density that were used at that time for visually graded lumber. It is important to note that the tabulated values do not correspond to those that would be calculated using the values of relative density used today.

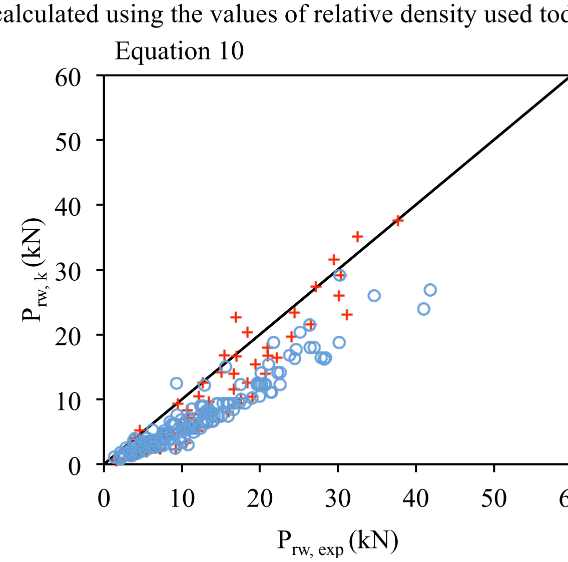

Figure 12: *Comparison of Equation (10) predicted values with 5th%-tile test values for sawn timber (+) and glulam (o) adjusted to standard load duration*

Figure 12 presents a comparison between the experimental data and the values predicted with Equation (10) using mean values of relative density used in the CSA O86-09. The equation tends to overestimate the resistance for larger diameters in sawn timber products.

6.6 Statistical comparison of design equations

Non-linear regression analysis was performed for the average values. The following statistical parameters were estimated for each equation predicting average values:

Mean error:

$$\bar{E} = \frac{\sum\left(y_i - \hat{y}_i\right)}{n} \tag{11}$$

Root mean square error:

$$RMSE = \sqrt{\frac{\sum\left(y_i - \hat{y}_i\right)^2}{n}} \tag{12}$$

Absolute percentage error:

$$RE(\%) = \frac{\sum\left(\frac{\left|y_i - \hat{y}_i\right|}{\hat{y}_i}\right)}{n} \times 100 \tag{13}$$

Moreover, since the statistical analysis was performed on non-linear models, Schabengerber [18] recommends calculating the goodness-of-fit of the model with the following pseudo R^2 equation:

Pseudo R^2:

$$R^2 = 1 - \frac{SSR}{SST_m} \tag{14}$$

where,

$$SSR = \sum\left(y_i - \hat{y}_i\right)^2 \tag{15}$$

$$SST_m = \sum\left(\bar{y} - y_i\right)^2 \tag{16}$$

$\bar{y}$ = mean measured stress

y_i = individual measured stress

$\hat{y}_i$ = individual predicted stress

Table 5 summarises these parameters. It can be seen that Equations (5) and (7), on average, overestimate, while Equations (1), (3) and (9) slightly underestimate the resistance. All of the equations, except Equation (3), give notable good fit to experimental data with RMSE less than 3.0 kN and pseudo R^2 value above 90%. It should be noted that Equation (3) shows overall the best fit to the experimental data and also has exponents rounded to two significant figures.

Table 5: *Statistical comparison of equations for mean values of withdrawal resistance*

Design Method Equations	Mean Error	RMSE	Abs. % Error	Pseudo R²
(1)	1.57	2.99	14.2%	92.8%
(3)	0.58	2.16	9.00%	96.3%
(5)	-1.05	5.12	13.4%	79.4%
(7)	-1.77	2.83	13.6%	93.7%
(9)	1.50	2.68	11.4%	94.3%

7 PROPOSED DESIGN EQUATION

Based on the analysis of the experimental database and statistical comparisons with five existing models for withdrawal resistance of threaded fasteners with diameters from 6 to 19 mm, the authors propose the adoption of Equation (2), which is currently used in CSA O86 for wood screws, as the withdrawal design model for all threaded fasteners in the new edition of the standard. It shows to be reasonably conservative and it allows harmonization of design of all threaded fasteners in withdrawal. Table 7 and Figure 13 show the impact of the proposed change for lag screws in visually graded sawn timber.

8 CONCLUSION

The lack of design equation for withdrawal of lag screws in glulam, discrepancies between design values obtained for lag screws and wood screws of the same diameters as well as lack of information for self-drilling screws in the Canadian standard for engineering design in wood (CSA O86) [1] served as motivation for this project. An experimental database included (n=2580) test results from recent studies conducted in Canada ([8], [9], [11], and [12]) and (n=563) results from the past studies ([6], [10], and [14]). Analysis of five design models showed that all of them predicted the average withdrawal resistance of threaded fasteners of 6 mm in diameter and greater reasonably well. Among those, Equation (3) serving as a basis for design of lag screws in the NDS [2] appeared to be the most precise according to the statistical parameters. However, Equation (2) used for design of wood screws in CSA O86 is proposed for adoption in the next edition of the Canadian timber design code, for the sake of harmonization of design for all threaded fasteners.

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Table 6: *Comparison of basic withdrawal resistance from CSA O86-09 lag screw (LS) table and wood screw (WS) equation*

Diameter mm (in.)		Northern species (SG=0.35)			Spruce-Pine-Fir (SG=0.42)			Spruce-Pine (SG = 0.46)			Douglas-Fir (SG=0.49)		
		LS (N/mm)	WS (N/mm)	Diff. (%)	LS (N/mm)	WS (N/mm)	Diff. (%)	LS (N/mm)	WS (N/mm)	Diff. (%)	LS (N/mm)	WS (N/mm)	Diff. (%)
6.4	(1/4)	27	42.2	56.2	31	58.2	87.8	37	68.4	84.8	74	76.5	3.4
7.9	(5/16)	42	50.1	19.3	42	69.2	64.7	55	81.3	47.8	97	90.9	-6.3
9.5	(3/8)	58	58.3	0.5	61	80.5	31.9	70	94.6	35.1	120	105.7	-11.9
11.1	(7/16)	70	66.2	-5.4	75	91.4	21.9	86	107.4	24.9	140	120.1	-14.2
12.7	(1/2)	84	74.0	-12.0	91	102.1	12.2	100	120.0	20.0	170	134.2	-21.1
15.9	(5/8)	110	88.9	-19.2	120	122.8	2.3	130	144.2	11.0	200	161.3	-19.3
19.1	(3/4)	130	103.3	-20.5	140	142.7	1.9	150	167.6	11.8	240	187.5	-21.9
22.2	(7/8)	150	116.9	-22.1	170	161.4	-5.0	180	189.6	5.4	280	212.1	-24.3
25.4	(1)	180	130.6	-27.5	190	180.3	-5.1	200	211.8	5.9	310	236.8	-23.6

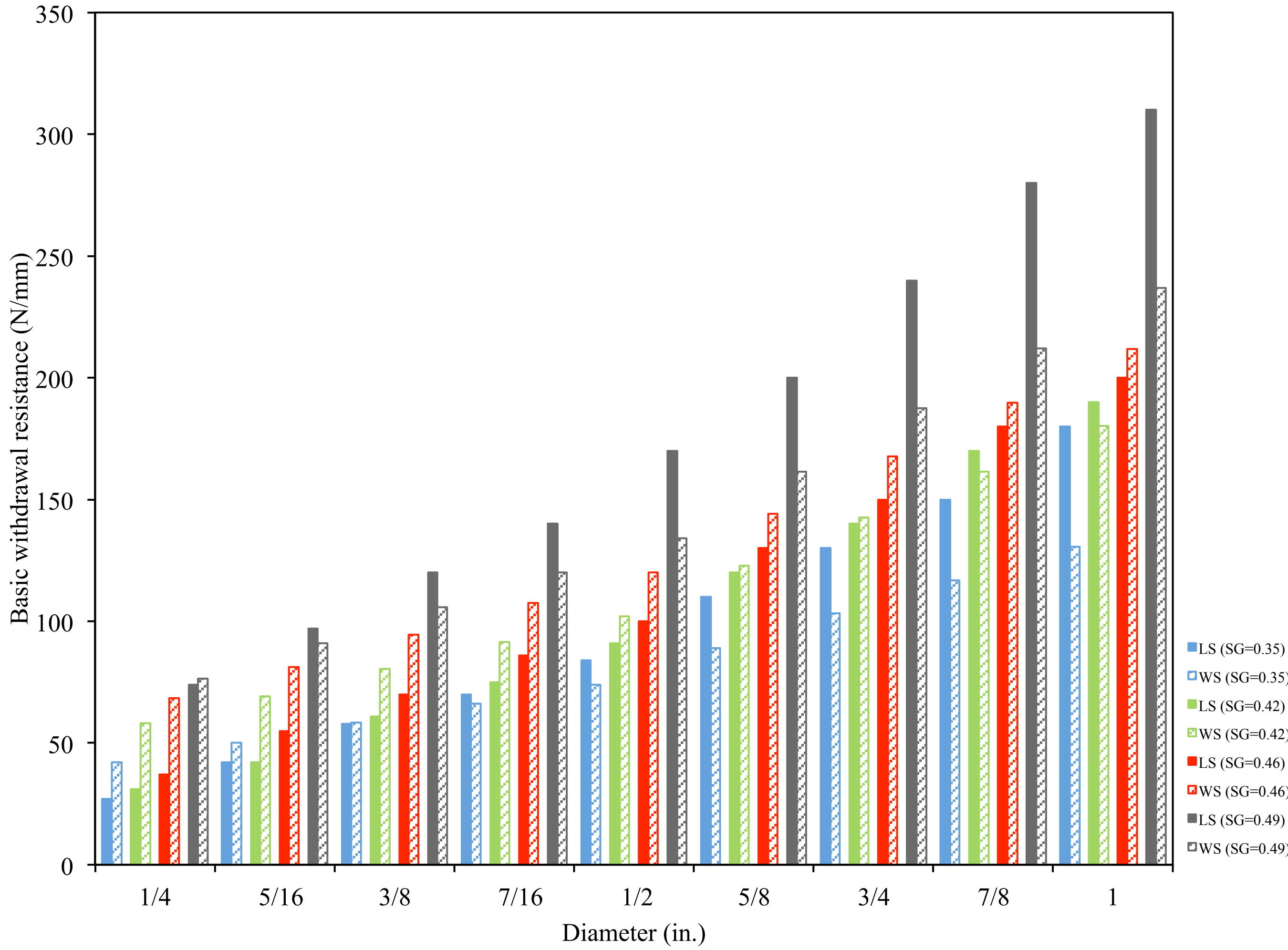

Figure 13: *Comparison of basic withdrawal resistance from CSA O86-09 lag screw (LS) table and wood screw (WS) equation*

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