Design Equations for Embedment Strength of Wood for Threaded Fasteners in the Canadian Timber Design Code

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1. INTRODUCTION

1.1 MOTIVATION

In the 1990s, the Canadian standard for engineering design in wood (CSA O86) adopted the European yield model for timber connections with dowel-type fasteners. It takes into account the yielding resistance of the fastener, the assembly's geometry and the embedment strength of wood. The latter is expressed as a function of the relative density of wood and diameter of the fastener. According to the design equations, the embedment strength increases in direct proportion with the relative density and decreases for the fasteners of greater diameters. In Canada, the embedment strength of wood is based on the work of Smith *et al.* (1988) and is expressed as follows, for parallel (P) and perpendicular (Q) to grain loading:

$$f_{P,k} = 50G(1-0.01d_F) \qquad f_{Q,k} = 22G(1-0.01d_F)$$

In the US, the National Design Specification for Wood Construction (NDS) indicates no relationship between the diameter and the embedment strength for loads parallel to the grain. Other researches also observed the weak relationship between the embedment strength calculated as the 5% diameter offset and the diameter for other loading angles.

1.2 OBJECTIVE

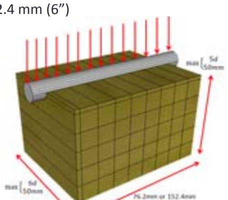
The goal of this study is to verify the influence of the fastener diameter on the embedment strength of threaded dowel-type fasteners of diameters 6.4 mm and greater.

2. BACKGROUND

The earliest studies on the embedment strength conducted in 1932 by Trayer (1932) established the relationship between bearing strength and length to diameter ratios (l/d) for bolts. In 1949, Johansen (1949) presented a yield model theory, which, according to Soltis (1986), was best to describe the Trayer's experimental observations. This model was then modified by Larsen *et al*. (1986) and became the well-known European yield model (EYM). In the 1980s, several studies were carried out in Europe and in North America for potential adoption of the EYM for design of dowel-type connections. As a result in Canada, the embedment strength equations based on the work of Smith *et al.* (1988) were developed. The Eurocode 5 (2004) equations for fasteners installed into wood with pre-drilled holes are equivalent to those in CSA O86 for parallel-to-grain direction and different for fasteners of diameters greater than 6 mm loaded perpendicular-to-grain. In the US timber design code (NDS), the embedment strength is called "dowel bearing strength" and its values are based on the work of Wilkinson (1991) who proposed equations that are independent of the fastener diameter in the parallel-to-grain direction. In 2002, Sawata and Yasumura showed that it was also true for the embedment strength perpendicular to grain when it is measured as 5%-diameter offset load. Later, Chui *et al.* (2006) reported test results for threaded fasteners of small diameters, which were different from those currently adopted in the design codes due to the inclusion of the axial tensioning effect.

3. METHODOLOGY

- Test Standard: ASTM D5764 Half-Hole Test Method
- Test Conditions: 65% ± 5% HR and 20˚C ± 3°C
- Fastener Insertion: Perpendicular to plane side
- Load Application: 0°, 45° and 90° to the grain
- Embedment length: 76.2 mm (3") and 152.4 mm (6")
- Specimen width: max {$5d_F$, 50 mm}
- Specimen depth: max {$6d_F$, 50 mm}
- Repetitions per series: n = 10
- Total number of tests: 960



4. MATERIALS

4.1 FASTERNERS

- LAG SCREWS

Fastener diameter mm (in.)	Threaded (T) or non-threaded (NT) portion	Lead hole diameter mm	Embedment length mm
6.35	NT	6.35	76.2
(1/4)	T	4.39	76.2
7.94	NT	7.94	76.2
(5/16)	T	5.56	76.2
9.53	NT	9.53	76.2
(3/8)	T	6.75	76.2
12.7	NT	12.7	152
1(/2)	T	9.13	152
15.9	NT	15.88	152
(5/8)	T	11.91	152
19.1	NT	19.05	152
(3/4)	T	14.29	152

4.2 WOOD PRODUCTS

- GLULAM

The wood products were generously provided by two Canadian suppliers.

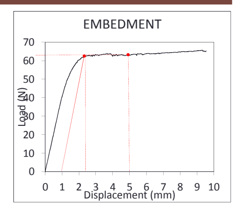
- Douglas-Fir
- Spruce-Pine-Fir
- Black Spruce

5. ANALYSIS OF RESULTS

5.1 ANALYSIS

- COLLECTION OF VALUES
  - Peak Load (kN)
  - Peak Load Displacement (mm)
  - 5% Diameter Offset Load (P_y)
  - 5% Diameter Offset Load Displacement (mm)

$$f_i = \frac{P_y}{l \cdot d}$$



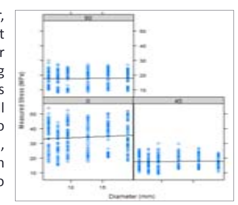
- EVALUATION OF THE DESIGN MODEL

Same procedure as for withdrawal was applied to the embedment data to evaluate the different design models.

5.2 EVALUATION OF THE INFLUENCE OF DIAMETER

1. SIMPLE RELATIONSHIP BETWEEN THE EMBEDMENTSTRENGTH AND THE DIAMETER

To evaluate the influence of the fastenenr diameter, a simple relationship between the embedment strength (dependent variable) and the diameter (independent variable) was examined using experimental data for each loading direction. Results of the simple linear regression indicate that for all angles the diameter was not significantly related to the measured stress (p-value equals 0.771 for 90°, 0.743 for 45° and 0.169 for 0° angles). The Figure on the right confirms this conclusion with a near zero slope of the least squares fit for all angles.



2. PARAMETER EVALUATION USING NON-LINEAR REGRESSION ANALYSIS

Second method to investigate the influence of the diameter (d_F) on the embedment strength (f_θ) used non-linear regression analysis to fit each model for each angle (θ). For example, the CSA O86 equations were expressed as follows (MPa):

$$f_{90} = \beta_{1a} \times G \times (1 - \beta_{2a} \times d)$$

$$f_0 = \beta_{1b} \times G \times (1 - \beta_{2b} \times d)$$

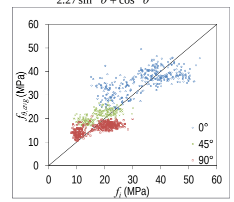
$$f_{45} = \beta_{1c} \times G \times (1 - \beta_{2c} \times d)$$

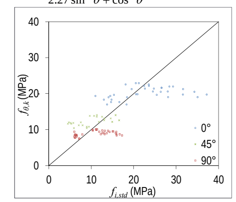
The analysis indicated that for all design models, the coefficient associated with the diameter (β_2) was close to zero and the associated p-value was always greater than 0.05. In other words, the influence of the diameter was not significant for any loading angle in any design model. This finding corresponds to those previously observed by Whale *et al.* (1987), Wilkinson (1991) and Sawata & Yasumura (2002) .

6. EVALUATION OF MODELS

- CSA O86

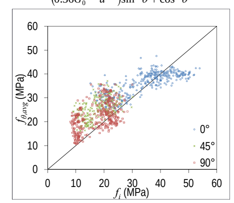
$$f_{\theta,avg} = \frac{82\rho_{12}(1-0.01d)}{2.27\sin^2\theta + \cos^2\theta} \qquad f_{\theta,k} = \frac{50G(1-0.01d)}{2.27\sin^2\theta + \cos^2\theta}$$

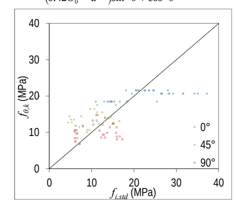




- National Design Specification (NDS)

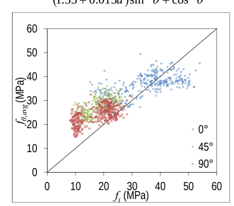
$$f_{\theta,avg} = \frac{77G_0}{(0.36G_0^{-0.45}d^{0.5})\sin^2\theta + \cos^2\theta} \qquad f_{\theta,k} = \frac{44G_0}{(0.42G_0^{-0.45}d^{0.5})\sin^2\theta + \cos^2\theta}$$

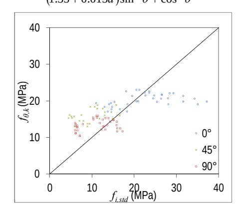




- Eurocode 5 (EN)

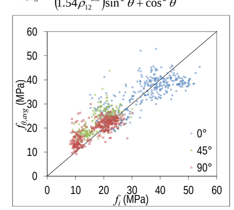
$$f_{\theta,avg} = \frac{82\rho_{12}(1-0.01d)}{(1.35+0.015d)\sin^2\theta + \cos^2\theta} \qquad f_{\theta,k} = \frac{50G(1-0.01d)}{(1.35+0.015d)\sin^2\theta + \cos^2\theta}$$

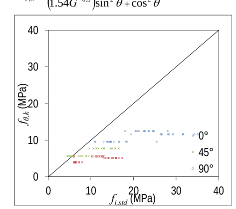




Since the diameter was proved to be non related to the embedment strength and since no design models predicted accurately the embedment strength compared to the experimental values, a new design model was created taking into account only the wood density:

$$f_{\theta,avg} = \frac{108\rho_{12}^{1.7}}{(1.54\rho_{12}^{-0.5})\sin^2\theta + \cos^2\theta} \qquad f_{\theta,k} = \frac{42G^{1.7}}{(1.54G^{-0.5})\sin^2\theta + \cos^2\theta}$$





67. CONCLUSIONS

Embedment tests were conducted on Canadian glulam products with lag screws. Three design models (Canadian, American and European) predicting embedment strength were evaluated statistically. None appeared to provide accurate predictions of the embedment strength in comparison with test results. Moreover, it was shown that the diameter in these design equations had no influence on the embedment strength expressed as 5% diameter offset. Therefore, the authors felt compelled to introduce a new embedment strength equation for the CSA O86 (2009) design standard, which does not account for the fastener diameter. This equation gave a better fit to measured stresses when analysed with nonlinear regression analysis for all tested angles.