Bolted Wood Connections Loaded Perpendicular-to-Grain: Effect of Wood Species

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Summary

This paper deals specifically with the splitting mode of failure, for bolted connections loaded perpendicular to grain in glued laminated timber (glulam). In 2004, a new design equation was developed by Lehoux and Quenneville to predict the ultimate load capacity of these splitting failures. Although the new design equation takes into account the many parameters that affect the ultimate load capacity, the equation was only validated for the Spruce-Pine glulam species. Therefore, the experimental program and research described in this document was undertaken to assess the effect of wood species on connection resistance.

It was observed that, as for loading situations governed by tension strength perpendicular to grain, the species has no effect on the splitting resistance of bolted connections.

1. Introduction

1.1 Background

In the Canadian wood design standard, the current method of calculating the resistance of bolted connections is based upon the European Yield Model. This model can only predict the capacity of connections failing in a ductile manner. However, bolted timber connections can fail in either a ductile manner, a brittle manner, or a combination of both. The Canadian code adequately represents ductile failures, but does not account for brittle failures. Therefore, the current wood design code has a critical void in its design standard, and a complete equation that predicts the resistance of a brittle (splitting) failure is needed. This would allow designers to calculate both the ductile and brittle resistance of a connection, and use the minimum value in design.

In a perfectly ductile connection, failure occurs when the wood crushes under the bolt shank, resulting in a bearing failure. The amount of crushing will increase with increasing load until the connection reaches a plastic state, where the load remains constant while crushing continues.

In contrast, a brittle failure involves fracture of the wood around the connection. In a perfectly brittle failure, tension forces in the wood create a crack before any ductile
behaviour (bearing failure) occurs. Once a crack develops, the strength in the connection is lost rapidly causing immediate failure. The location of this crack in perpendicular to grain connections usually initiates around the bolt holes farthest from the loaded edge.

Pure brittle and pure ductile behaviours are rare, with the majority of bolted connections failing due to a combination of both. In these connections, some ductile behaviour occurs first, and then, with increasing load, the beam fails due to brittle fracture.

1.2 Bolted Connections – Ductile Failures

The European Yield Model (EYM) is currently used in the Canadian standard for connections with bolts, lag screws, and drift pins. It is based upon four equations for double shear connections. The equations predict the strength of a dowel-type joint due to either a bearing failure of the joint members, or the simultaneous development of a bearing failure of a joint member and a plastic hinge formation in the fastener.

For the ductile failure mode, a connection resistance does vary depending on which glulam species is used in design. In the Canadian Wood Design standard, the effect of wood species is taken into account when a designer specifies the embedding strength of the wood. This is because the embedding strength is dependent on the density of wood, which is species dependent.

1.3 Bolted Connections – Brittle (Splitting) Failures

Lehoux and Quenneville [1] have proposed an equation that estimates the resistance of the splitting mode of failure of bolted connections loaded perpendicular to grain. The proposed equation follows the theory of Foschi and Longworth [2] for riveted timber connections. This theory is presently used in the current Canadian wood design code [3]. The approach is based on a stress analysis of the connection, which was completed using finite element model to predict the stresses around the cluster of bolts. The splitting equation also includes timber’s volume/size effect, and the effect of the connection size and configuration.

As a result of using the theory of Foschi and Longworth, the splitting resistance of a bolted connection, according to Lehoux and Quenneville, can be determined by the following equation. It should be noted that this equation was only validated for the Spruce-Pine glulam species.

\[
q_{wb} = \frac{200(n_R \times d \times t)^{0.8}}{A_t B_c C_b \times 10^3 \times (n_c \times d)^{0.2}}
\]

[1]

Where:
\[ n_R = \text{number of rows}, \]
\[ n_c = \text{number of bolts per row}, \]
\[ d = \text{bolt diameter}, \]
\[ t = \text{width of wood member}, \] and
A_b, B_b, C_b = coefficients based on the bolted connection geometry
A_b = coefficient depending on n_R and n_c,
B_b = coefficient depending on S_p and S_Q, and
C_b = coefficient depending on the ratio [(e_Q+S_Q)/(beam depth)].

Since 1998, over sixty different bolted timber connections loaded perpendicular to grain have been tested in the laboratory at the Civil Engineering Department of the Royal Military College of Canada. Using the configurations that failed in a brittle (splitting) fashion, the above equation was developed.

For the brittle (splitting) failure mode, it is not known how or if a connection's resistance varies depending on the glulam species. Therefore, the main objective of this research was to study the impact of wood species (Spruce-Pine vs. Douglas-Fir) on the splitting resistance of bolted connections loaded perpendicular to grain.

1.4 Effect of Glulam Species on the Splitting Resistance

In the Canadian design approach to bolted connections loaded perpendicular to grain, the effect of wood species is taken into account by specifying the density of the glulam species. Because the EYM’s failure mode includes embedment of the bolt in the timber (bearing failure), the EYM adequately accounts for the effect of wood species in ductile failures. However, when considering brittle (splitting) failures, the failure is due to tensile forces perpendicular to grain, and not wood bearing resistance. Recent research by Blass and Schmidt [4] suggests that the tensile strength perpendicular to grain shows no significant correlation with the density of glulam. Therefore, the method of taking into account the species effect in ductile failures can not be applied to brittle (splitting) failures. This has revealed the need to study the species effect on brittle failures, and more specifically, the species effect on glulam's ability to resist tension stresses perpendicular to grain.

The brittle (splitting) mode of failure is also encountered in the Canadian Wood Design standard in the design of riveted connections and notched beams. When analyzing these design procedures, it is seen that the Canadian Wood Design standard is inconsistent in its approach to dealing with the effect of wood species.

1.5 Riveted Connections Loaded Perpendicular to Grain

In the Canadian code, the effect of species is taken into account by a material factor. In a given connection, the code reduces a connection resistance when using Spruce-Pine glulam, but does not apply the reduction factor when using Douglas-Fir glulam. This reduction factor was adopted in the 2001 standard [3] from studies completed by Karacabeyli and Fraser [5]. In their study, Karacabeyli and Fraser tested ductile failures of rivet connections loaded perpendicular to grain, and found that ductile failures with Spruce-Pine glulam had approximately 80% of the resistance when compared to Douglas-Fir glulam. The two then suggested that due to lack of testing, the same reduction factor found from ductile failures, be applied to brittle (splitting) failures.
Obviously the species factor for brittle Spruce-Pine connections was an approximation, and suggests that more research be directed towards the effect of species for brittle (splitting) failures.

1.6 Notched Beams

Brittle (splitting) failure is also encountered in the design of notched beams. The Canadian wood design code [3] allows for notches on the tension side at the support for both sawn timber and glulam beams. However, when notches are present, the designer must ensure that beam fracture (splitting) at the re-entrant corner of the notch be avoided. To eliminate splitting, the Canadian code reduces the shear force resistance at the support of a notched beam.

When designing according to the Canadian code, the design procedure has no species effect when using sawn timber, but includes a species effect when using glulam. For sawn timber, the reason for not having a species effect is based upon experimental testing by Smith et al. [6]. In this research, sawn timber beams of both Douglas-Fir and Spruce-Pine-Fir were tested to failure. Resulting from these tests, Smith et al. state that the differences between species and stress grades is small, and suggest that the strength be considered equal between species.

As for glulam, the Canadian code reduces the strength of Spruce-Pine when compared to the resistance of Douglas-Fir. The author was not able to find where or when the Canadian standard adopted the design of notched glulam beams. Therefore, no information is given here on the species effect.

2. Experimental Program

The splitting equation by Lehoux and Quenneville was developed for connections subjected to monotonic loading, consisting of steel-wood-steel type connections, with the connection group located at midspan of the specimen. Therefore, the laboratory work in this research consisted of testing additional configurations in the same manner. All specimens were fabricated from glued laminated timber.
Laboratory testing was conducted in accordance with the American Society for Testing and Material (ASTM) standard procedures [7], [8]. Ultimate load capacities were calculated for each joint configuration using the 5th percentile approach consistent with the ASTM standard procedures [9].

The effect of timber species on the joint behaviour was examined by using two different glulam species: Spruce-Pine and Douglas-Fir. Identical joint configurations were used for both species which made it possible to study the species effect on the joint behaviour and resistance. In total, five unique configurations were tested for both species, and thus, ten groups were loaded to failure. These configurations are shown in the following table.

<table>
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<th>Gp #</th>
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<th>t</th>
<th>Depth</th>
<th>L</th>
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<th>e</th>
<th>e_p</th>
<th>e_0</th>
<th>S_0</th>
<th>S_p</th>
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Note: n_R is number of rows, n_c is the number of bolts per row. Other variables are shown on Figure 2.

3. Results & Discussion

To evaluate the species effect on the splitting resistance of glulam, a comparison of both species (Douglas-Fir & Spruce-Pine) was completed. All five bolted configurations were compared in three ways. First, the experimental average resistance for each group was compared using a traditional normal distribution t-test (using a 95% confidence level). Secondly, the calculated normal duration 5th percentile resistances were compared between the two species, because these 5th percentile values are used in the Canadian
design standard as the reference resistance for each configuration. Finally, the behaviour of the groups and failure mode was compared between the two species.

The experimental resistances of the five unique configurations, listed in Table 2, were compared using a t-test. From the results of the t-test, groups 1, 2, and 5 resulted in no significant difference between the species. Therefore, even though the Spruce-Pine and Douglas-Fir values vary slightly, both species are statistically from the same population, and no difference between species is apparent when comparing experimental resistances. However, a statistical difference does exist between the species for groups 3 and 4.

<table>
<thead>
<tr>
<th>Group #</th>
<th>Ultimate Load</th>
<th>t-Test Result</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Spruce-Pine</td>
<td>Douglas-Fir</td>
</tr>
<tr>
<td>1</td>
<td>58.7 (12.0)</td>
<td>56.2 (10.3)</td>
</tr>
<tr>
<td>2</td>
<td>32.6 (20.1)</td>
<td>32.5 (17.4)</td>
</tr>
<tr>
<td>3</td>
<td>83.8 (12.0)</td>
<td>116.1 (7.8)</td>
</tr>
<tr>
<td>4</td>
<td>41.1 (14.0)</td>
<td>48.7 (15.2)</td>
</tr>
<tr>
<td>5</td>
<td>30.2 (8.0)</td>
<td>31.3 (6.8)</td>
</tr>
</tbody>
</table>

From examining the 5th percentile resistances, also listed in Table 2, groups 1, 2, 4, and 5 all have a high species factor (Spruce-Pine / Douglas-Fir) of 0.96, 0.88, 0.88, and 0.94 respectively. However, group 4 has a much more significant species factor of 0.65.

To understand the effect the species has on the resistance of bolted connections loaded perpendicular to grain, potential load-slip curves are shown in Figure 3.

![Figure 3: Governing failure modes and potential load-slip curves for bolted connections loaded perpendicular to grain](image)
From observation of the failure modes, groups 1, 2, and 5 represented pure splitting failures, with little to no ductile behaviour evident (mode I in Figure 3). The behaviour of these groups can be compared to the groups used by Lehoux and Quenneville [1] to develop the splitting equation. However, groups 3, and 4 exhibited significant ductile behaviour before splitting occurred, resulting in a mixed failure mode (mode II in Figure 3). Because groups 3 and 4 initially failed in a ductile manner, they do not represent the splitting formula developed by Lehoux and Quenneville. Therefore, only groups 1, 2, and 5 can be used to assess the effect of wood species on the splitting resistance of glulam.

Based on the results of groups 1, 2, and 5, it can be concluded that the splitting strength of bolted connections loaded perpendicular to grain does not differ significantly between Spruce-Pine and Douglas-Fir species. This conclusion is similar to the findings of Blass and Schmid [4]. It can also be concluded that the splitting equation developed by Lehoux and Quenneville can now accommodate both the Douglas-Fir and Spruce-Pine wood species without the need for a material correction factor.

Riveted connections loaded perpendicular to grain share the same brittle failure mode as bolted connections, and are based upon the same theory by Foschi and Longworth [2]. It follows that if the species effect from this research is applied to bolted connections, it should also be applied to riveted connections. Therefore, it is recommended that the Canadian standard remove the material reduction factor for Spruce-Pine glulam, for brittle wood failures with riveted connections loaded perpendicular to grain.

Brittle (splitting) failure is also encountered in the design of notched timber beams. Because it was found that the splitting resistance of bolted connections does not vary significantly between the Douglas-Fir and Spruce-Pine species, it is suggested that the species effect in notched timber glulam members should be changed so that no reduction is applied to the Spruce-Pine species. This would be inline with the design approach for sawn timber, and also correspond with results from Blass and Schmid [35].

4. Conclusions

As a result of the laboratory testing and analysis, a few conclusions can be drawn. First, the splitting resistance of bolted connections loaded perpendicular to grain does not vary significantly between Douglas-Fir and Spruce-Pine species. The splitting equation by Lehoux and Quenneville is now validated for bolted connections with both the Spruce-Pine and Douglas-Fir glulam species.

The current material reduction factor (H) for wood failures when riveted connections are loaded perpendicular to grain is not based on adequate testing, and is an approximation. From the results in this research, it is recommended that the Canadian code remove the reduction for Spruce-Pine glulam and other species groups, and consider the strength equal to Douglas-Fir.

In the Canadian standard, the species effect in notched timber glulam beams conflicts with the results from this study. The species effect in the design of notched glulam
members should be re-evaluated so that no reduction is given to the Spruce-Pine species when compared to Douglas-Fir species.

5. Recommendations

To further understand the behaviour of brittle (splitting) failures in bolted glulam connections loaded perpendicular to grain, more research needs to focus in two areas. First, the effect of end distance (e) is not well understood. Attention should be directed towards this phenomenon so that bolted connections can be designed effectively in industry. Finally, experimental tests with single shear connections should be completed so that single shear connections are accurately represented in the Canadian Code.

6. References


