Article citation info:
Cook S., Ghavidel A., Zhou J. 2024. Dimensional stability and mechanical performance of face-glued spruce-pine-fir and Douglas-fir studs. *Drewno. Prace naukowe. Doniesienia. Komunikaty* 67 (214): 00032. https://doi.org/10.53502/wood-193420

Łukasiewicz Poznań Institute of Technology

Drewno. Prace naukowe. Doniesienia. Komunikaty
Wood. Research papers. Reports. Announcements

Journal website: https://drewno-wood.pl

Dimensional stability and mechanical performance of face-glued spruce-pine-fir and Douglas-fir studs

Sophia Cook
Amir Ghavidel*
Jianhui Zhou

University of Northern British Columbia, Canada

Article info
Received: 20 January 2024
Accepted: 16 September 2024
Published: 31 October 2024

Keywords
glued lumber
shape stability
shear strength
warp mitigation
modulus of rupture
and elasticity

Warpage of dimensional lumber has been identified as the major issue for its use in wood construction prefabrication in North America. Face-gluing is a promising technique to mitigate warping of dimensional lumber. This paper studies the dimensional stability and mechanical performance of 2-ply face-glued lumber as a means of reducing warpage in both spruce-pine-fir (S-P-F) and Douglas-fir (D. fir) lumber. Planks were paired and subsequently laminated based on their initial dynamic modulus of elasticity (MOE) and shape compatibility. Warp was measured in twist, bow, and crook at varying moisture contents. Mechanical performance was measured in terms of the MOE, modulus of rupture (MOR), and shear strength. This pairing regime between component planks offers a means to reduce the twist and bow tendencies of face-glued lumber while increasing the uniformity of lumber strength. Flexural MOE and MOR performances were consistent with visual grades No.1/No.2, showing the potential of face-glued lumber as a value-added product for the automatic prefabrication of wood constructions.

DOI: 10.53502/wood-193420

Introduction

Light-frame wood construction has been the major construction system in North America for small residential houses since its invention in the 1840s. Mid-rise light-frame wood construction has also gained increasing market share as a viable and economic solution for apartment buildings, due to the recent changes in Canada allowing its use up to six stories. Dimensional lumber has several benefits as a construction material: it has a high strength-to-density ratio; it is renewable; it sequesters carbon; and it is biodegradable at the end of its life. However, one major disadvantage of dimensional lumber is its tendency to warp under varying humidity and temperature conditions due to its anisotropic and hydrophilic properties. This causes end-user dissatisfaction with the quality of dimensional lumber (Johansson et al., 1994). Warp in dimensional lumber is an issue for the growing wood construction prefabrication industry in North America, where automatic framing equipment is designed to handle straight lumber. To accommodate these limitations, dimensionally stable laminated strand lumber (LSL) is often used instead, increasing the cost and weight of construction. The challenge is to create alternatives to LSL that are more cost-effective and lighter. This has already been accomplished in European markets, where 2- and 3-ply face-glued lumber, known as duo and trio lumber, is used

* Corresponding author: amir.ghavidelesfahlan@unbc.ca

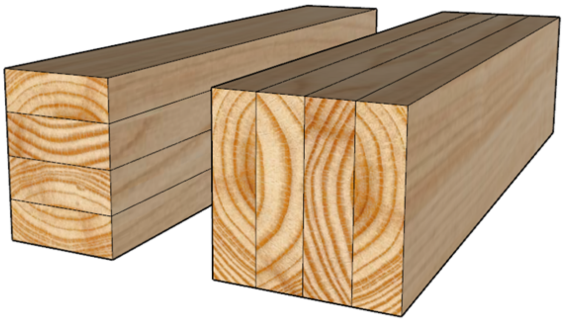


Fig. 1. Face-glued lumber manufactured in North America (left) and Europe (right)

with the planks in specific orientations to reduce the tendency of the lumber to warp.

Several studies have been conducted to date examining the mechanisms behind different parameters of warpage (Cai and Dickens, 2007; Johansson and Kliger, 2002; Yoon and Park, 2002). Forms of warp in wood include cup, twist, bow and crook, all of which are caused by complex spatial variations in the material properties and spiral grain angle of the wood. Twist has been attributed to several factors: the lumber's spiral grain angle; the species radial and tangential shrinkage coefficients (Ormarsson and Cown, 2005); and its distance from the pith (Ormarsson et al., 1999). As the spiral grain angle in a board increases, so does its tendency to twist, as the direction of shrinkage and swelling follows the grain, causing directional variation in the dimensional change throughout the wood. The species' radial and tangential shrinkage coefficients as well as the radius of ring curvature influence the severity of this change. As the radius of ring curvature increases towards the pith, so does the ability of a board to twist (Ormarsson et al., 1999). Ormarsson et al. (1999) also observed that twist was not dependent on the ring orientation within a board. Johansson and Kliger (2002) attributed bow and crook to residual stresses in the wood and uneven longitudinal shrinkage. Bow and crook tend to worsen further from the pith, as they are influenced both by the spiral grain angle of the wood and by its stiffness properties (Ormarsson and Cown, 2005).

Eriksson et al. (2004) reported that halving a piece of dry lumber and gluing the halves back together with one board flipped radially reduces the tendency to twist, and that symmetric cut and glue orientations produced the greatest reduction in that tendency. Serrano and Cassens (2001) found improvements in twist, but not bow, with green gluing. Additionally, the results of Eriksson et al. (2005) show that different board orientations in face-glued lumber with four boards glued into a 2-by-2 matrix affected the severity of twist, at varying moisture contents, although it is unclear how the results of two-plane gluing transfer to one-plane gluing. The effects of modulus of elasticity (MOE) on warp tendencies in 2-ply face-glued lumber were not examined in any of these studies.

Research into face-glued lumber has focused on the use of lumber that originated from the same larger piece and has symmetric and mirrored cut patterns (Eriksson et al., 2004). Therefore, studies have not been conducted to examine how face-glued lumber warps when it contains boards with different origins and therefore different MOEs and cut patterns. This may be because of difficulties in finding a control population.

Unlike in Europe, 2-ply face-glued lumber has not been identified in North American markets. Few examples of light-frame products have been identified, and they are poorly distinguished in marketing from their larger glue-laminated timber counterparts. Moreover, structural face-glued lumber approved by the National Lumber Grades Authority (NLGA) (2015) in Canada has a different member arrangement than those in European markets. As shown in Fig. 1, Canadian face-glued lumber has several laminations on its thin faces, rather than the wide face as seen in the European 2- and 3-ply face-glued products.

To address these research gaps, the objective of this study is to develop 2-ply face-glued lumber by examining the dimensional stability and mechanical performance of spruce-pine-fir (S-P-F) and Douglas-fir (D. fir) face-glued lumber. Dimensional stability will be measured in terms of the bow, crook, and twist of the lumber, and the mechanical properties will be quantified in terms of the MOE, modulus of rupture (MOR), and shear strength, with reference to North American testing standards.

Materials and methods

1. Materials and fabrication

Sixty 19 × 89 mm^2 (1×4) by 2.43 m long ungraded Canadian S-P-F lumber planks were selected from a local hardware store in Prince George, British Columbia. In-store selection criteria eliminated planks with significant defects and warp. Another group of twenty-four 2.70 m long 23 × 99 mm^2 rough sawn D. fir planks were selected from 62 planks donated by a local sawmill. These were chosen for minimal visual defects and sufficient thickness to plane. The reference group consisted of six 1.80 m long 38 × 89 mm^2 (2×4) J-graded S-P-F lumber planks. J-grade is a special lumber grade with minimal defects and warp. The raw material was equilibrated to laboratory conditions over the course of 2 months.

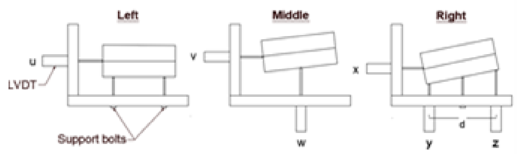
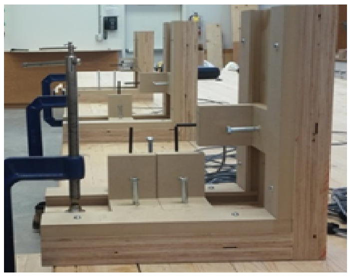
Thirty face-laminated S-P-F and twelve laminated D. fir pieces were fabricated. Planks were paired based on their initial dynamic MOE and shape compatibility. The lowest MOE plank was paired with the highest MOE plank, the second lowest to the second highest, and so forth. MOE-paired planks whose shapes were incompatible for gluing were re-paired to allow gluing; six of the face-glued S-P-F boards were paired in this way. In terms of the relative orientation of the planks in the face-glued lumber, planks were oriented with their sapwood on the bond line wherever possible. All face-glued D. fir boards achieved this orientation; however, five of the 30 face-glued S-P-F boards had one member's heartwood on the bond line. These five boards became the Type 2 face-glued S-P-F subgroup; the others were designated Type 1. These face-glued S-P-F subgroups are illustrated in Fig. 2. One half (15) of the face-glued S-P-F boards contained at least one pith part. Two of the reference group also contained pith; however, no pith was observed in the face-glued D. fir.

Before gluing, the rough sawn D. fir planks were planed to 19 mm in thickness. All face-glued lumber was bonded with LePage Polyurethane glue. Pressure was applied with bar clamps while curing. After lamination, all face-glued lumber was cut to 2.40 m and the face-glued D. fir lumber was planed to 89 mm in width. The edges of the face-glued S-P-F lumber were only sanded to remove excess glue

2. Dimensional stability

The warp, quantified by the twist, bow, and crook, of the face-glued lumber was calculated using the apparatus shown in Table 1. The warp measuring apparatus is based on similar devices used by Perstorper et al. (2001). These measurements were determined using five linear variable differential transformers (LVDTs), accurate to 0.1 mm.

Table 1. Warp measuring apparatus and definitions of twist, bow and crook

<table>
<tr><td colspan="2">
</td><td></td></tr>
<tr><td colspan="3">Definitions of warp</td></tr>
<tr><td>$Twist = \left|tan^{-1}\left(\frac{y-z}{d}\right)\right|$</td><td>$Bow = w$</td><td>$Crook = \left|\frac{u+x}{2} - v\right|$</td></tr>
<tr><td colspan="3">where u, v,…, z are the displacements of the LVDTs (in mm) relative to the LVL calibration piece
Note: the geometric equations for warp do not include calibration to the LVL piece</td></tr>
</table>

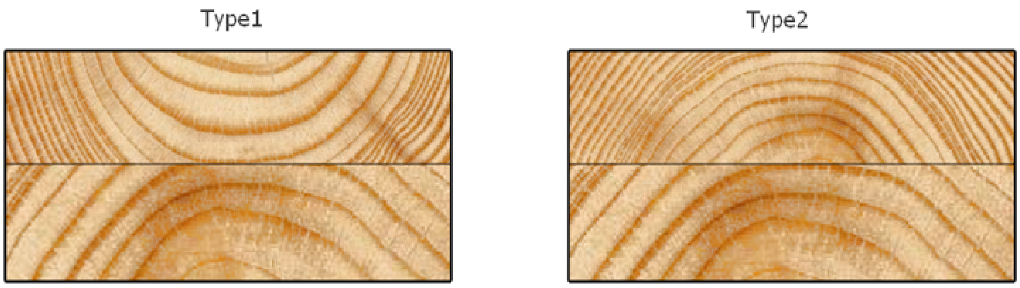


Fig. 2. Two types of lamination orientations examined in the S-P-F group

Displacements were calibrated to a piece of laminated veneer lumber used as a straight stud reference. The equations and the apparatus used to determine the twist, bow, and crook are presented in Table 1.

The initial moisture content of all groups was measured at around 8%. The humidity chamber used to condition the lumber to the two other target moisture contents, 13% and 18%, is shown in Fig. 3. At each target moisture content, the warp and dynamic MOE were measured, using the applied apparatus and a stress wave device, respectively. Three weeks were needed to condition the lumber from 8% to 13% MC, and then again from 13% to 18% MC. At the end of the last conditioning phase, the face-glued and reference S-P-F lumber had a moisture content of 16%, while that of the face-glued D. fir lumber was 19%. The temperature was maintained at 21 °C (the temperature of the laboratory). The moisture content of the lumber was monitored daily, using a Delmhorst® RDM3™ pin-type resistance moisture meter.

3. Mechanical properties

Twelve randomly selected face-glued S-P-F boards and all twelve face-glued D. fir boards underwent mechanical testing to determine the flexural MOE, MOR, and shear strength of the groups, once dimensional stability measurement was complete. Stress wave tests to determine dynamic MOE (MOE_d) were conducted on all lumber planks using a FAKOPP Microsecond Timer before lamination and then again on the reference boards and resulting face-glued lumber at each target moisture content. In the setup shown in Fig. 4, the time-of-flight (TOF) in μs for a stress wave created at the left transducer by the hammer to reach the right terminal is related to the by equation (1). The velocity of longitudinal acoustic waves in a wood member can be determined through TOF acoustic measurement. In this method, a mechanical or ultrasonic impact generates a longitudinal wave within the wood member (Arriaga et al., 2023; Nocetti et al., 2024).

$$MOE_d = \rho \left(\frac{L}{TOF}\right)^2 1000000 \qquad (1)$$

where L is the length of the board (m), and ρ is the mass density of the board (kg/m^3) determined from the dimensions and mass of the board.

In comparing the dynamic MOE of the lumber planks to the face-glued lumber, the moisture content adjustment factor introduced by Barrett and Hong (2010) was applied to the dynamic MOE of the component lumber planks.

Fig. 3. Humidity chamber used to adjust the moisture content of specimens

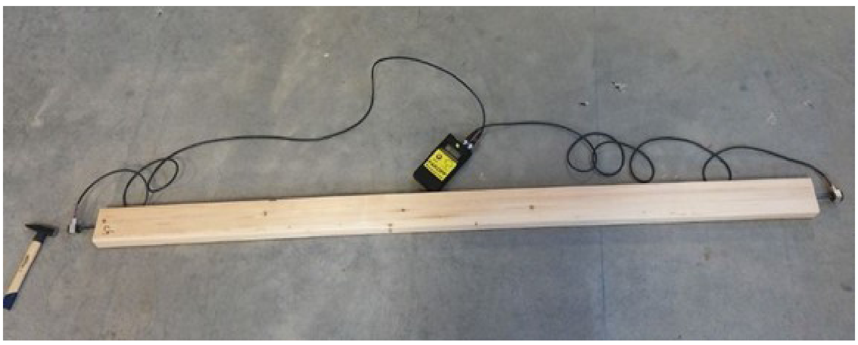


Fig. 4. Stress wave test setup to determine the dynamic MOE of the board

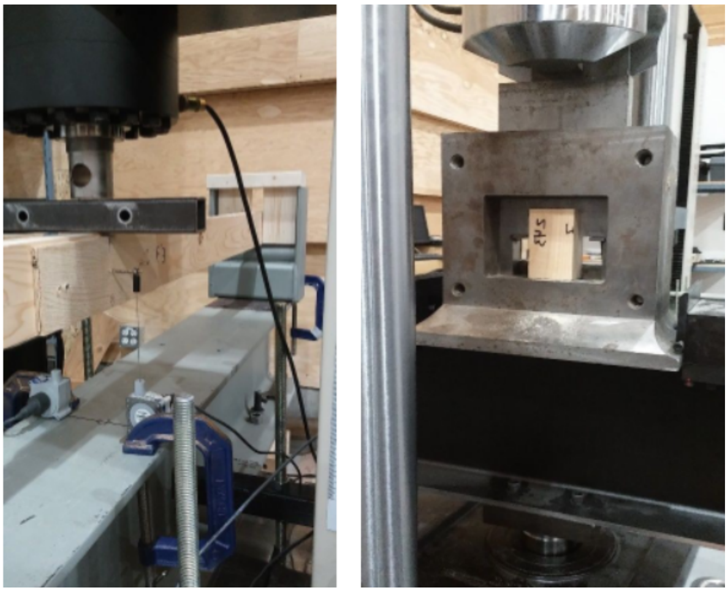


Fig. 5. Bending test setup (left) and block shear test setup (right)

Flexural MOE and MOR were determined by center point edgewise bending tests, with reference to ASTM (2015) Standard D198. The lumber was cut to 1958 mm to allow a span-to-depth ratio of 20 with one depth of overhang on each end. ASTM Standard D198 (2015) specifies equations (2) and (3) for the determination of flexural MOE () and MOR. The setup is shown in Fig. 5. A loading rate of 5.0 mm/min was applied.

$$MOE_f = \frac{Pl^3}{4bd^3\Delta} \quad (2)$$

$$MOR = \frac{3P_{max}l}{2bd^2} \quad (3)$$

where P is the increment of applied load on the specimen (N), P_{max} is the applied load on the specimen at failure (N), b is the width of the specimen (mm), d is the depth of the specimen (mm), l is the distance between the reaction supports (mm), and Δ is the increment of deflection of the specimen under the incremental load (mm).

The shear strengths of the specimens were determined following ASTM Standard D905 (2013). Percentage wood failure was calculated. The bond area was 2500 mm^2 and specimens were loaded at 0.90 mm/min. The shear strength (fv) is given by equation (4). Fig. 5 shows the test setup.

$$f_v = \frac{P_{max}}{bd} \quad (4)$$

where b and d are respectively the width and depth of the specimen's bond area (mm).

Results and discussion

1. Dimensional stability

The dimensional stability performance of the face-glued S-P-F lumber over the S-P-F reference group is mixed. The results are shown in Fig. 6. The change in warp between groups with varying moisture contents are compared at a 95% significance level ($\alpha = 0.05$). From 8% to 13% moisture content, the face-glued S-P-F lumber has a higher stability in crook ($p = 0.00$), but lower stability in bow ($p = 0.00$) compared to the reference group. From 8% to 16% moisture content, the face-glued lumber is still less stable in bow ($p = 0.00$); however, no difference is seen in the change in crook compared to the reference group ($p = 0.33$).

Examining the performance of the different plank orientations in face-glued S-P-F lumber, Type 2 lumber is more stable than Type 1 lumber from 8% to 13% and from 8% to 16% moisture content ($p = 0.00$ in both cases).

In terms of twist, no significant difference is seen in the change in twist between the face-glued and reference S-P-F group or between the Type 1 and Type 2 orientations from 8% to 13% or 8% to 16% moisture contents. The lack of difference between the change in twist of these groups conflicts with the results of Eriksson et al. (2004), who found a reduction in twist tendencies when boards were bifurcated and glued back together with one board flipped. There may be an explanation for this. Eriksson et al. (2004) used a reference group from the same log and position as the face-glued boards and not high-quality J-graded boards. This suggests that the twist tendency of the face-glued S-P-F is as good as the high-quality J-graded boards.

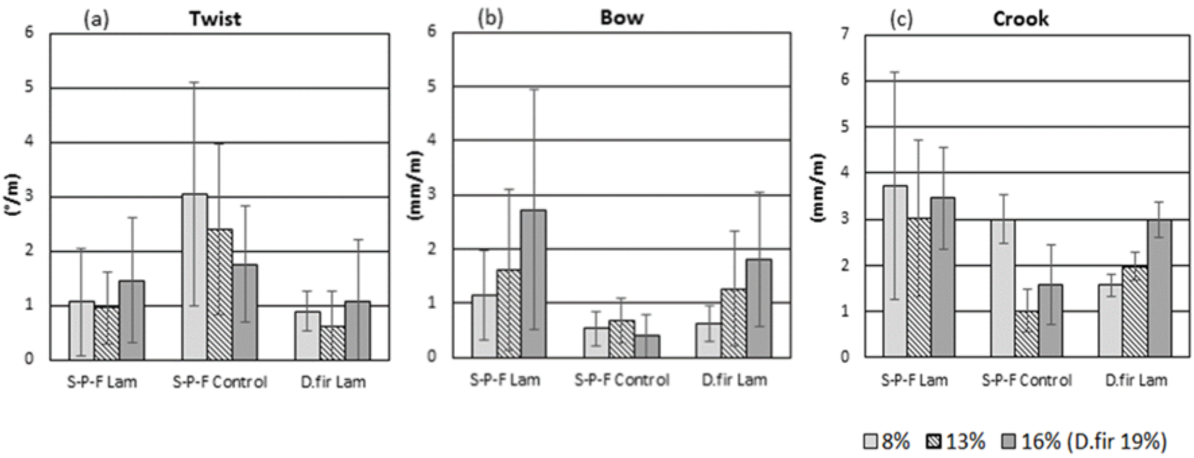


Fig. 6. Twist, bow and crook of S-P-F and D. fir face-glued lumber

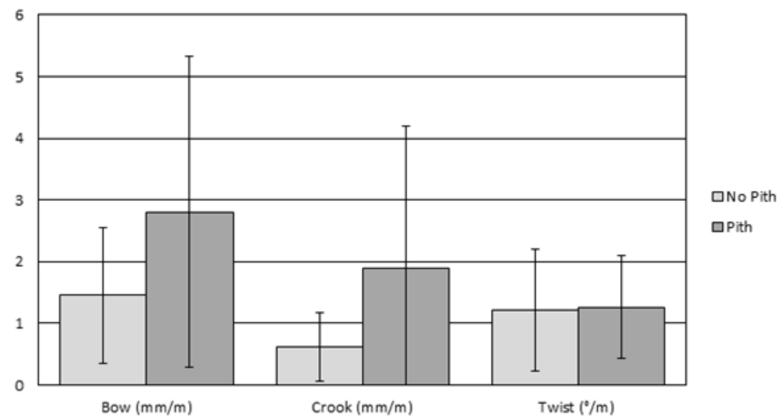


Fig. 7. Effect of the presence of pith on the warp of face-glued lumber

Moreover, Ormarsson et al. (1999) observed that twist in 3-ply face-glued lumber may be more pronounced if the component plank orientations are not contrasting. The results of this study indicate that that bow can worsen as well. This suggests that differences in the properties of the component planks, such as differences in their MOE and their ring orientation, influence the shape stability of the resulting face-laminated board. These differences may be more pronounced in our results, as the origin and ring orientation of the planks are uncontrolled.

As seen in Fig. 6, changes in twist and bow between S-P-F and D. fir face-glued lumber follow similar trends, whereas in crook, similar trends are observed between the face-glued and reference S-P-F groups. This suggests that changes in twist and bow between moisture contents is influenced by lamination; however, species-specific factors may dominate in the case of crook.

Fig. 7 summarizes the effects of the presence of pith on the dimensional stability of the face-glued S-P-F lumber. Face-glued S-P-F lumber containing at least one pith part is less stable in crook ($p = 0.03$) and bow ($p = 0.04$) than samples without pith between 8% and 16% moisture content ($\alpha = 0.05$). Differences in twist are not significant ($p = 0.44$). The mean differences in the change of bow, crook and twist from 8% to 16% moisture content were 1.4 mm, 1.3 mm, and 0.1°. The standard deviation for the change in bow and crook is also less for face-glued boards without pith than for those with a pith part (1.1 mm vs. 2.5 mm and 0.6 mm vs. 1.9 mm respectively).

These results show the tendency for bow and crook in face-glued S-P-F lumber to increase with the presence of at least one pith part, in contrast to the behavior of solid lumber, which tends to have less bow and crook closer to the pith (Ormarsson et al., 1999). The increase in bow and crook with the presence of pith may stem from differences in the coefficients of shrinkage/swelling and directional MOEs between component planks.

The influence of the percentage difference in the dynamic MOE of the component planks of a face-glued board on its warp was examined with respect to the dynamic MOE of the face-glued lumber and by grouping both the S-P-F and D. fir lumber together. As seen in Table 2, there is a significant increase in all warp parameters for boards with an MOE difference greater than

Table 2. Mean and significance results comparing the warp in face-glued lumber with more or less than 20% difference in MOE between component planks

	MOE difference	Bow	Crook	Twist
Mean	≤ 20%	2.5 mm	2.1 mm	1.8°
	> 20%	6.6 mm	4.3 mm	3.1°
P-value (H_0 = 0, α = 0.05)		0.00	0.03	0.03
Difference		Yes	Yes (but likely no)	Yes

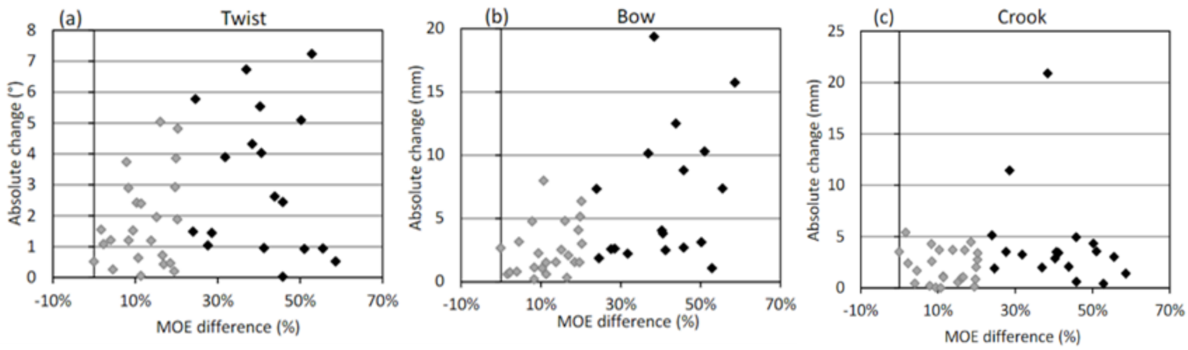


Fig. 8. Influence of the difference in the initial MOE of two component planks on the warp of face-glued lumber

20%; however, the statistical changes in crook likely result from the two outliers observed in Fig. 8c. Moreover, the variability of change in twist and bow tends to increase as the difference in MOE increases. These results show that bow (and twist as product of bow and crook) tendencies of face-glued lumber are sensitive to the relative change in the longitudinal bending stiffness of the component planks. These results are supported by Li et al. (2016)as a key geometry parameter, was independent of three key material parameters; and (4, who found that cupping was influenced by changes in the tangential shrinkage coefficient and tangential MOE of 2-ply face-glued densified balsam fir. By this model, crook would not be sensitive to changes in the longitudinal MOE of 2-ply face-glued lumber, as this change is through the thickness of the lumber and not its width. Therefore, minimizing the longitudinal MOE difference between component planks minimizes the tendency of face-glued lumber to bow. These stiffness sensitivities to warp also agree with the results of Ormarsson and Cown (2005), and may explain the improvements in twist observed by Eriksson et al. (2004); it can be assumed that there is little variation in MOE between component planks sawn from adjacent positions within the same log.

2. Mechanical properties

As seen in Fig. 9, both the face-glued D. fir and S-P-F lumber meet Select Structural (SS) grade in terms of their dynamic MOE at all examined moisture contents. At 8% moisture content, the average densities of the face-glued S-P-F, the reference S-P-F, and face-glued D. fir lumber were 440, 470, and 500 kg/m3 respectively. Most notably, gluing the boards based on initial MOE reduced the MOE standard deviation from 2,000 to 460 MPa and from 2,200 to 990 MPa in the face-glued boards for D. fir and S-P-F respectively, creating more predictable stiffness characteristics. However, as described in section 3.1.2, this pairing pattern results in higher warp tendencies in face-glued lumber with greater differences in the MOE of their component planks. Therefore, the results suggest that pairing planks for minimal difference in MOE reduces the warp tendencies of the boards, but may increase the variation in the MOE of the face-glued lumber, as the group averaging effects seen in Fig. 8 would be lessened.

In terms of flexural MOE, the face-glued S-P-F and D. fir lumber performed well at a mean of 9,600 and 11,500 MPa respectively at 12% moisture content. The flexural MOEs were less than the dynamic MOEs, but this was expected and has been observed by others (Wang, 2013). Face-glued S-P-F had a mean MOR of 45.3 MPa, and 58.2 MPa was observed for the face-glued D. fir. All specimens failed in tension, often at knots. As seen in Table 3, both the flexural MOE and MOR results are consistent with CSA O86 (2014) No.1/No.2-graded lumber.

The efficacy of the face-glued lumber in terms of block shear strength was not as high. Table 3 shows the mean and fifth percentile values for the block shear tests. The mean shear strength for the face-glued S-P-F

Table 3. Mechanical testing results for flexural MOE, MOR, and block shear strength

	Flexural MOE			MOR			f_v	
Group	Mean (MPa)	Parametric 25th percentile (MPa)	CoV (%)	Mean (MPa)	Tolerance limit (MPa)	Parametric 25th percentile (MPa)	Mean (MPa)	Parametric 25th percentile (MPa)
S-P-F	9600	7300	12	45.3	29.0	18	4.9	3.2
D. fir	11500	10100	5.7	58.2	39.0	17	7.2	4.5

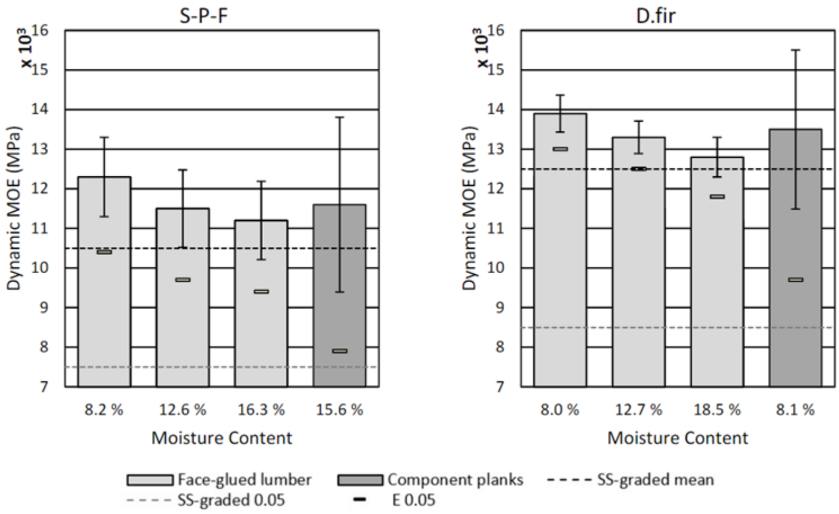


Fig. 9. Dynamic MOE of face-glued lumber at different moisture contents, and comparison with the MOE of raw material and Select Structural grade

lumber (4.9 MPa) was below the minimum allowable mean shear strength (5.3 MPa) and both face-glued groups were well below CSA O122 (2016) wood failure tolerances. Wood failure ranged from 0% to 30% in the face-glued S-P-F lumber and from 0% to 60% in the face-glued D. fir lumber, averaging 15% and 20% wood failure respectively. These wood failure percentages are well below the specified minimum mean of 80% wood failure and the fifth percentile tolerance limit of 60% given in CSA O122 (2016). Despite this, the face-glued D. fir lumber did meet the minimum allowable mean of 6.65 MPa. Both groups also met the CSAO122 (2016) minimum allowable shear strength of a test specimen. These results show the limitations of bar clamps in controlling the quality of the glue line, and highlight the importance of ensuring uniformly distributed pressure and the correct application time of the glue.

Conclusions

This study investigated the dimensional stability and mechanical properties of 2-ply face-glued Spruce-Pine-Fir (S-P-F) and Douglas-fir (D. fir) lumber to address the warpage issues that challenge the wood construction prefabrication industry in North America. The research demonstrated that face-gluing is an effective technique for mitigating warp, particularly in crook, while maintaining the strength properties of the lumber. However, the results indicated that while face-glued lumber shows improved stability in some aspects, it also exhibited greater bow tendencies, particularly when the modulus of elasticity (MOE) differences between component planks exceeded 20%. This highlights the importance of carefully selecting and pairing planks with minimal MOE differences to reduce the risk of warp, especially bow.

The mechanical performance of the face-glued lumber was promising, with both S-P-F and D. fir meeting Select Structural (SS) grade requirements for dynamic MOE. Flexural MOE and modulus of rupture (MOR) results were consistent with industry standards, demonstrating the potential of face-glued lumber as a value-added product in the construction industry. However, challenges remain in achieving consistent glue lines and adequate shear strength, as the block shear strengths for face-glued lumber fell below the specified tolerances, likely due to limitations in the gluing process, such as the use of bar clamps.

Acknowledgements

The Natural Sciences and Engineering Research Council of Canada (NSERC) is greatly acknowledged for supporting this project through the Undergraduate Student Research Award. The authors also thank Timber Span Wood Products Inc. for the donation of the Douglas-fir specimens; Michael Billups for building the warp measuring apparatus and other test preparations; Ryan Stern for technical support; and Anna Woschitz for assisting with mechanical property and warp tests.

Funding

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under Grant [# 501052].

References

Arriaga, F., Wang, X., Íñiguez-González, G., Llana, D.F., Esteban, M., Niemz, P., 2023. Mechanical Properties of Wood: A Review. Forests. 14(6):1202. https://doi.org/10.3390/f14061202

ASTM. 2013. Standard D 905-08 (Reapproved 2013) Standard Test Methods of Strength Properties of Adhesive Bonds in Shear by Compression Loading. West Conshohocken: ASTM International

ASTM. 2015. Standard D 198-15 Standard Test Methods of Static Tests of Lumber in Structural Sizes. West Conshohocken: ASTM International

Barrett, J.D., Hong, J.-P., 2010. Moisture content adjustments for dynamic modulus of elasticity of wood members. Wood Sci. Technol. 44, 485–495. https://doi.org/10.1007/s00226-009-0292-z

Cai, Z., Dickens J.R., 2004. Wood composite warping: modeling and simulation. Wood and Fiber Science, 36:174–185.

CSA. 2014. CSA-O86-14: Engineering design in wood. Toronto: CSA Group

CSA. 2016. CSA-O122-16: Structural glue-laminated timber. Toronto: CSA Group

Eriksson, J., Ormarsson, S., Petersson, H., 2005. An experimental and numerical study of shape stability in laminated timber columns. Holz Als Roh- Werkst. 63, 423–429. https://doi.org/10.1007/s00107-005-0058-8

Eriksson, J., Ormarsson, S., Petersson, H., 2004. An experimental study of shape stability in glued boards. Holz Als Roh- Werkst. 62, 225–232. https://doi.org/10.1007/s00107-004-0468-z

Johansson, G., Kliger, R., Perstorper, M., 1994. Quality of structural timber-product specification system required by end-users. Holz Als Roh- Werkst. 52, 42–48. https://doi.org/10.1007/BF02615017

Johansson, M., Kliger, R., 2002. Influence of Material Characteristics on Warp In Norway Spruce Studs. Wood Fiber Sci. 325–336.

Li, L., Gong, M., Chui, Y.H., Liu, Y., 2016. Modeling of the cupping of two-layer laminated densified wood products subjected to moisture and temperature fluctuations: model application. Wood Sci. Technol. 50, 39–51. https://doi.org/10.1007/s00226-015-0775-z

NLGA., 2015. NGLA SPS 6: Special Products Standard for Structural Face-Glued Lumber. New Westminster: National Lumber Grades Authority

Nocetti, M., Aminti, G., Vicario, M., Brunetti, M., 2024. Mechanical properties of ancient wood structural elements assessed by visual and machine strength grading. Construction and Building Materials, 411, https://doi.org/10.1016/j.conbuildmat.2023.134418.

Ormarsson, S., Cown, D., 2005. Moisture-Related Distortion of Timber Boards of Radiata Pine: Comparison With Norway Spruce. Wood Fiber Sci. 424–436.

Ormarsson, S., Dahlblom, O., Petersson, H., 1999. A numerical study of the shape stability of sawn timber subjected to moisture variation. Part 2: Simulation of drying board. Wood Sci. Technol. 33, 407–423. https://doi.org/10.1007/s002260050126

Perstorper, M., Johansson, M., Kliger, R., Johansson, G., 2001. Distortion of Norway spruce timber. Part 1. Variation of relevant wood properties. Holz Als Roh- Werkst. 59, 94–103. https://doi.org/10.1007/s001070050481

Serrano, R., Cassens,D., 2001. Reducing warp and checking in plantation-grown yellow-poplar 4 by 4's by reversing part positions and gluing in the green condition. Forest Products Journal, (37–40), Forest Products Society.

Wang, X., 2013. Stress Wave E-Rating of Structural Timber-Size and Moisture Content Effects. USDA For. Serv. For. Prod. Lab. Gen. Tech. Rep. FPL-GTR-226 2013, 38–46.

Yoon, H.S., Park, S.W., 2002. Determining the Structural Parameters That Affect Overall Properties of Warp Knitted Fabrics Using Cluster Analysis. Textile Research Journal, 72 (11):1013-1022. doi:10.1177/004051750207201114