Effect of Low Temperatures on the Block Shear Strength of Norway Spruce Glulam Joints

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The block shear strength of Norway spruce (*Picea abies* (L.) Karst.) glulam joints was tested under low temperatures. Glulam samples were glued with the three of the most common outdoor structural adhesives. The cold temperatures tested were 20, −20, −30, −40, −50, and −60 °C. Within the temperature test range, the block shear strength of the glulam joints was resistant to the effect of temperature. As the temperature decreased, the joints' block shear strength did not show any significant change. In most cases, phenol-resorcinol-formaldehyde (PRF) adhesive yielded the strongest block shear strength, while melamine-formaldehyde (MF) adhesive yielded the weakest block shear strength. Melamine-urea-formaldehyde (MUF) adhesive yielded similar results to those of MF adhesives for all temperatures tested. The block shear strengths of the glulam joints with PRF, MUF, and MF adhesives were not sensitive to temperature change. The results indicated that PRF, MUF, and MF adhesives are stable for outdoor structural engineered wood construction in cold climates. The results also suggest that the SS-EN 14080 (2013) standard for the block shear method may not be the proper standard for testing differences in shear strength at different temperatures. The EN 302-1 (2011) standard could be more suitable for this purpose.

Keywords: Block shear strength; Norway spruce; Outdoor structural adhesives; Glulam joints

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INTRODUCTION

The development of modern timber engineering has created a renewed use of wood as a building material. In light of environmental issues, the importance of increasing the use of wood-based structures becomes more and more clear, and it promotes the development of new, sustainable construction solutions.

There has been a wide range of applications of engineered wood products in structures worldwide in the last few decades. Glued-laminated timber (glulam), laminated veneer lumber (LVL), and cross-laminated timber (CLT) are commonly used in Europe and North America. Glued-laminated timber (glulam) is an engineered wood product fabricated by gluing lumber laminations together with a waterproof adhesive. Glulam became a popular and favourable material for wide span wood structures because of its lower variability in strength, greater flexibility in shape and length, and, of course, its attractive appearance. There are many large structures made from glulam around the world, including many timber bridges. For instance, in the north of Quebec province in

Canada (the temperature during winter could be -45 °C), Macaisagi Timber Bridge is made of a box-beam structure using cross-laminated timber (CLT) webs screwed to structural glued-laminated timber beams. Both CLT and glulam are made from spruce. This bridge has 68 m long span, and it can carry 180 tons custom truck heavy load. It has performed well since completion in 2011. Also in 2011 a cable-stayed timber footbridge, Älvsbacka Bridge, was erected in Skellefteå, Sweden. The Älvsbacka Bridge consists of approximately 200 tons of Norway spruce glulam. The bridge is located in the northern part of Sweden, where temperatures can range from below -30 °C to over 30 °C during the year.

As a consequence, concerns have arisen about the adhesive quality and bondline integrity of these engineered wood products, requiring that the adhesive joints in the engineered wood products be as strong and durable as the wood itself, especially when the strength properties of the engineered wood products are affected by both low temperatures and significant temperature changes. This issue is particularly important in regions such as Scandinavia, Greenland, the Alps, Canada, Alaska, Russia, Mongolia, northern China, and northern Japan. Wooden constructions in these areas are frequently exposed to low temperatures for a large portion of the year. However, thermal effects are usually not considered in the design and estimation of the service lifetime of wooden constructions.

Since the 1960s, the effects of cold temperatures on the mechanical properties of wood have been investigated. According to previous studies, the modulus of elasticity, compression, and bending strength of wood were all significantly increased with decreasing temperature, (Kollmann and Cote 1968; Geissen 1976; Gerhards 1982; USDA 2010; Jiang *et al.* 2014; Niemz *et al.* 2014; Zhao *et al.* 2015). Although the shear strength of wood has had very limited research attention at low temperatures, Yu and Östman (1983) investigated the tensile strength properties of particleboards between −15 °C and 45 °C.

Wood and adhesives have very different swelling and shrinkage coefficients. The glue line of most adhesives is also more brittle than wood. If not compensated for, any differences between the thermal properties of the wood and the adhesives can lead to performance problems when the construction is exposed to large temperature changes. In these cases, the design needs to compensate for differential movement of the components while still preserving structural integrity. The performance of glue lines at elevated temperatures is well documented (Frangi *et al*. 2004; Falkner and Teutsch 2006; Clauss *et al*. 2011). However, not much information is available on the stability of glue lines at low temperatures, especially extremely cold temperatures, although some studies of timber bridges in cold climates have been reported (Kainz and Ritter 1998; Wacker 2003, 2009).

The shear strength is a key index to assess the quality of glued wood products. Many different test methods have been proposed to determine the shear properties of wood and wood-based materials, such as block shear tests, torsion of prismatic bars, anticlastic bending, multipoint bending, the Iosipescu shear test, in-plane shear loading, *etc.* (Yoshihara and Matsumoto 2005). However, it is difficult to achieve a uniform state of shear stress in the test zone (Bodig and Jayne 1993). Shear test performance of glue lines is one of the important requirements during the quality control of bondlines in glulam manufacturers. For practical reasons, the one-sided block shear test is considered to be the most efficient method. The specimens are simple to fabricate, and the test process is easy to carry out. There are several standards regarding block shear tests of bondlines: in Europe, SS-EN 14080 (2013), in the USA, ASTM D 905-03 (2003), and more internationally, ISO 12579 (ISO 2006).

Recently, there have been some studies on the shear strength of solid wood and glued wood joints, both at elevated temperature (Clauss *et al*. 2011) and at low temperatures (Wang *et al.* 2015, 2016), according to EN 301 (2013) and EN 302-1 (2011). The latter studies investigated the shear strength of Norway spruce and Scots pine wood and glued joints in a cold climate (up to −60 °C). Although the block shear test of bondlines is the most common method used for the quality control of bondlines in glulam manufacturers, there have not been any studies on this topic so far.

The objective of this study was to determine the effect of low temperatures (20 °C to −60 °C) on the block shear properties of Norway spruce glulam bondlines. The three most common outdoor structural adhesives were tested at the selected temperatures according to the test protocol provided in SS-EN 14080 (2013).

EXPERIMENTAL

Materials

Bondline block shear strength experiments were carried out on Norway spruce (*Picea abies* (L.) Karst.) glulam samples. The average oven-dried density of the samples was 447 ± 28 kg/m^3, and the moisture content (MC) was 12% ± 1%. To test the bondline integrity of Norway spruce glulam under cold conditions, the three most common outdoor structural adhesives, those used in Martinsons AB (Skelleftea, Sweden) commercial glulam products, were used. The poly-condensation adhesives used for the study were as follows:

- Phenol-resorcinol-formaldehyde adhesive (PRF)
- Melamine-formaldehyde adhesive (MF)
- Melamine-urea-formaldehyde adhesives (MUF)

These adhesives have been certified according to the EN 301 (2013) and EN 302 (2011) standards for application in engineered wood products. In this study, the block shear strength of glued Norway spruce glulam joints was tested at different temperatures, according to SS-EN 14080 (2013). Table 1 shows the adhesives and the optimal gluing process information for the tested glulam samples, provided by Martinsons AB (Skelleftea, Sweden). Bonding pressure, pressing time, pressing temperature, and the adhesive amount applied, according to the glulam production mill at Martinsons AB, are also included.

Table 1. Adhesives and Optimal Gluing Process Information According to the Manufacturer

Adhesive	PRF A010/H010	MF 1265/7565	MUF 1247/2526
Hardener Ratio	14.1%	47.4%	29.1%
Application Amount (g/m^2)	212	211	219
Wood Moisture Content (%)	12	12	12
Bonding Pressure (MPa)	0.4	0.4	0.3
Pressing Time (min)	9	9	10
Pressing Temperature (°C)	84	86	88

The data were analyzed using the statistical software package IBM SPSS Statistics, Version 20 (IBM Corporation, New York, USA). An analysis of variance (ANOVA) was carried out using a 5% level of significance. When significant differences were found, Duncan's multiple-range test was performed to reveal any differences shown by the adhesives at different temperatures.

Methods

The glulam beams were cut into specimens with dimensions 40 mm to 50 mm (*b*) × 40 mm to 50 mm (*t*) × *l* mm, according to SS-EN 14080 (2013), as shown in Fig. 1. To ensure that the loaded surfaces were smooth, parallel to each other, and perpendicular to the direction of the glue line, the specimens were planed on the top and bottom surfaces. Ten specimens were prepared for each adhesive and temperature, and there were six tests performed on each specimen (Fig. 1). In total, 180 specimens were produced, and 180 × 6 tests were performed. All specimens were stored under standard climatic conditions (20 °C and 65% relative humidity) until equilibrium moisture content was reached. A mean value of 11.6% moisture content was found for the specimens.

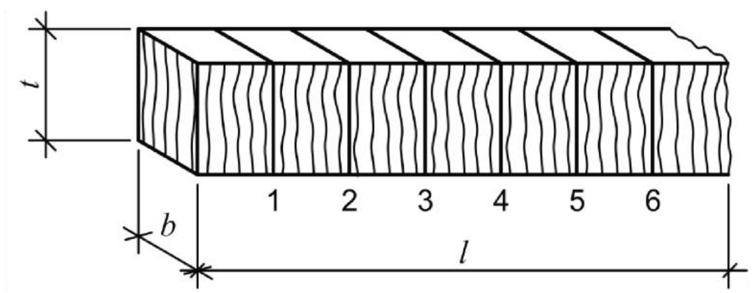

Fig. 1. Tested sample of glulam (adapted from SS-EN 14080 (2013) (Fig. D. 2))

To investigate the influence of temperature on glulam block shear strength, 10 specimens of each test set were tempered in a special climate chamber (at the company Adopticum in Skellefteå, Sweden) for 24 h at 20, −20, −30, −40, −50, and −60 °C, respectively. The block shear tests were executed in a universal testing machine equipped with a 100-kN load cell (Instron 5500R, Grove City, USA) at the SP Sustainable Built Environment (Skellefteå, Sweden) (Fig. 2). Under ramp loading, a shear stress was applied at the glue line between laminations of the glued laminated timber until failure occurred. The tests were performed in a position-controlled setup with a displacement rate of 2 mm/min to make sure the failure occurred within 20 s.

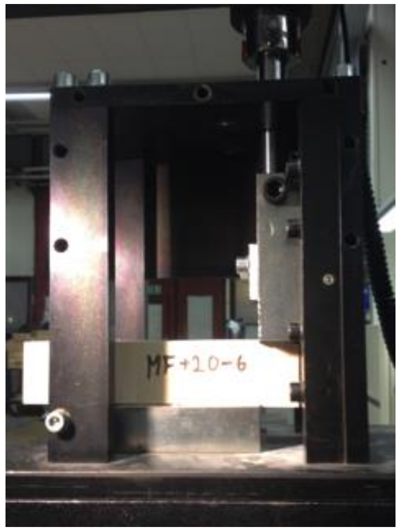

Fig. 2. Shear test machine and test specimen

RESULTS AND DISCUSSION

Impact of Temperature on Block Shear Strength for Each Type of Adhesive

Presented in Table 2 and Fig. 3 are the block shear strengths of Norway spruce glulam joints at different temperatures. The joints did not show a clear trend of decreasing shear strength as temperature decreased. Figure 3 shows the block shear strength of the bondline with three adhesives at various temperatures. When the temperature changed from 20 to −20 °C, the block shear strength of the glulam bondline with PRF, MUF, and MF increased.

Table 2. Block Shear Strengths (MPa) of Norway Spruce Glulam Joints at Different Temperatures

Temp. / Adhesive	20 °C	−20 °C	−30 °C	−40 °C	−50 °C	−60 °C	Total Block Shear Strength Change [c] (%)
PRF	10.24 (1.46) [a] A [b]	12.02 (1.60) B	12.10 (1.46) B	11.99 (1.68) B	10.79 (1.59) A	12.01 (1.67) B	-17.3
MUF	9.74 (1.54) A	11.16 (1.27) B	10.89 (1.55) B	10.79 (1.61) B	10.75 (1.56) B	10.79 (1.38) B	-10.8
MF	9.70 (1.11) A	10.78 (1.59) B	11.43 (1.64) C	10.34 (2.07) A, B	9.99 (1.42) A	9.67 (1.39) A	0.3

[a] Values in parentheses are sample standard deviations.
[b] Values with the same capital letter in each row are not statistically different at the 0.05 significance level.
[c] Total block shear strength change (%) = {(block shear strength$_{20\ °C}$ – block shear strength$_{-60\ °C}$) / block shear strength$_{20\ °C}$} × 100.

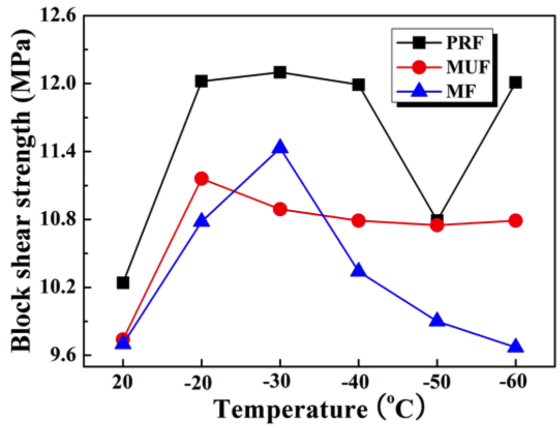

Fig. 3. Bondline block shear strength of Norway spruce glulam joints bonded with three specified adhesives at various temperatures

PRF

The block shear strength of the glulam bondline with PRF resin showed the lowest value at 20 °C. When the temperature was decreased from 20 to −20 °C, the block shear strength increased in a statistically significant manner (10.24 to 12.02 MPa) at the 0.05 significance level (P value less than 0.05). It remained higher until −40 °C (11.99 MPa). The block shear strength then dropped substantially at −50 °C (10.79 MPa), but at −60 °C, it was surprisingly increased again, showing the high value (12.01 MPa).

Statistically, the block shear strengths were categorized into two temperature sectors with no overlap: 1) 20 and −50 °C; and 2) −20 to −40 °C, and −60 °C. In Sector 1, at 20 and −50 °C, the block shear strengths were significantly lower than those in Sector 2 at −20 to −40 °C, and −60 °C. Phenol-resorcinol-formaldehyde adhesive is historically the most established adhesive for cold setting bondline applications, and it is conventionally used in load-bearing constructions of engineered wood. The data presented in Table 2 indicated that the block shear strength of PRF adhesive-bonded Norway spruce is stable under cold temperatures.

MUF

The block shear strength of MUF adhesive-bonded Norway spruce glulam joints showed the lowest value at 20 °C (9.74 MPa), and it increased significantly when the temperature decreased from 20 to −20 °C (11.16 MPa). However, the change in block shear strength did not demonstrate statistical difference from −20 to −60 °C (11.16 to 10.79 MPa). Decreasing temperature did not seem to affect the block shear strength of MUF adhesive-bonded Norway spruce glulam.

MF

The block shear strength of MF adhesive-bonded Norway spruce glulam joints displayed the second lowest value at 20 °C (9.70 MPa). When the temperature decreased from 20 to −20 °C, the block shear strength increased in a significant manner (9.70 to 10.78 MPa). The highest value was at −30 °C (11.43 MPa), and then it dropped significantly at −40 °C (10.34 MPa). For −50 and −60 °C (9.99 and 9.67 MPa, respectively), it decreased much more, showing the lowest value at −60 °C.

Statistically, the block shear strengths were categorized into three temperature sectors with an overlap: 1) 20, −40, −50, and −60 °C; 2) −20 and −40 °C; 3) −30 °C. As with PRF, the data in Table 2 indicated that the block shear strength of MF adhesive-bonded Norway spruce is difficult to explain.

Impact of Temperature on Wood Failure for Each Type of Adhesive

Tables 3 demonstrates the wood failure percentage of block shear Norway spruce glulam joints at various temperatures. Norway spruce glulam did not show a clear trend of increasing wood failure percentage of block shear strength as temperature decreased.

Table 3. Wood Failure (%) of Norway Spruce Glulam Joints at Various Temperatures

Adhesive/ Temp.	20 °C	−20 °C	−30 °C	−40 °C	−50 °C	−60 °C
1-PRF	78.9 (25.1)[1] A, B[2]	78.5 (22.3) A, B	82.1 (15.7) A, B	73.8 (24.1) A	78.8 (17.6) A, B	85.3 (14.7) B
2-MUF	86.6 (24.0) A, B	78.4 (31.2) A	87.1 (19.6) A, B	90.8 (17.7) B	77.6 (28.1) A	79.4 (24.8) A, B
3-MF	84.8 (22.7) A	86.3 (18.6) A	84.3 (16.4) A	94.5 (8.1) B	95.6 (6.7) B	88.9 (19.9) A, B

[1] Values in parentheses are sample standard deviations.
[2]Values with the same capital letter in each row are not statistically different at the 0.05 significance level.

PRF

The wood failure percentage of block shear strength of the glulam bondline with PRF resin showed a low value at 20 °C. It did not change significantly when the temperature decreased from 20 to −30 °C (78.9% to 82.1%). The lowest value was observed at −40 °C (73.8%), but it then increased a bit at −50 °C (78.8%). At −60 °C, however, it increased, showing the highest value (85.3%).

Statistically, the block shear strengths were categorized into two temperature sectors with no overlap: 1) −40 °C; 2) 20 to −30 °C, and −50 °C; and 3) −60 °C. In Sector 1 at −40 °C, the wood failure percentage of block shear strength was significantly lower than that in Sector 3 at −60 °C.

MUF

The wood failure percentage of block shear strength of the glulam bondline with MUF resin displayed quite a high value at 20 °C (86.6%), but it demonstrated significantly lower values at −20 and −50 °C (78.4% and 77.6%). The highest wood failure percentage was at −40 °C (90.8%). The trend is up and then down; it is difficult to explain the reason.

MF

The wood failure percentage of block shear strength of MF adhesive-bonded Norway spruce glulam joints showed the lowest values at 20 to −30 °C (84.8% to 84.3%). The value increased significantly when the temperature decreased to −40 °C (94.5%) and −50 °C (95.6%), but when the temperature decreased further to −60 °C, the wood failure percentage decreased (88.9%).

Statistically, the wood failure percentage of block shear strength of the glulam bondline with MF resin was categorized into two temperature sectors with an overlap: 1) 20 to −30 °C, and −60 °C; 2) −40, −50, and −60 °C. The wood failure percentage was significantly lower in Sector 1 than in Sector 2.

Discussion

The data in Table 2 indicated that the block shear strengths of PRF, MUF, and MF adhesive-bonded Norway spruce glulam joints are difficult to explain. The block shear strength difference at different temperatures may be due to the difference in the elastic properties of different adhesives. Stiffness of an adhesive may affected glulam block shear strength. It follows that low temperature may affect the elastic properties of an adhesive, resulting in a reduction of the block shear strength. Such issues should be more investigated in the future.

Moreover, the differences in the block shear strengths of different adhesive-bonded Norway spruce glulam joints may originate from the adhesives' ultrastructure differences. For example, PRF adhesive is mainly constructed with benzene rings, whereas MUF adhesive is composed of a urea component and melamine ring. It is assumed that these structures react differently at different temperature levels, but the reactions to wood of the different adhesives are quite speculative, and therefore inconclusive, because of the limitations of the test/analysis methods used.

The results of Wang *et al.* 2015 (Fig. 4) on the shear strength (according to EN 302-1) of Norway spruce wood joints bonded with the same three specified adhesives (PRF, MUF, and MF) at different temperatures showed a clear trend of decreasing shear strength when the temperature decreased.

However, the block shear strength of PRF, MUF, and MF adhesive-bonded Norway spruce glulam demonstrated a strange trend in this study (Fig. 3). The reason might be because it is difficult to shear (cut) exactly on the bondline, which is only 0.1 mm in width. This result may lead to the conclusion that the SS-EN 14080 (2013) standard for block shear might not be a proper standard to follow for testing the differences in shear strength at different temperatures.

The EN 302-1 (2011) standard, "Adhesives for load-bearing timber structures – Test methods – Part 1: Determination of longitudinal tensile shear strength," might possibly be a better standard for measuring the differences in shear strength at different temperatures.

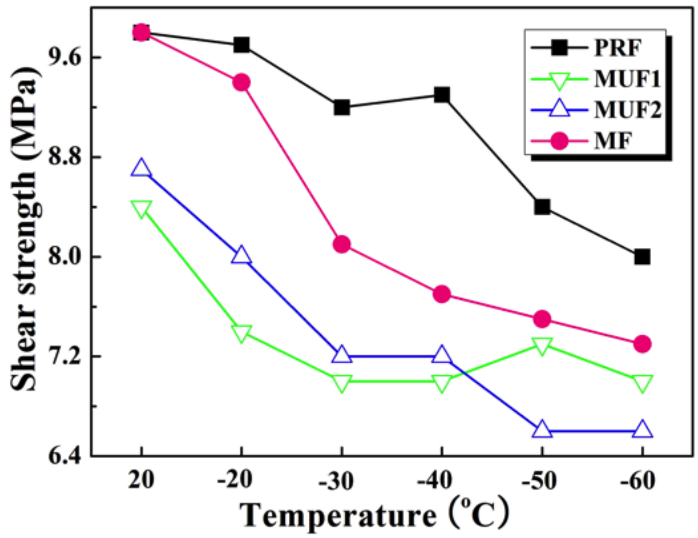

Fig. 4. Bondline shear strength (according to EN 302-1) of Norway spruce wood joints bonded with three specified adhesives at different temperatures (adapted from Wang *et al.* 2015)

CONCLUSIONS

1. The block shear strengths of Norway spruce glulam with PRF, MUF, and MF adhesive-bonded joints at temperatures of 20, −20, −30, −40, −50, and −60 °C were studied. Generally, within the temperature test range, the block shear strengths of Norway spruce glulam joints did not show the effects of temperature changes. As the temperature decreased, the joints' block shear strength did not show any statistically significant change. In most cases, PRF adhesive yielded the strongest block shear strength, while MF adhesive yielded the weakest block shear strength. The block shear strength yielded by MUF adhesive was very similar to that of MF adhesives for all temperatures tested.
2. The block shear strength of Norway spruce glulam joints with PRF, MUF, and MF adhesives was not sensitive to temperature change. These results indicate that PRF, MUF, and MF adhesives could be stable for outdoor structural engineered wood construction in cold climates.
3. The data created through the block shear experiment were, for most of the results, difficult to explain, unlike Norway spruce shear results according to EN 302-1 (2011) (Wang *et al*. 2015). This discrepancy suggests that the SS-EN 14080 (2013) standard for block shear may not be the proper standard to follow for testing the differences in shear strength at different temperatures. The EN 302-1 (2011) standard could be more suitable for this purpose.

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