Technical University of Denmark

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# WOOD CONSTRUCTION UNDER COLD CLIMATE
## Part one: Impact of cold temperatures on the shear strength of different adhesives glued wood joints of Norway spruce and Scots pine

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**ABSTRACT:** As wood constructions increasingly use engineered wood products worldwide, concerns arise about the integrity of the wood and adhesives system. The glueline stability is a crucial issue for engineered wood application, especially under cold climate. In this study, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) joints (150mm x 20mm x 10mm) were bonded with seven commercially available resins (PUR, PVAc, EPI, MF, MUF1, PRF and MUF2) and tested at six temperatures (20, -20, -30, -40, -50 and -60 °C), respectively. Generally, for both species, temperature changes significantly affected shear strength of wood joints. As temperature decreased, the shear strength decreased. PUR resin resulted in the strongest shear strength at all temperatures tested. MF resin responded to temperature changes in a similar ways as the PUR resin. The shear strength of wood joints with EPI resins was sensitive to temperature change. MUF, PRF and PVAc resins demonstrated different characters with Norway spruce and Scot pine. At room temperature, all types of adhesive showed relative stability, in terms of shear strength variation. While at low temperature, the shear strength varied considerably. More specimens need to be tested in further work to more completely present the issue. The EN 301 and EN 302 may need to be specified based on wood species.

**KEYWORDS:** Engineered Wood Products, Glueline Stability, Cold Climate, Shear Strength.

## 1 INTRODUCTION

The building industry is increasingly using engineered wood products such as glued-laminated timber (glulam), laminated veneer lumber (LVL), structural-composite lumber (SCL), and cross laminated timber (CLT). Engineered wood applications in bridges are also common in Europe and North America. With no doubt, adhesive qualities and the bondline integrity are the key parts of these engineered wood products and play an important role in the performance of these products. The response of bondlines to temperature changes will affect the integrity of a wood structure. The knowledge of the integrity is important in the regions and countries like Scandinavia, Greenland, Alps, Canada, Alaska, Russia, Mongolia, North China and North Japan. Wood constructions in these areas are frequently exposed to low temperatures for quite a long time period each year. In addition to that, thermal effects are usually not considered in the design and service life of wood constructions. Wood and adhesives have different properties in terms of swelling and shrinkage. The cured adhesives are also often more brittle than wood. If not compensated for, different properties between wood and adhesives, such as thermal properties may lead to performance problems when the wooden construction is exposed to large temperature changes. Relatively, the performance of bondlines at elevated temperatures is quite well documented [1, 2, 3]. Not much information is available on the stability of bondlines at low temperatures and especially under extremely cold conditions, though some studies have been conducted on timber bridges in cold climates [4, 5, 6].

The objective of the whole project is to determine how engineered wood product reacts when exposed to temperatures from 20 to -60°C. But in this paper (Part I - it is the first step of the whole project), the shear strength of

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Norway spruce and Scots pine wood joints bonded with seven commercially available adhesives was tested at the selected temperatures, according to EN 302-1 (2011).

# 2 MATERIALS AND METHODS

## 2.1 MATERIALS

### 2.1.1 Wood

The wood components used for the tests in this study were Norway spruce (Picea *abies*) and Scots pine (*Pinus sylvestris*) with the average density of 450 and 470 kg/m$^3$ and equilibrium moisture content (EMC) of 12%. The growth ring angle (angle between growth rings and glued surface of the specimen) of the wood was between 30 and 90°.

### 2.1.2 Adhesives

To test the bondline integrity under cold conditions, seven different commercially available adhesives from different producers were chosen. These seven adhesives vary in their chemical composition and most of the resins have been certified according to EN 301 (2006), EN 302 (2011) and EN 15425 (2008) [7, 8, 9]. standards for engineered wood products application. These seven adhesives are:

- One-component polyurethane resin (PUR)
- Poly(vinyl acetate) resin (PVAc)
- Emulsion-polymer-isocyanate resin (EPI)
- Melamine-formaldehyde resin (MF)
- Melamine-urea-formaldehyde resin (MUF1)
- Phenol-resorcinol-formaldehyde resin (PRF)
- Melamine-urea-formaldehyde resin (MUF2)

Table 1 demonstrates the formula and operational parameter information during gluing for each adhesive, recommended by the adhesive manufacturers. The pressure, pressing time, and adhesive amount applied in this study were according to the adhesive suppliers' recommendations.

***Table 1:*** *Adhesives and related gluing process information settings*

| Adhesive | Adhesive hardener ratio | EN301/ 302 certifi-cation | Wood MC (%) | Pressure (MPa) | Pressing Time (Minute) | Temp. ($^o$C) |
|---|---|---|---|---|---|---|
| PUR | -- | √ | ≥8 | 0.3 | 30 | 20 |
| PVAc | -- | -- | 7-10 | 0.3 | 30 | 20 |
| EPI | 100:15 | √ | 8-15 | 0.3 | 30 | 20 |
| MF | 100:100 | √ | ≈12 | 0.3 | 70 | 20 |
| MUF1 | 100:20 | √ | ≈12 | 0.3 | 15 | 90 |
| PRF | 100:15 | √ | ≈12 | 0.5 | 60 | 40 |
| MUF2 | 100:100 | √ | ≈12 | 0.5 | 120 | 20 |

## 2.2 METHODS

### 2.2.1 Solid wood specimens preparation

To obtain a reference value for the strength of the glued specimens, non-glued solid wood specimens with same dimensions were tested. These specimens were prepared according to the requirements of EN 302-1.

### 2.2.2 Testing procedure

The shear strength tests were conducted according to EN 302-1. To investigate the influence of the temperatures on shear strength, 15 specimens of each test set were tempered in a special climate chamber (Vötsch industrietechnik vcv7120-5) (at the Department of Civil Engineering at Technical University of Denmark) for twelve hours at -20, -30, -40, -50 and -60°C, respectively (Due to technical problem, Scots pine samples could not be tested at -60°C for this paper). The tests were executed on a universal testing machine in the climate chamber (Figure 1) at the designed temperature. The tests were performed in a position-controlled model with a feed speed of 2 mm/min. After the shear strength test, the wood failure percentage of each tested specimen was estimated visually in a graded scale of 5%-steps, as recommended in EN 302-1.

***Figure 1:*** *Climate chamber, shear test machine and test specimens*

### 2.2.3 Data analyse

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, and the 5% level of significance was used. When significant differences were found, Duncan's multiple-range test was performed to reveal the difference caused with different adhesives at different temperatures. And significant differences were marked by different letters.

Based on Duncan test, the performance of bondlines with different adhesives was discussed within different temperature zones, to further reveal the difference in different adhesives.

# 3 RESULTS AND DISCUSSION

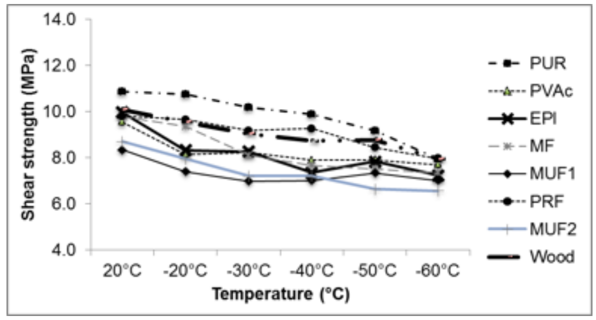
## 3.1 TEMPERATURE IMPACT ON SHEAR STRENGTH FOR EACH TYPE OF GLUE

Presented in Table 2 and Figure 2 (1) are the shear strength of Norway spruce bondlines and control samples. Presented in Table 3 and Figure 2 (2) are the shear strength of Scots pine bondlines and control samples at different temperatures. The general trend was that as temperature decreased, the shear strength of wood joints with and without adhesives decreased. Shear strength variations also changed with temperature. Compared to 20°C, the shear strength tested at -30°C had greater variation, indicating that a good quality control of bondline for low temperature application was more challenging than for normal temperatures. Wood failure percentages of wood joints with seven types of glue at six different temperatures are demonstrated in Table 4 (Norway spruce) and Table 5 (Scots pine). Detailed discussion follows.

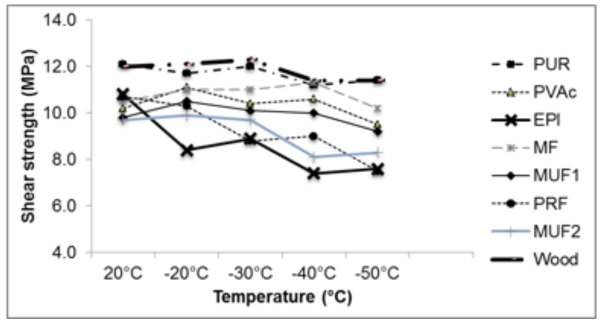
***Table 2:*** *Shear strengths (MPa) of Norway spruce wood joints at different temperatures*

| Temp. /Glue | PUR | PVAc | EPI | MF | MUF1 | PRF | MUF2 | Wood |
|---|---|---|---|---|---|---|---|---|
| 20°C | 10.9 (1.0)[1] A[2] | 9.6 (0.6) A | 10.0 (1.1) A | 9.8 (0.9) A | 8.3 (1.1) A | 9.8 (1.0) A | 8.7 (0.7) A | 10.1 (0.9) A |
| -20°C | 10.8 (2.3) A, B | 8.1 (1.2) B | 8.3 (1.6) B | 9.4 (2.3) A | 7.4 (1.2) A | 9.7 (1.8) A | 7.9 (1.1) A, B | 9.5 (1.1) A, B |
| -30°C | 10.2 (2.9) A, B | 8.2 (1.2) B | 8.3 (2.0) B | 8.1 (2.5) A, B | 7.0 (1.9) A | 9.2 (2.0) A, B | 7.2 (1.9) B, C | 9.0 (0.9) A, B, C |
| -40°C | 9.9 (1.5) A, B | 7.9 (1.9) B | 7.3 (1.5) B | 7.7 (1.4) B | 7.0 (2.2) A | 9.3 (1.4) A, B | 7.2 (1.3) B, C | 8.7 (1.3) B, C |
| -50°C | 9.2 (1.3) B, C | 7.9 (1.8) B | 7.8 (1.4) B | 7.5 (1.2) B | 7.3 (1.6) A | 8.4 (1.7) A, B | 6.6 (0.9) C | 8.8 (1.5) B, C |
| -60°C | 7.9 (1.4) C | 7.7 (1.1) B | 7.2 (1.5) B | 7.3 (1.7) B | 7.0 (0.7) A | 8.0 (1.4) B | 6.6 (1.3) C | 8.0 (0.9) C |
| Total shear strength change (%)[3] | 27.5 | 19.8 | 28.0 | 25.5 | 15.7 | 18.4 | 24.1 | 20.8 |

*[1] Values in parentheses are sample standard deviations.*
*[2] Values with the same capital letter in each column are not statistically different at the 0.05 significance level.*
*[3] Total shear strength change (%) = ((Shear Strength $_{20°C}$ - Shear Strength $_{-60°C}$)/ Shear Strength $_{20°C}$)*100.*



(1)



(2)

***Figure 2:*** *Bondline shear strength of tested wood specimens with different types of glues at different temperatures (1) Norway spruce (2) Scots pine*

***Table 3:*** *Shear strengths (MPa) of Scots pine wood joints at different temperatures*

| Temp. /Glue | PUR | PVAc | EPI | MF | MUF1 | PRF | MUF2 | Wood |
|---|---|---|---|---|---|---|---|---|
| 20°C | 12.1 (1.5)[1] A[2] | 10.2 (1.5) A, B | 10.8 (2.0) A | 10.5 (2.0) A | 9.8 (1.4) A | 10.7 (0.9) A | 9.7 (1.5) A | 12.0 (2.0) A |
| -20°C | 11.7 (3.0) A | 11.1 (1.6) A | 8.4 (4.6) A, B | 11.0 (2.1) A | 10.5 (1.4) A | 10.3 (2.6) A | 9.9 (2.4) A | 12.1 (1.5) A |
| -30°C | 12.0 (2.7) A | 10.4 (1.9) A, B | 8.9 (3.2) A, B | 11.0 (2.6) A | 10.1 (1.7) A | 8.8 (3.1) A, B | 9.7 (1.8) A | 12.3 (1.6) A |
| -40°C | 11.2 (1.8) A | 10.6 (1.7) A, B | 7.4 (2.2) B | 11.3 (1.7) A | 10.0 (1.5) A | 9.0 (3.3) A, B | 8.1 (3.9) A | 11.4 (1.6) A |
| -50°C | 11.4 (2.2) A | 9.5 (1.6) B | 7.6 (2.2) B | 10.2 (2.4) A | 9.2 (1.8) A | 7.5 (2.5) B | 8.3 (1.9) A | 11.4 (2.0) A |
| Total shear strength change (%)[3] | 5.8 | 6.9 | 29.6 | 2.9 | 6.1 | 29.9 | 14.4 | 5.0 |

*[1] Values in parentheses are sample standard deviations.*
*[2] Values with the same capital letter in each column are not statistically different at the 0.05 significance level.*
*[3] Total shear strength change (%) = ((Shear Strength $_{20°C}$ - Shear Strength $_{-50°C}$)/ Shear Strength $_{20°C}$)*100.*

***Table 4:*** *Wood failure percentage (%) of Norway spruce wood joints bonded with different types of glue*

| Glue/Temp. | 20°C | -20°C | -30°C | -40°C | -50°C | -60°C |
|---|---|---|---|---|---|---|
| PUR | 77 (28)[1] A[2] | 75 (23) A, B | 73 (33) A, B | 70 (36) A | 72 (33) A | 65 (34) A, B |
| PVAc | 83 (21) A | 93 (10) A, B | 92 (12) A | 82 (28) A | 83 (22) A | 86 (15) A |
| EPI | 83 (29) A | 82 (24) A, B | 77 (37) A, B | 74 (40) A | 76 (38) A | 58 (27) B |
| MF | 84 (16) A | 95 (14) A | 87 (28) A, B | 88 (26) A | 85 (18) A | 80 (21) A, B |
| MUF1 | 72 (35) A | 69 (41) B | 55 (40) B | 58 (43) A | 91 (13) A | 55 (39) B |
| PRF | 71 (17) A | 74 (30) A, B | 79 (29) A, B | 79 (25) A | 69 (30) A | 76 (18) A, B |
| MUF2 | 73 (27) A | 76 (37) A, B | 71 (31) A, B | 76 (33) A | 87 (17) A | 76 (28) A, B |

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

***Table 5:*** *Wood failure percentage (%) of Scots pine wood joints bonded with different types of glue*

| Glue/Temp. | 20°C | -20°C | -30°C | -40°C | -50°C |
|---|---|---|---|---|---|
| PUR | 85 (25)[1] A, B[2] | 83 (30) A | 91 (15) A | 91 (16) A, B | 98 (4) A |
| PVAc | 93 (11) A, B | 98 (6) | 95 (19) A | 98 (6) A | 100 (0) A |
| EPI | 79 (29) B | 53 (45) B | 64 (45) B, C | 59 (44) C | 66 (44) C |
| MF | 99 (5) A | 97 (8) A | 100 (0) A | 99 (3) A | 100 (0) A |
| MUF1 | 90 (16) A, B | 96 (10) A | 93 (22) A | 95 (9) A | 93 (17) A, B |
| PRF | 77 (25) B | 75 (30) A | 59 (38) C | 73 (25) B, C | 63 (30) C |
| MUF2 | 82 (22) A, B | 84 (30) A | 83 (28) A, B | 60 (45) C | 76 (34) B, C |

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

### 3.1.1 Solid wood specimens

As temperature decreased from 20 to -60°C, the shear strength of tested solid Norway spruce wood specimens decreased from 10.1 to 8.0 MPa, indicating that temperature changes had a statistically significant impact on wood shear strength. It dropped 20.8% from 20 to -60°C. The shear strength decreased significantly and was lower than 10 MPa already at -20°C, not meeting the standard requirement (EN 301, 2006). This indicates that the impact of low temperature on wood and wood composite products needs further attention. The related standards may need updating. Statistically, shear strengths tested were categorized into three overlapped temperature zones: 1) 20 to -30°, 2) -20 to -50°C and -30 to -60°C. In Zone 1 at 20°C, the solid wood shear strength was significantly higher than that in Zone 2 at -40 and -50°C, and the shear strength in Zone 3 at -60°C. This indicates that as temperature dropped, the solid wood shear strength was gradually decreased. Since general trend showed that MOE and bending strengths of wood increased as temperature decreased [10]. Further research is needed to verify these test results.

The shear strength of tested solid Scots pine wood specimens decreased only from 12.0 to 11.4 MPa, showing the temperature changes had no statistically significant impact on wood shear strength. The shear strengths were always higher than 10 MPa at 20 to -50°C, meeting the standard requirement (EN 301, 2006).

Compared to Norway spruce, when subject to different temperatures, Scots pine did not show a trend of shear strength as temperature decrease. The reason for this observation needs to be found in the future research.

### 3.1.2 PUR

Similar to solid wood, as temperature decreased from 20 to -60°C, the shear strength of tested PUR bondlines with Norway spruce wood joints decreased from 10.9 MPa to 7.9 MPa, indicating that temperature changes had a significant impact on the shear strength of PUR resin bonded wood joints. The shear strength dropped 27.5% from 20 to -60°C (Table 2). Statistically, shear strengths tested were categorized into three temperature zones with some extent of overlap: 1) 20 to -40°C, 2) -20 to -50°C and -50 to -60°C. In Zone 1 at 20°C, the wood joint shear strength was significantly higher than that in Zone 2 at -50°C, and the shear strength in Zone 3 at -60°C. This indicates that as temperature dropped, the shear strength of the PUR resin bonded wood joints was gradually decreased. Though shear strength decreased significantly, there was no significant difference in wood failure percentage, from 77% at 20ºC to 65% at -60ºC (Table 4).

For Scots pine, very similar to solid wood, the shear strength of PUR resin bonded wood joints decreased only from 12.1 to 11.4 MPa, showing the temperature changes had no statistically significant impact on shear strength. The shear strengths were always higher than 10 MPa at 20 to -50°C, meeting the standard requirement (EN 301, 2006). The wood failure percentage of Scots pine did not show any significant difference with PUR bonds (Table 5).

### 3.1.3 PVAc

As temperature decreased from 20 to -60°C, the shear strength of PVAc resin bonded Norway spruce wood joints decreased from 9.6 to 7.7 MPa, a drop of 19.8%. Compared to solid wood and PUR resin bonds, all of the shear strength of PVAc resin bonded wood joints were lower, at any temperature tested. Statistically, shear strengths tested were categorized into two temperature zones with no overlap: 1) 20°C and 2) -20 to -60°C. It shows that when temperature decreased from 20°C to -20°C, the wood joint shear strength was significantly decreased, indicating that the shear strength of wood joints with PVAc was sensitive to temperature change. However, when temperature further decreased from -20 to -60°C, the shear strength did not decrease much. It was also noticed that the wood joints bonded with PVAc resin was lower than 10 MPa even at 20°C, not meeting the minimum shear strength requirement of EN 301. This is an important observation for further work and discussion with the standard and glue properties. For wood failure percentage, there was no significant difference among samples at different temperatures, from 83% at 20ºC to 86% at -60ºC.

As temperature decreased from 20 to -50°C, the shear strength of PVAc resin bonded Scots pine wood joints decreased from 10.2 to 9.5 MPa, a drop of 6.9%. The shear strength was significantly different at -50°C. Same as Norway spruce, no significant difference was found for the wood failure percentage of Scots pine with PVAc bonds, from 93% at 20ºC to 100% at -50ºC.

#### 3.1.4 EPI

Similar to PVAc resin, the shear strength of tested EPI resin bonded wood joints decreased significantly when temperature decreased from 20 to -20°C, indicating that shear strength developed by EPI resin was sensitive to temperature changes. As temperature decreased from 20 to -60°C, shear strength decreased from 10.0 to 7.2 MPa, a drop of 28%. Compared to solid wood and PUR resin bonds, the shear strength of EPI resin bonded wood joints was lower, at any lower temperature tested. Statistically, shear strengths tested were categorized into two temperature zones with no overlap: 1) 20°C and 2) -20 to -60°C. Within Zone 2, as temperature decreased from -20 to -60°C, the shear strength did not decrease much. Same as PUR and PVAc resin bonds, statistically, no significant difference could be found at all tested temperatures in wood failure percentage, even though it dropped from 83% at 20°C to 58% at -60°C.

For Scots pine samples, shear strength developed by EPI resin was sensitive to temperature changes. Even when temperature decreased from 20 to -20°C, the shear strength decreased significantly from 10.8 to 8.4 MPa. Total shear strength of EPI resin bonded Scots pine wood joints decreased from 10.8 to 7.6 MPa from 20 to -50°C, dropped 29.6%. For the wood failure percentage, there is no statistical significant difference of Scots pine boned with EPI. It varied from 79% at 20°C to 66% at -50°C.

#### 3.1.5 MF

The shear strength of MF resin bonded Norway spruce wood joints decreased significantly (25.5%), when temperature decreased from 20 to -60°C. Compared to solid wood and PUR resin bonds, the shear strength of MF resin bonded wood joints was lower, at any temperature tested. Statistically, shear strengths tested were categorized into two temperature zones with some overlap: 1) 20 to -30°C and 2) -30 to -60°C, indicating a relative good bondline quality developed by MF resin, as compared with MUF resins (MUF1 and MUF2). The wood failure percentage at different temperatures was not significant different. It varied from 84% at 20°C to 80% at -60°C.

For Scots pine, the shear strength of MF resin bonded wood joints was not significantly different (2.9%) when temperature decreased from 20 to -50°C. The shear strengths were always higher than 10 MPa from 20 to -50°C, meeting the standard requirement (EN 301, 2006). Almost full wood failures were found for Scots pine bonds with MF for all temperatures tested (99% at 20°C till 100% at -50°C).

#### 3.1.6 MUF (MUF1 and MUF2)

The shear strength of MUF1 resin bonded Norway spruce wood joints, as temperature decreased from 20 to -60°C, decreased 15.7%. When temperature changed from -20 to -60°C, it did not affect statistically the wood failure percentage, though it dropped from 72 % to 55%.

As temperature decreased from 20 to -60°C, the shear strength of MUF2 resin bonded wood joints decreased from 8.7 to 6.6 MPa. These values were the lowest of all tested glue types. The total shear strength drop was 24.1%. The wood failure percentage at different temperatures was not significantly different from each other and it varied from 73% at 20°C to 76% at -60°C. Statistically, shear strengths obtained were categorized into three temperature zones with some extent of overlap: 1) 20 to -20°C, 2) -20 to -40°C, and -30 to -60°C, indicating the MUF2 resin was relatively sensitive to temperature change.

For Scots pine, the shear strengths of MUF1 and MUF2 resin bonded wood joints were not significantly different, when temperature decreased from 20 to -50°C (For MUF1: 9.8 to 9.2 MPa and for MUF2: 9.7 to 8.3 MPa). There is no statistical significant difference in the wood failure percentage for Scots pine bonds with both MUF1 and MUF2.

#### 3.1.7 PRF

Conventional PRF resin is historically the most established resin for cold setting bondline applications. However, the data in Table 2 indicate that the shear strength of PRF resin bonded Norway spruce did not meet the EN 301 requirement, which may be due to the test parameters selected.

As temperature decreased from 20 to -60°C, the shear strength of PRF resin bonded wood joints decreased from 9.8 to 8.0 MPa, a 18.4% drop, indicating that temperature changes had a significant impact on the shear strength. The shear strengths of wood joints bonded with PRF resin at different temperatures were varied as compared to that of solid wood at corresponded temperature. But wood failure percentage showed no significant difference at temperature range from 20 to -60°C. Statistically, shear strengths tested were categorized into two temperature zones with some extent of overlap: 1) 20 to -50°C, 2) -30 to -60°C. In Zone 1 at 20°C, the wood joint shear strength was only significantly higher than that in Zone 2 at -60°C, indicating that as temperature dropped, the shear strength of the PRF resin bonded wood joints was moderately decreased, showing that the bondline integrity was quite stable during temperature change.

For Scots pine, as temperature decreased from 20 to -50°C, the shear strength of PRF resin bonded wood joints decreased from 10.7 to 7.5 MPa, a 29.9% drop, indicating that temperature changes had a significant impact on the shear strength. The shear strength was significantly different at -50°C, but no statistical significant difference was found for the wood failure percentage of Scots pine bonds with PRF (from 77% at 20°C to 63% at -50°C).

In general, there is no statistical significant difference in the wood failure percentage both for Norway spruce and Scots pine bonded with the same adhesive for all the temperatures tested. But the statistical significant difference was found in the wood failure percentage both for Norway spruce and Scots pine at same temperature bonded with different adhesives (see Tables 4 and 5).

## 4 CONCLUSIONS

Following conclusions can be drawn:

1. Generally, for both species, temperature changes significantly affected shear strength of wood joints. As temperature decreased, the shear strength decreased.
2. PUR resin resulted in the strongest shear strength at all temperatures tested. MF resin responded to temperature changes in similar ways as the PUR resin. The shear strength of wood joints with EPI resins was sensitive to temperature change. MUF, PRF and PVAc resins demonstrated different characters with Norway spruce and Scots pine.
3. At room temperature, all types of adhesive showed relative stability, in terms of shear strength variation. While at low temperature, the shear strength varied considerably. More specimens need to be tested in further work to more completely present the issue. More formulations should be tested to represent those entire classes of wood adhesives.
4. Since the data created through the experiment mostly did not meet the shear strength requirement of EN 301 and EN 302, especially at low temperatures. It suggests that the influence of diminished shear strength of bondlines at low temperature on load carrying capacity of glulam should be studied to develop new design methods of products.

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