Effect of Cold Temperatures on the Shear Behavior of Glued Laminated Beams

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ABSTRACT

This study evaluated the effects of subfreezing temperatures and moisture content on the shear behavior of glulam beams. Full-scale glulam beams (79 mm by 229 mm deep) at two moisture contents (12 and 28 percent) and three temperatures (20°C, 0°C, and -40°C) were tested in four-point bending until failure. Temperature was observed to affect the failure mechanism of the beams, with the beams tested at 0°C and 20°C failing in shear and the beams tested at -40°C failing in tension. Further, the strengths of the beams and their stiffnesses were observed to increase with decreasing temperature, with these effects being more pronounced in the higher moisture content beams. Over the temperature range of 20°C to -40°C, the 12 percent moisture content beams observed strength and stiffness gains of 17 and 22 percent, while the 28 percent moisture content beams observed respective gains of 37 percent and 66 percent.

KEYWORDS

Cold effects

Glulam beams

Wood

Shear strength

Stiffness

1 INTRODUCTION

Glued-laminated (glulam) timber beams are commonly used in external applications in which the beams are exposed to varying moisture conditions and temperatures. The research discussed herein investigated how these conditions affect the performance of glulam beams, and in particular this research investigated how varying moisture content (MC) and subfreezing temperatures affect the shear capacity and stiffness of shear-critical glulam beams. This research will give designers a better understanding of these elements in these conditions and may ultimately result in safer, more economical designs.

A significant amount of research has been conducted over the past fifty years on the behavior of wood specimens at various temperatures and MCs. However, a majority of these studies have investigated the reversible and non-reversible effects of elevated temperatures, with less work being done on the effects of cold temperatures. Gerhards [1] provided a summary of the work completed at the time (1982) on the effects of temperature on clear wood samples, which included cold temperatures. In general, this work indicated that the strength and stiffness of clear wood and timber tend to increase with decreasing temperatures. Furthermore, increased MC was shown to amplify the increase in flexural properties at subfreezing temperatures. Green and Evans [2] and Green et al. [3] investigated how the modulus of elasticity of clear wood is affected by cold temperatures and subsequently how this may affect mechanical grading techniques. The findings from this research were similar to previous results, indicating an increase in modulus with decreasing temperature, with this effect being more predominant in timber with higher MCs. The United States Forest Service *Wood Handbook* [4] includes a section based on this previous research that outlines the effects of cold temperatures on the bending properties of clear wood, including potential adjustment factors.

Szmutku et al. [5] investigated the effects of freezing on the strength and stiffness of green spruce, and found that freezing rate had a significant effect on the strength/stiffness of the test specimens once thawed. That is, it was found that the post-frozen strength/stiffness of the specimens decreased with decreasing freezing rate due to the deleterious effects of larger ice crystals observed in the specimens

frozen at slower rates. However, their work did not include an investigation on the effect of freezing rate on the frozen properties of the wood.

The effect of temperature (including cold temperatures) on the modulus of elasticity and bending strength of wood-based panels has also been investigated. Ayilimis et al. [6] investigated the effects on plywood, medium density fiberboard, and oriented strandboard, while Bekhta and Marutzky [7] and Suzuki and Saito [8] investigated the effects on particle board. Similar to what was found for the strength and stiffness of clear wood, the strength and stiffness of the wood panels was observed to increase with decreasing temperature.

The studies discussed thus far have focused on wood products for use in construction; some research has been conducted on the effects of cold temperatures on live trees, with similar conclusions. Silins et al. [9] investigated the effects of temperature on standing lodgepole pines and found that the modulus of elasticity and tensile strength of the trees increased with decreasing temperatures. Umbanhowar [10] and Schmidt and Pomeroy [11] focused their work on the effects of cold on the branches of trees, with similar results.

The increased strength and stiffness of wood with decreasing temperatures observed in this previous research may be due to the formation of ice crystals within the wood cells, as was postulated by Schmidt and Pomeroy [11]. Further, these effects may also be attributed to the stiffening of cellulose fibrils from the formation of ice, similar to the effects of adhesives [6]. Ayilimis et al. [6] also concludes that for wood products containing adhesives, the cold temperature effects may also be attributed to observed increases in the strength and stiffness of the adhesives used in the products. The continued strength/stiffness gain below the freezing point of water may be explained by the fact that ice observes an increase in strength/stiffness with decreasing temperature [12].

To date, little to no research has been conducted on the effects of cold temperatures on the strength and stiffness of engineered wood structural elements, specifically glued laminated timber. The objective of the project discussed herein was to quantify the effects of freezing on the performance glulam beams,

including the effects on stiffness, shear strength, and failure mechanism. It should be noted that this research did not include the studying the effects cyclic moisture contents and repeated freeze-thaw cycles. Shear-controlled failures were targeted rather than flexural failures in order to explore the extent to which the interaction of the adhesives and the wood may be unfavorably affected by the environmental conditions.

2 EXPERIMENTAL EVALUATION

To characterize the effects of subfreezing temperatures and MC on the shear behavior of glulam beams, duplicate specimens at three temperatures and two MCs (a total of 12 beam tests) were tested in four-point bending until failure. The testing temperatures were 20°C, 0°C, and -40°C. The target MCs were 12 percent and 28 percent; values that represent typical service conditions and the fiber saturation point, respectively. The fiber saturation point was chosen as an upper limit on the moisture content because, in unfrozen beams, moisture contents above this point have little to no effect on performance. However, this may not be the case in frozen beams, and this should be investigated further in future research. A summary of the testing matrix is provided in Table 1.

2.1 Materials

The 1576-mm long 24F-V4 glulam beams tested in this research had cross-sectional dimensions of 79-by-229 mm, which consisted of six 79-by-38 mm Douglas fir laminations. The adhesive used for face bonding of the separate laminations was a phenol-resorcinol-formaldehyde, while the adhesive used in the finger joints was a melamine-urea-formaldehyde. The MCs of the specimens were determined with a handheld moisture meter prior to testing, and verified after testing by monitoring moisture loss after drying. At the time of purchase, the beams had MCs of approximately 12 percent. Six of the beams, to be tested at 12 percent MC, were wrapped in plastic to avoid moisture loss and stored at 20°C until testing. The remaining six beams were conditioned at 20°C and 100 percent humidity until they reached their constant saturation point, which was at approximately 28 percent. Upon reaching this point, the

beams were removed from the cure room and wrapped in plastic to prevent moisture loss. To allow for the beams to uniformly achieve the testing temperatures, the beams were placed in the structures cold chamber at the testing temperature for 48 hours prior to testing. This amount of time was estimated via a heat transfer model (and verified in one specimen) to be adequate for the beams to come to equilibrium. While the rate of freezing may effect the strength/stiffness of the frozen specimens (as was observed by Szmurku et al. [5] for thawed specimens), this was not studied/controlled in the research discussed herein.

To further prepare the specimens, vertical lines were drawn on the beams prior to testing in order to observe any potential horizontal movement due to a horizontal shear failure.

2.2 Test Setup and Instrumentation

The beams were tested at the various temperatures in the Structural Testing Cold Chamber housed in the Subzero Science and Engineering Research Facility in the Civil Engineering Department at Montana State University. The beams were tested in four-point bending until failure while monitoring the applied force and resultant midspan deflection. The test setup used in this research is prescribed by ASTM D3737 [13] for determining the shear strength properties of glulam beams. This methodology estimates allowable shear stresses for the beams based on their observed ultimate shear strengths. An illustration of the test setup including dimensions is provided in Figure 1, while the actual configuration is shown in Figure 2. The clear span of the beams was 1449 mm, with the two point loads applied at 585 mm from the ends. The load was applied pseudo-statically with a 229-kN hydraulic actuator at a rate that targeted reaching the maximum load at 10 minutes. The load was measured with a load cell attached to the end of the actuator, while displacement was measured with a string-potentiometer attached at the midspan of the beam. Lateral bracing was provided on the top of the beam at the midspan to prevent potential issues with lateral torsional buckling. This lateral bracing was allowed to rotate with the deflecting beam; therefore, it did not provide any additional vertical resistance to the beam.

2.3 Calculation of Shear Stress and Stiffness

The shear stress (F_v) of the beams was calculated (where applicable) from the shear force (V), the width of the beam (b) and the depth of the beam (d) with the following equation: $F_v = \frac{3V}{2bd}$. The shear force on the beam for this loading condition was $V = \frac{P}{2}$, where P is the applied load at failure. It should be noted this equation for shear stress might not be accurate for the beams studied in this investigation, as the fundamental mechanics behind these equations may vary for deep beams at ultimate loads. Further, the cold temperatures may also affect these mechanics. However, this parameter is promoted by ASTM as a metric for the shear capacities of glulam beams (ASTM D3737) [13], and is thus included in the table of results. To provide a metric for evaluating the relative change of stiffness associated with temperatures and MC, the stiffness of the beams (K) was defined from their overall force-deflection response as the secant stiffness between 0 load and 40 percent of the ultimate load. While it may be more beneficial to report local material stiffness metrics, such as elastic modulus or shear modulus, these parameters could not easily be extracted from the force-deflection data as has been done in previous research [6, 14]. The methods used in this previous research were not applicable to the research discussed herein because of large shear deformations and the unknown relationship between elastic modulus and shear modulus.

3 EXPERIMENTAL RESULTS

A summary of test results is provided in Table 1, and the measured force-deflection responses of the beams at 20°C, 0°C, and -40°C are provided in figures 3 through 5, respectively. As can be observed in these figures, all of the beams initially exhibited a linear-elastic response up to about 50 percent of the ultimate load. After which, the response became nonlinear prior to failure. In all of the beams, except those tested at -40°C, the failure mechanism was horizontal shear, noted by horizontal cracks forming near the ends of the beam, as shown in Figure 6. These horizontal cracks typically formed near the interface between laminations, indicating that the glue may be the source of failure; however, upon further examination, the cracks formed in the wood just beyond the glue line. All of the beams at -40°C

failed in a brittle fashion due to tension near the middle of the beam, as shown in Figure 7. The beams at this temperature broke completely into two pieces, and had no reserve capacity after failure. Because these beams did not fail in shear the ultimate shear stresses (F_v) are not reported for the -40°C beams in Table 1.

It should be noted that the shear-stress values for the beams tested at 20°C are within the ranges reported in previous research on the shear capacity of glulam beams [14]. It should also be noted that although this test series only had two specimens tested at each point of interest, the averages of the two results may be good estimates of population averages because the differences between individual nominally matched results are small. Further, previous research on the shear capacity of glued laminated beams has indicated that the variability of this property is fairly low, with coefficients of variation of around 10 percent [14, 15].

4 DISCUSSION OF RESULTS

4.1 Comparison of force-deflection responses

The force-deflection responses of representative beams at 12 percent MC and 20°C, 0°C, and -40°C are shown in Figure 8. A similar plot is provided for the beams with 28 percent MC in Figure 9. As can be observed in these figures, the strength and stiffness of the beams with both 12 percent and 28 percent MC increases with decreasing temperature, with the effect on stiffness being more pronounced in the beams with 28 percent MC.

4.2 Ratios of strength and stiffness to strength and stiffness at 20°C

To further evaluate the effect of temperature and MC on strength, the ratios of ultimate load to ultimate load at 20°C are plotted versus the various temperatures for both MCs in Figure 10. As can be observed in this figure, the effect of temperature on the ultimate load is more pronounced in the 28 percent MC beams than the 12 percent MC beams. The 28 percent MC beams experienced respective increases of 31 percent and 37 percent at the 0°C and -40°C temperatures, while the 12 percent MC beams had increases

of only 14 and 17 percent. Also observable in this figure is the apparent diminishing effect of temperature observed for both MCs, with the increases between 20°C and 0°C being greater than the increases between 0°C and -40°C. This diminishing effect of temperature on strength is consistent with previous research on the bending strength of wood panels [6] and on the bending strength of clear wood specimens [1]. However, drawing concise conclusions about the effect of cold temperatures on the shear capacity of glulam beams is complicated by the fact that the -40°C beams failed in tension rather than shear. That is, the actual shear capacities of the beams at -40°C would be greater than what could be deduced from this data due to the beams failing prematurely in tension rather than shear.

As was done for strength, the ratio of stiffnesses to the stiffness at 20°C are plotted in Figure 11 for both MCs. As can be seen in this figure, the gain in stiffness with decreasing temperature appears to be bilinear, with the effect being more pronounced for temperatures less than 0°C. Also, as was seen for strength, the effect of temperature on stiffness is more pronounced for the 28 percent MC beams. The stiffnesses of the 28 percent MC beams increased 16 and 66 percent at 0°C and -40°C, while the 12 percent MC beams increased only 14 and 22 percent. This bilinear effect, and this effect being more pronounced in high MC specimens is consistent with what Green and Evans [3] found for the elastic modulus of clear wood specimens.

4.3 Effect of MC at various temperatures

A comparison between absolute strengths and stiffnesses of the two moisture contents at the various temperatures is made in Figure 12. In this figure, the ratios of ultimate load and stiffness of the 28 percent MC beams to the ultimate load and stiffness of the 12 percent MC beams are plotted versus temperature. At 20°C the 28 percent MC beams broke at a lower load and had less stiffness than the 12 percent MC beams, with ratios of 86 percent and 84 percent respectively. The reduced strength observed in the high MC beams relative to low MC beams is consistent with NDS reduction factors to account for MC, which recommends a reduction factor of 87.5 percent to account for this high MC [16]. There is very little discrepancy between the strengths of the 12 and 28 percent MC beams at 0°C and -40°C, with

load ratios near 1.0. As for stiffness, the 28 percent MC beams were less stiff than the 12 percent MC beams at 20°C and 0°C, while the 28 percent MC beams exceeded the 12 percent MC beams at -40°C.

4.4 Mechanisms for increased strength and stiffness with decreasing temperature

These observed increases in strength and stiffness with decreasing temperatures are consistent with previous research and could be due to the combined effects of the formation of ice crystals within the wood cells, the stiffening of cellulose fibrils from the formation of ice, or the increased strength and stiffness of the adhesives used in the beams. The continued strength gain with decreasing temperatures below freezing may be attributed to the increased strength/stiffness of the ice [12] within the beams. However, the effect of temperature on ice is imbalanced, with the effect being more pronounced with compressive strength and adhesion, than with tensile strength [12, 17]. This observed imbalance in strength gain may partially explain why the failure mechanism of the glulam beams in this research switched from shear to tension at -40°C. That is, the effect of temperature on the factors controlling shear capacity (e.g., adhesion between fibrils) may be more positively affected than those controlling the tension failure.

5 CONCLUSIONS

To determine the effects of temperature and MC on the shear behavior glulam beams, a total of twelve full-scale specimens (duplicate specimens at two MCs and three temperatures) were tested in four-point bending until failure. Based on this study the following conclusions can be made:

1. Temperature affected the observed failure mechanism of the glulam beams. All of the beams tested at 20°C and 0°C failed in shear, while those tested at -40°C failed in tension, indicating that the effects of temperature on the factors controlling shear were more positively affected by decreasing temperature than those controlling tension.
2. The strength and stiffness of the beams increased with decreasing temperature, with the effect being more pronounced in the higher MC beams. The effect on strength appeared to diminish for

temperatures below 0°C, but this is clouded by the fact -40°C beams did not fail due to shear.

Conversely, the effect on stiffness was observed to increase with temperatures below 0°C.

3. Although the observed shear failures occurred at the boundary between laminations, they did not occur due to failure of the adhesives.

While this research provided useful information regarding the effects of sub-freezing temperatures on the shear behavior of glulam beams, further research is required to more fully characterize these effects and increase the impact of this research. For example, testing a larger number of samples over more temperatures would be beneficial. Further, the effect of temperature will most likely vary between wood species, and thus this research should be expanded to other species.

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Table Captions

Table 1: Test matrix and results

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Designation	T	MC	Load	Failure	Fv			K		
	(°C)	(%)	(kN)			Average (Mpa)	cov (%)	(kN/mm)	Average (kN/mm)	cov (%)
20-12a	20	12	117.4	shear	4.85	4.73	3.6	7.3	7.1	4.6
20-12b			111.7	shear	4.61			6.9		
0-12a	0	12	125.4	shear	5.18	5.39	5.3	8.1	8.1	0.0
0-12b			135.2	shear	5.59			8.1		
-40-12a	-40	12	146.8	tension	-	-	-	8.5	8.8	5.8
-40-12b			121.1	tension	-			9.2		
20-28a	20	28	97.4	shear	4.03	4.05	1.0	6.5	5.9	14.3
20-28b			98.8	shear	4.08			5.3		
0-28a	0	28	129.0	shear	5.33	5.31	0.5	7.1	6.9	2.4
0-28b			128.1	shear	5.30			6.8		
-40-28a	-40	28	143.7	tension	-	-	-	10.2	10.3	1.0
-40-28b			125.4	tension	-			10.4		

Figure Captions

Figure 1: Loading schematic and dimensions

Figure 2: Load frame and specimen in structures cold lab prior to testing

Figure 3: Force-deflection response of beams at 20°C

Figure 4: Force-deflection response of beams at 0°C

Figure 5: Force deflection response of beams at -40°C

Figure 6: Typical shear failure (12 percent MC at 20°C)

Figure 7: Typical tension failure of beam at -40°C (28 percent MC)

Figure 8: Force-deflection response of 12 percent MC beams at 0°C, 20°C and -40°C

Figure 9: Force-deflection response of 28 percent MC beams at 0°C, 20°C and -40°C

Figure 10: Ratio of measured ultimate load to ultimate load at 20°C

Figure 11: Ratio of measured K to K at 20°C

Figure 12: Ratio of ultimate load and stiffness at 28 percent MC to those at 12 percent at various temperatures

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