Mechanical Performance of Polyurethane and Epoxy Adhesives in Connections with Glued-in Rods at Elevated Temperatures

Mathieu Verdet,[a,b] Alexander Salenikovich,[b,]* Alain Cointe,[a] Jean-Luc Coureau,[a] Philippe Galimard,[a] Williams Munoz Toro,[c] Pierre Blanchet,[b] and Christine Delisee [a,d]

Glued-in rods have successfully been used for connections or reinforcement of timber structures due to their high strength and stiffness. However, their performance is potentially sensitive to temperature. This paper deals with an experimental investigation of the connections and adhesives in elevated temperatures. First, dynamic mechanical analysis (DMA) tests were performed to characterize an epoxy (EPX) and a polyurethane (PUR) adhesive. The evolution of the stiffness and the glass transition temperature, T_g, were measured in the range of 30 °C to 120 °C. Then, a total of 66 specimens with glued-in rods and the same adhesives were tested under a static tensile load at 20 °C, 40 °C, 50 °C, 60 °C, and 70 °C. In both types of tests, the EPX outperformed PUR due to its higher stiffness at temperatures of up to 40 °C; however, it showed a more rapid degradation of the stiffness and strength than the PUR at higher temperatures. No direct correlation was established between the T_g and the performance of the connections. The test results suggest that timber structures with glued-in rods may be vulnerable in service at temperatures above 40 °C.

Keywords: Glued-in rods; Timber connections; Epoxy; Polyurethane; Dynamic Mechanical Analysis

Contact information: a: Institute of Mechanical Engineering, UMR 5295, Bordeaux University, Bordeaux, France; b: Department of Wood and Forest Sciences, Laval University, Quebec, Canada; c: Nordic Structures, Montreal, Canada; d: Bordeaux Science Agro, Bordeaux, France;
** Corresponding author: alexander.salenikovich@sbf.ulaval.ca*

INTRODUCTION

With the development of tall and large timber buildings, there is an increasing need for connections that provide high stiffness and strength, elevated temperatures and fire resistance, and a general aesthetic appeal. At the same time, adhesive technology has been developed for various applications with structural timber products, such as glulam, cross-laminated timber, structural composite lumber, and their connections. Timber connections using glued-in rods take advantage of the structural adhesives that provide a high rigidity and load capacity. During the last 30 years, multiple applications have been developed for the reinforcement of existing structures, for restoration or renovation (Klapwijk 1978; Taupin 1980), and for new construction. In parallel, numerous investigations have characterized the mechanical performance of these connections, which present a complex multi-material system. A number of influential parameters have been studied and summarized in the recent state-of-the-art reports by Steiger *et al.* (2015) and Tlustochowicz *et al*. (2011).

Whereas the geometry and material properties have always been considered, the effects of the service conditions have not been specifically addressed in the design rules for glued-in-rod connections (Connolly and Mettem 2003; Steiger *et al.* 2004). Ambient temperatures up to 50 °C are classified as normal service conditions for structural adhesives and for timber structures in European (EN 301 2006), Swiss (SIA 265 2012), and Canadian (CSA O86 2014) standards. The American timber design standard (NDS 2014) provides temperature adjustment factors for some reference design values "for structural members that will experience sustained exposure to elevated temperatures of up to 150 °F (65 °C)". However, these factors only reflect the loss of the wood strength under prolonged heating (Ross 2010) and do not apply to the connections or the adhesives. These adjustments have been based on the report by Gerhards (1982) who summarized the research results on the immediate effects of moisture and temperature on elastic and strength properties of wood. In his report, it was shown that the modulus of elasticity and the shear strength parallel-to-the-grain of wood in air-dry condition were reduced less than 10% at 50 °C relative to the room temperature, while other properties experienced greater effects, especially when coupled with higher moisture condition. More recently, De la Cruz Sanchez (2006) investigated the elastic constants of black spruce and measured a 5% to 15% decrease of of the Young's and shear moduli of air-dry wood in various directions between 30 °C and 50 °C.

Studies by Aicher *et al.* (1998b, 2002) revealed that the glue line performance depends on the ambient temperature. Aicher and Dill-Langer (2001) and Custodio *et al.* (2009) identified various degrees of decrease in the strength and the stiffness of glued-in rod connections with three different adhesives under long-term exposure to a high temperature of 55 °C and 85% humidity. Lartigau *et al.* (2015) determined an intrinsic critical temperature of glued-in rod connections associated with the glass transition temperature (T_g) for two epoxy adhesives: 48 °C for Rotafix and 58 °C for Sikadur 330.

The glass transition temperature, T_g, is often used to characterize the resistance of adhesives to high temperature, and it strongly depends on the type of adhesive, its formulation, thermal history, and age (Custódio *et al.* 2009). T_g can be determined by differential scanning calorimetry (DSC) and differential thermal analysis (DTA) or dynamic mechanical analysis (DMA). DMA is the most sensitive method, and it also provides mechanical properties, such as the storage modulus and the loss modulus of the adhesive, in the entire range of the studied temperatures. The thermal performance of polyurethane (PUR) and epoxy (EPX) has been reported (Richter and Steiger 2005; Cruz and Custódio 2006). Both adhesives display a significant viscoelastic deformation, and there are large differences in their response to temperatures between 40 °C and 50 °C.

To expand the research on the relations between the adhesive properties and the performance of glued-in-rod connections at elevated temperatures, this paper reports the results of DMA tests on PUR and EPX adhesives followed by static tensile tests on the connections with small-diameter steel glued-in rods conducted at different temperatures. The main goal of this investigation was to compare the mechanical performance of these two adhesives with the glued-in rods in various thermal conditions under a static loading. An attempt was made to correlate the evolution of the storage modulus obtained from the DMA tests on the adhesives with the stiffness of the connections in order to predict the performance of the connections in service. The T_g obtained from the DMA tests was compared to the transition of the adhesive properties. The effects of temperature on the mechanical properties of wood have not been isolated.

EXPERIMENTAL

Dynamic Mechanical Analysis (DMA) Tests on Adhesives

The DMA test method was used in this study for two main reasons. First, it offered the evaluation of mechanical stress/strain relationships of the adhesives, unlike other thermal methods based on chemical reactions. Second, it provided the history of the stiffness and viscosity of the adhesives in the range of temperatures from 30 °C to 120 °C, including the transition points, and a very accurate determination of the T_g. The DMA tests were performed as the first step in the study in order to define the temperatures for the static tests on the glued-in rods.

DMA test principle

The DMA test principle is presented in Fig. 1a. A sinusoidal strain, ε, is applied to the specimen, and the corresponding stress, σ, is measured to determine the complex modulus, E^*. Since this test is performed in a dynamic regime, the response has the same frequency, but different amplitude and a phase lag. The signals can be written as follows,

$$\sigma = \sigma_0 \sin(t\omega + \delta) \tag{1}$$

$$\varepsilon = \varepsilon_0 \sin(t\omega) \tag{2}$$

where ω is the frequency of the strain oscillation, t is time, and δ is the phase lag between the stress and the strain. Consequently, E^* can be expressed as $E^* = \sigma_0/\varepsilon_0 \,.\exp(\mathrm{i}\delta)$, where $\mathrm{i}^2 = -1$, or as $E^* = E' + \mathrm{i}\, E''$, where E' is the storage modulus, E'' is the loss modulus, and $Tan\ \delta = E''/E'$ is the loss factor. Figure 2b shows an example of the evolution of E', E'', and $Tan\ \delta$ from 30 °C to 110 °C.

Physically, the storage modulus, E', represents the elastic portion and the stored energy in the material. For materials that have an elastic behavior, E' matches the Young's modulus, E. The loss modulus, E'', measures the energy dissipated and represents the viscous portion. The loss factor, $Tan\ \delta$, quantifies the degree of viscoelastic behavior as a ratio between the elastic part and the viscous part of the adhesive. When $\delta = 0$, it represents the perfect elastic case, while $\delta = \pi/2$ represents the pure viscous case. It is also used to determine the glass transition temperature, T_g.

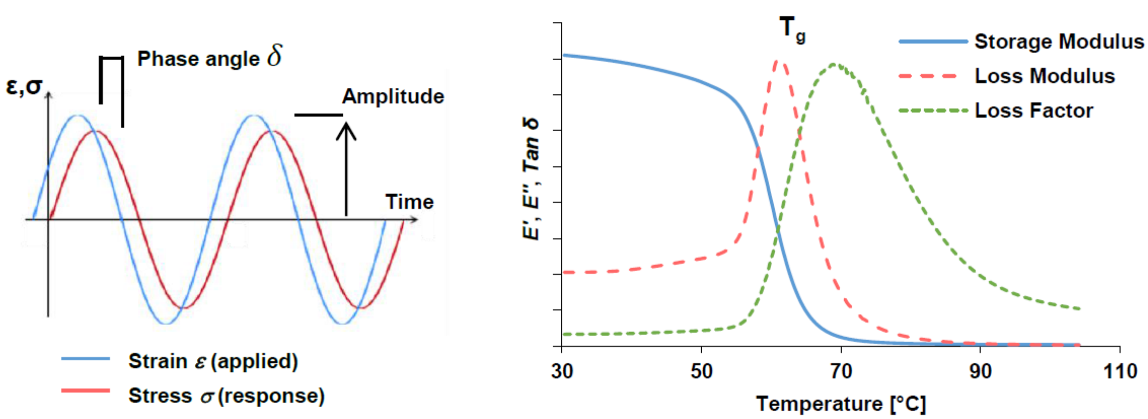

Fig. 1. a) DMA signals; b) typical storage modulus, loss modulus, and loss factor of EPX

Test materials

Two bi-component structural adhesives were considered. Polyurethane (PUR; Purbond CR 421, Purbond, Sempach Station, Switzerland) is certified for structural applications of up to 50 °C (TYPE 1 in EN 301 (2006)) and is specially formulated for glued-in rods. Epoxy (EPX; Sikadur 330, Sika, Le Bourget, Switzerland) is used to bond reinforcements to concrete and timber structures. The adhesive formulations were prepared in accordance with the manufacturer's instructions. To obtain a homogenous material without air bubbles, the specimens were molded in a Teflon matrix. The specimen dimensions were 55 mm × 10 mm × 3 mm. A total of six samples per adhesive were prepared, three for the preliminary trials and three for the main tests presented below.

DMA test procedure

The testing machine Q800 DMA (TA Instruments, New Castle, USA) was used with dual cantilever support as shown in Fig. 2. The furnace with the specimens was operated at a progressive temperature ramp of 5 °C/min. After the preliminary trials, the amplitude of the applied strain was fixed at 0.05% for EPX and 0.1% for PUR. A frequency of 1 Hz was chosen to measure the properties at a speed compatible with the static tests, as was done by Richter and Steiger (Richter and Steiger 2005). Three replicates were tested for each adhesive. Three months later, two of the three specimens were retested.

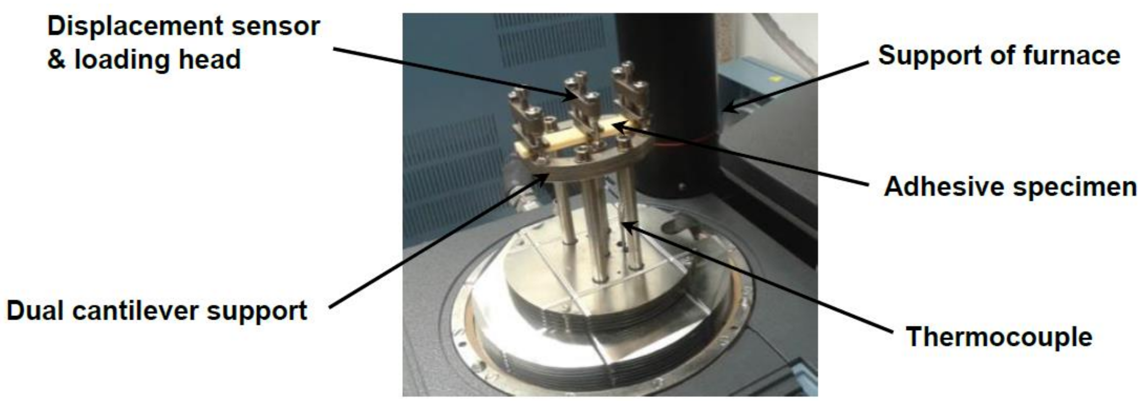

Fig. 2. Dual cantilever support with a specimen in the Q800 DMA testing machine

Static Tests on Glued-in Rods

The DMA tests revealed great differences between the EPX and the PUR in terms of evolution of the adhesive stiffness and the viscosity under increasing temperature. The static tests on glued-in rods were performed to validate the observed trends and to establish a relationship with the DMA tests for the development of a prediction model. This model would be useful for estimating the risks associated with the performance of glued-in rod connections in structural applications under high temperatures. To achieve these objectives, the strength and stiffness of the connections were studied in five temperature regimes. These test results were also compared with those obtained by Lartigau *et al.* (2015) for glued-in rods in pull-compression configuration with the same EPX adhesive.

Test specimens

The test specimens were composed of wood members with small-diameter, glued-in steel threaded rods, in a pull-pull configuration, as illustrated in Fig. 3. A total of 96 specimens were prepared. Half of the specimens were glued with the PUR and half with the EPX adhesive. The threaded rods were steel grade 8.8 (ISO 898-1 2013), with a diameter of 8 mm and a length sufficient to ensure wood failure during the test (Aicher *et al*. 1998a). The control for the glued-in length of the rods was 50 mm. Half of the specimens were fabricated with the control length on both ends (50/50), and half of the specimens had a 92-mm glued-in length on one end (50/92). The test matrix showing the number of specimens per test series is detailed in Table 1. Only one EPX (50/50) specimen was tested at 60 °C because the performance of the connection was essentially equivalent to that observed at 70 °C.

The wood members were glulam timber produced from Black spruce (*Picea mariana* Mill.) grown in Eastern Canada. This wood species is widely used in structural timber products in Eastern Canada. The wood blocks were 50 mm × 50 mm in cross-section with a length of 245 mm. The length of the specimens was sufficient to ensure no interactions between the two rods, and the cross-section was large enough to satisfy the minimum edge distance, according to the design recommendations (IRABOIS 1999).

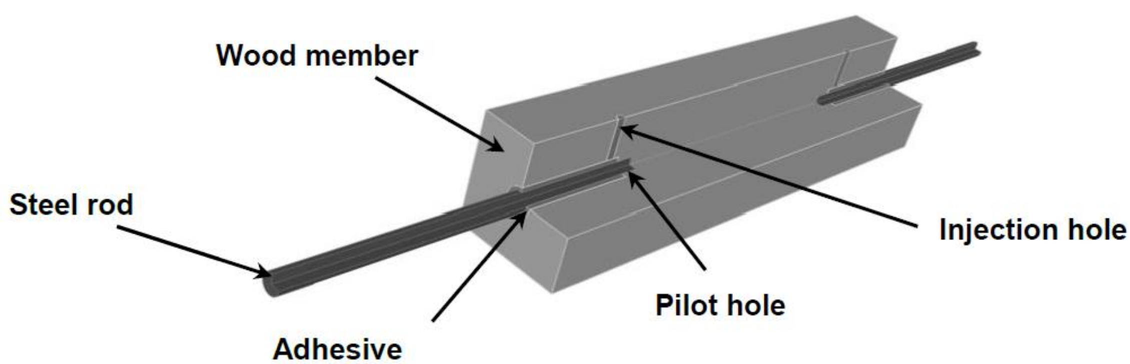

Fig. 3. Specimen of glued-in rod connection (pull-pull configuration)

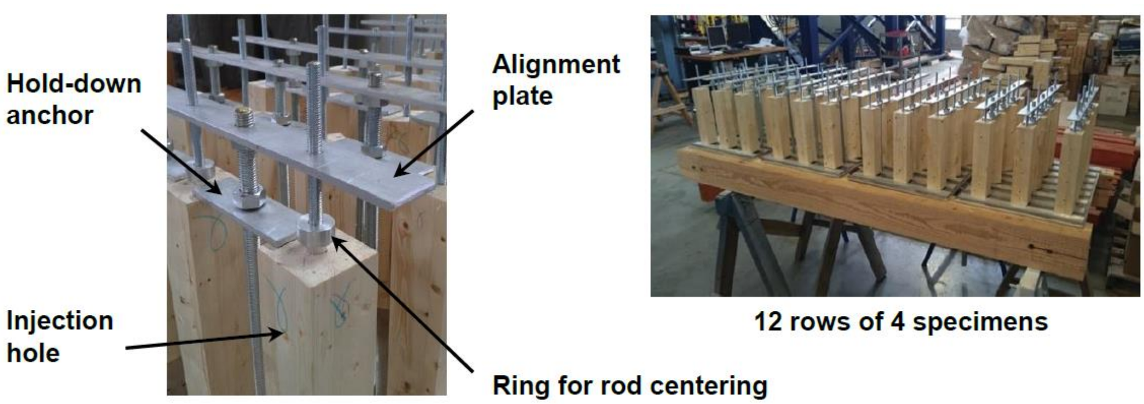

Fig. 4. Setup for fabrication of glued-in rod specimens

At each end of the specimen, a pilot hole of 8 mm in diameter was drilled 8 mm deeper than the glued-in length of the threaded rod to allow its proper concentric alignment. The main hole, 12 mm in diameter, was drilled providing a glue line thickness of 2 mm.

Perpendicular to the axis, a small-diameter hole was drilled to inject the adhesive. The rods were glued at each end in a vertical position using a mechanical fixture on top of the specimens (Fig. 4), which was designed to facilitate the fabrication and cure of up to 12 rows of four specimens at the same time. After fabrication, the specimens were stored in a conditioning room at 20 °C and 65% relative humidity (RH) until reaching constant mass.

Table 1. Test Matrix of Glued-in Rod Connections

Test Series		Temperature			
	20 °C	40 °C	50 °C	60 °C	70 °C
EPX 50/92 mm	12	4	3	-	4
EPX 50/50 mm	0	3	4	1	3
PUR 50/92 mm	12	4	4	-	3
PUR 50/50 mm	0	3	3	-	4

Test procedure

Following the DMA tests described above and also considering the results obtained earlier by Lartigau *et al.* (2015), five discrete temperatures have been selected for the tests of the connections: 20 °C, 40 °C, 50 °C, 60 °C, and 70 °C. The temperature of 20 °C was used as a reference according to European and ASTM test standards. The temperature of 40 °C represents a common exposure of the structures during service. The temperature of 50 °C is the Eurocode (EN 1995-1 2005) and the CSA O86 (2014) upper limit for which the design values for dry service conditions apply. The temperature of 70 °C matches the inflection point of the PUR storage modulus, and the T_g of EPX.

To ensure a homogeneous temperature in the specimens during the tests, each specimen was preheated in an oven to the target temperature, and it was immediately transferred to the mechanical MTS Alliance RT50 press (MTS System Corporation, Eden Prairie, Minnesota, USA) equipped with a heating chamber preheated to the same temperature and tested (Fig. 5). The temperature inside the specimens was measured using thermocouples fixed in the glue line at the ends of the rods before bonding to ensure that the entire length of the rods achieved the target temperature.

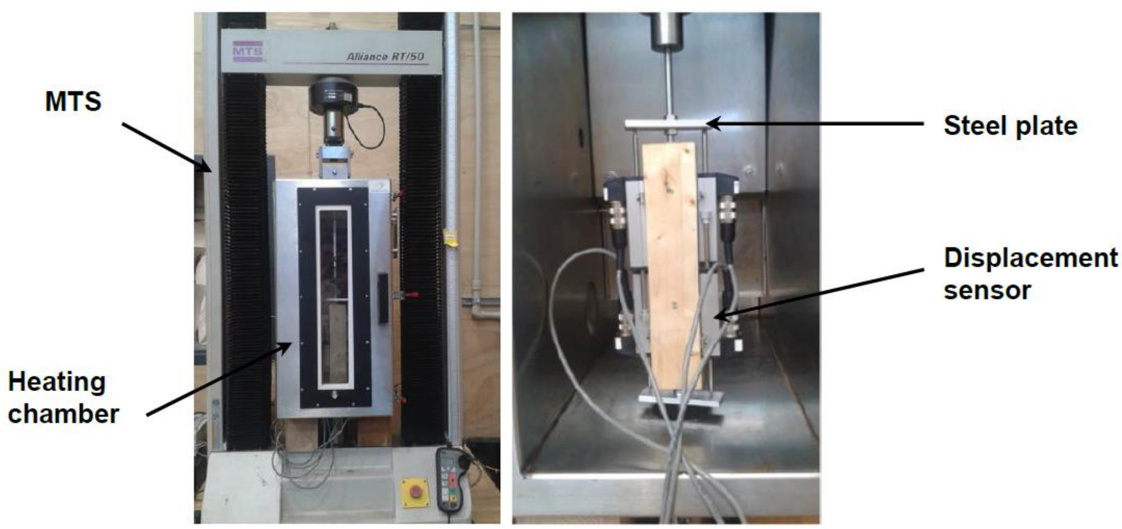

Fig. 5. a) Set up on MTS press; b) instrumented glued-in rod specimen

The relative humidity in the oven and in the heating chamber was not controlled. Therefore, to prevent moisture loss, the ends of the specimens were coated with an emulsion of wax. Immediately after the tests, small samples were extracted in the middle and at each end of the wood blocks to determine the moisture gradient along the connection.

Tests were performed with a constant crosshead displacement of 0.5 mm/min without preload. Thereby, the failure at 20 °C was achieved between 2 min and 5 min, as prescribed in the standard EN 408 (2010) for tensile tests. For other temperatures, the same test speed was maintained. Two linear variable displacement transducers (LVDT's) were placed on opposite sides at each end of the specimen to measure the average slip of each rod. The LVDT's were fixed at a distance of 50 mm from the ends of the wood member, and a steel plate was bolted 13 mm above and below, as illustrated in Fig. 5b.

RESULTS AND DISCUSSION

DMA Tests on Adhesives

The DMA tests provided information on the stiffness and viscosity for the adhesives in relation to the storage modulus, loss modulus, and loss factor as a function of temperature. A very good repeatability was observed for all measured parameters, with a variation between the specimens of less than 1 °C. Moreover, similar values were found when the specimens were retested three months later. These parameters are discussed in the following paragraphs.

Loss factor, glass transition temperature, and storage modulus

Figure 6 shows the curves of the loss factor, *Tan* δ, that were used to determine T_g. According to these curves, the values of T_g were 69 °C and 86 °C for EPX and PUR, respectively. Note that a value of T_g = 60 °C was obtained by Lartigau *et al.* (2015) for the same EPX adhesive using the DSC method.

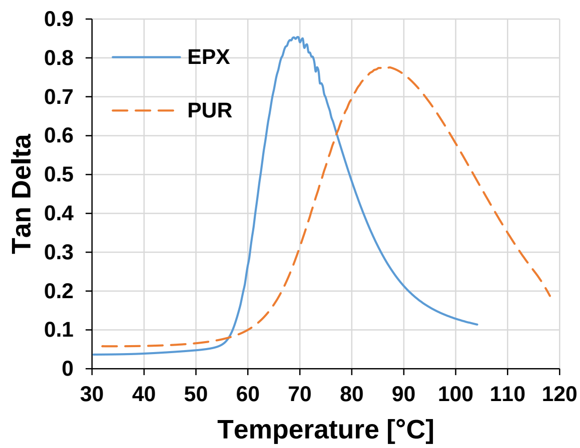

Fig. 6. Evolution of the loss factor with the increasing temperature for PUR and EPX

To study the correlation between the T_g and the mechanical properties used to develop a prediction model for glued-in rod connections, the evolution of the storage modulus or the modulus of elasticity as a function of temperature was plotted for EPX and PUR (Fig. 7). The first important observation was the difference in the amplitude of the curves between the adhesives. For a normal service range of temperatures under 50 °C, the storage modulus of EPX was two times higher than that of the PUR. When the temperature increased, the storage modulus decreased for both adhesives. At 50 °C, the values of the modulus declined by 10% and 11.6% for EPX and PUR, respectively. The curves showed a large drop beyond 50 °C for both adhesives, largely before the T_g. The EPX curve showed a significantly steeper drop than the PUR, so that the two curves crossed at approximately 62 °C. By the time the temperature reached the T_g, a near zero value of the storage modulus was measured, 160 MPa for EPX and 75 MPa for PUR. Consequently, the T_g did not appear to be a criterion of transition for the mechanical properties, although it is often used to evaluate the risk of failure due to high temperature (Aicher and Dill-Langer 2001; Custódio *et al.* 2009; Lartigau *et al.* 2015).

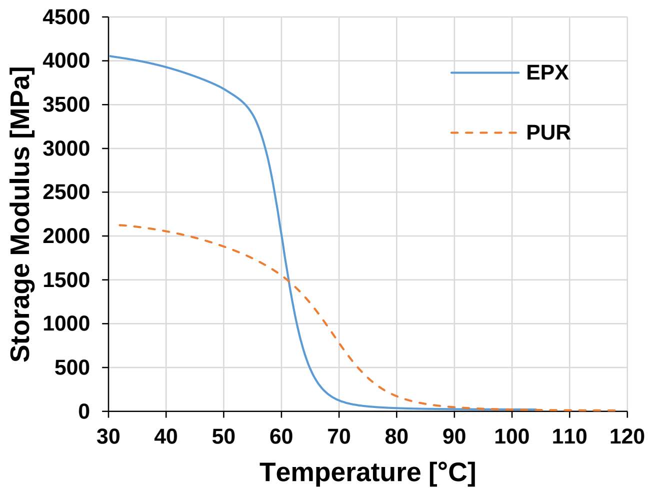

Fig. 7. Evolution of the storage modulus with the increasing temperature for EPX and PUR

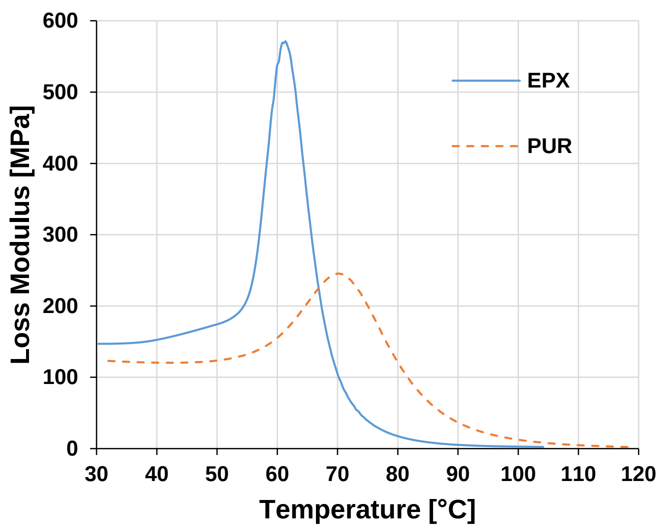

Fig. 8. Evolution of the loss modulus with the increasing temperature for EPX and PUR

Loss modulus

In Fig. 8, the loss modulus curves of the EPX and the PUR are plotted. The loss modulus matches the dissipated energy induced by the loading at each temperature. Nonetheless, the simplest form to understand the viscoelastic behavior is to look at the loss factor, Tan δ, plotted in Fig. 6. For temperatures up to 50 °C, the loss factor and the loss modulus are nearly constant, having similar values for both adhesives, as opposed to the storage modulus, which was two times higher for the EPX than for the PUR. Beyond this temperature, the adhesives become more viscous.

Static Tests on Glued-in Rods

The results of 66 static tests are presented in this study. The remaining 30 specimens were subjected to creep tests that will be presented in a future publication. The sampling procedure for both the static and the creep tests was based on the density of the wood specimens in order to minimize the dispersion of test results between the sets due to the inherent variability of the wood material. The mean density at 12% moisture content was determined using an oven-dry method after the tests; it was 560 kg·m^{-3} with a standard deviation of 17 kg·m^{-3}. The moisture content of all specimens was 12% ± 1%, with a gradient of less than 1%.

Load/slip curves

Figure 9 illustrates the load/slip curves of glued-in rod connections with the EPX and PUR adhesives tested at the different temperatures. At 20 °C and 40 °C, the connections demonstrated an elastic behavior with high stiffness up to failure at very small displacements, less than 0.5 mm. The failure was located in the wood, and a quasi-brittle behavior was observed. As the temperature increased beyond 40 °C, the behavior of the connections changed dramatically. The connections with both adhesives demonstrated a great loss in resistance and stiffness. They developed a plastic behavior, and the failure occurred in the adhesive at the slip greater than 1.5 mm, and the rods were pulled out from the adhesive.

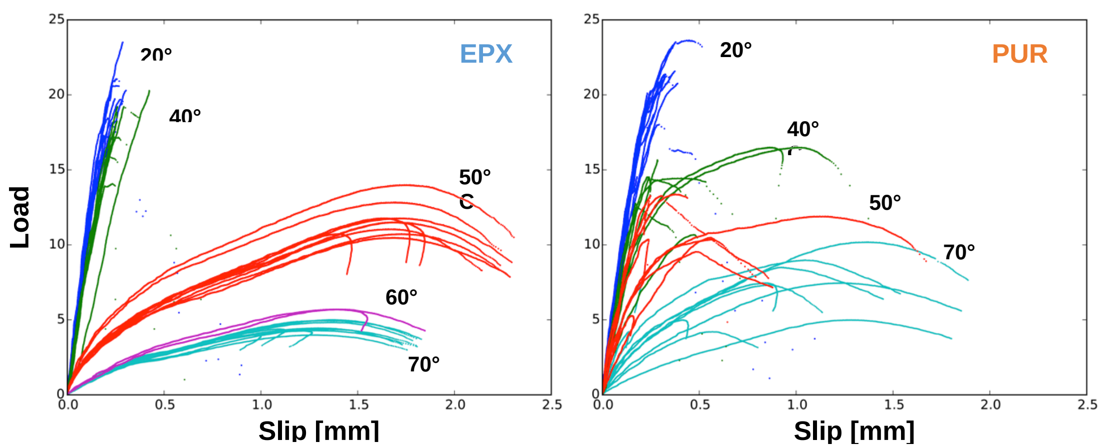

Fig. 9. Load/slip curves of glued-in rod connections tested at different temperatures

For EPX glued-in rods, these results differed from the results obtained earlier by Lartigau *et al.* (2015) (not shown here), who observed some stiffness degradation but did not observe a deterioration of strength at temperatures below 60 °C. Potential reasons for the discrepancies are as follows. The tests by Lartigau *et al.* were conducted on sawn wood of a different species, Norway spruce (*Picea abies* L.), and the ambient conditions were not controlled. Their specimens were preheated in an oven to a desired temperature prior to the test, but the loading took place at a room temperature. Therefore, the moisture content of the wood and the temperature of the materials during the test were unknown. As opposed to the tests by Lartigau *et al*. (2015), the results presented in this paper were obtained for the specimens fabricated from the well-conditioned glulam timber and the tests were conducted under thorough temperature control, as described above.

Stiffness degradation

The stiffness of the connections was estimated using the initial slip modulus, k_i, calculated in the spirit of the EN 26891 (1991) standard for joints with mechanical fasteners as follows: $k_i = 0.4F_{max}/v_i$, where F_{max} is the maximum load (kN), and v_i is the corresponding slip, in mm. At temperatures of 50 °C and higher, the connections exhibited a nonlinear performance well below $0.4F_{max}$, presumably because the elastic limit was exceeded, especially the connections with the EPX adhesive. Figure 10 shows the k_i values for all of the connections tested at different temperatures, including the mean values per series, except for the EPX at 60 °C, where only one specimen was tested. The red triangles indicate the specimens with serious defects of large air bubbles or juvenile wood presence; hence, the data points were considered outliers and removed from the statistics.

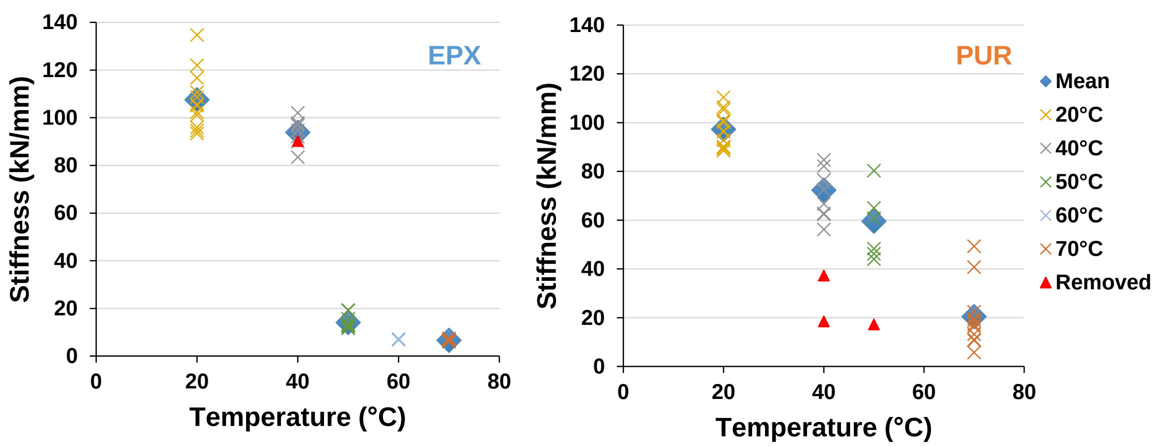

Fig. 10. Stiffness of EPX and PUR glued-in rod connections tested at different temperatures

The mean values, the average loss relative to the control values at 20 °C and the coefficient of variation (CV) of the slip modulus, k_i, per test series are presented in Table 2. From Fig. 10 and Table 2, it was concluded that the initial stiffness decreased in near linear proportion to the temperature increase in the case of the PUR specimens. The trend was not linear for the EPX; a great drop in the stiffness is observed beyond the temperature of 40 °C. At 40 °C, the stiffness loss was 26% for PUR and 13% for EPX; at 50 °C, the loss was 39% and 87%, respectively.

Although no direct correlation was found comparing these results with the DMA characterization of adhesives, there were similar trends. The EPX adhesive and the connections showed a higher initial stiffness at temperatures of up to 40 °C, but they lost it more rapidly than the PUR at higher temperatures.

Table 2. Stiffness of EPX and PUR Glued-in Rod Connections Tested at Different Temperatures

	EPX				PUR			
	Number of specimens	k_i (kN/mm)	Loss (%)	CV (%)	Number of specimens	k_i (kN/mm)	Loss (%)	CV (%)
20 °C	12	108	-	11	12	97.2	-	8
40 °C	9	93.8	13	6	9	72.2	26	15
50 °C	11	14.1	87	19	9	59.5	39	24
60 °C	2	6.96	94	48	-	-	-	-
70 °C	10	6.59	94	7	11	20.4	79	64

Strength degradation

Figure 11 shows the values of the maximum load, F_{max}, for all of the connections tested at different temperatures, including the mean values per series, except for the EPX at 60 °C, where only one specimen was tested. For the symmetrical (50/50) specimens, the same failure load is shown for both ends. As mentioned above, the red triangles indicate the specimens with serious defects of large air bubbles or juvenile wood presence; these data points were considered outliers and removed from the statistics.

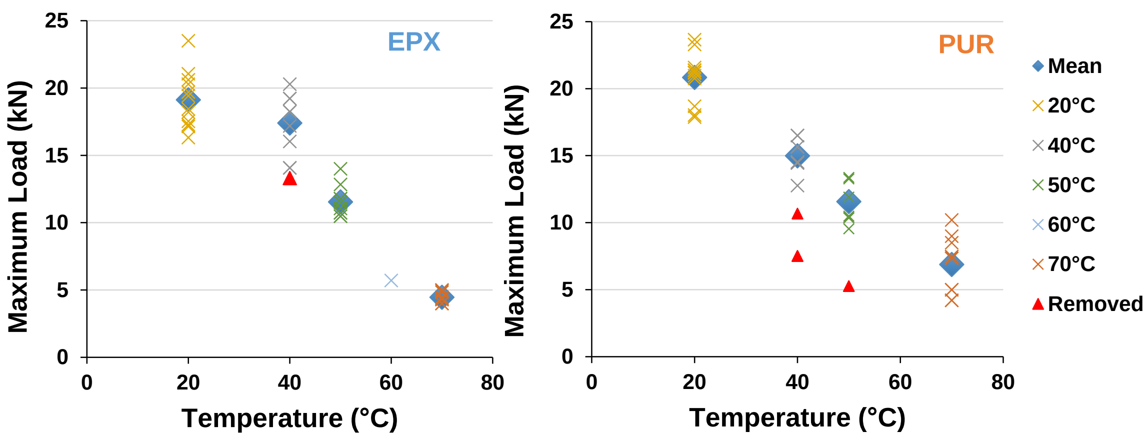

Fig. 11. Maximum loads of EPX and PUR glued-in rod connections tested at different temperatures

The mean values, the average loss relative to the control values at 20 °C, and the CV of the maximum loads per test series are presented in Table 3. From Fig. 11 and Table 3, it was concluded that the strength degradation of the connections at higher temperatures followed a similar trend as observed for the stiffness. Although in this case, the PUR specimens had a slightly higher strength at the room temperature, they lost 28% at 40 °C, whereas the EPX specimens lost only 9%. However, at 50 °C, the connections with both adhesives reached an equivalent strength losing 44% and 40% of their initial strength, respectively. Overall, comparing Tables 2 and 3, the relative loss of the strength of the specimens at higher temperatures was less dramatic than that of the stiffness.

Table 3. Maximum Loads of EPX and PUR Glued-in Rod Connections Tested at Different Temperatures

	EPX				PUR			
	Number of specimens	F_{max} (kN)	Loss (%)	CV (%)	Number of specimens	F_{max} (kN)	Loss (%)	CV (%)
20 °C	12	19.1	-	11	12	20.8	-	9
40 °C	9	17.4	9	13	7	15.0	28	9
50 °C	11	11.5	40	9	8	11.6	44	14
60 °C	1	5.70	70	-	-	-	-	-
70 °C	10	4.46	76	8	11	6.9	67	29

Implications for design

The stiffness of the glued-in rod connections is influenced by the stiffness of the constituent materials and plays a key role in design recommendations. For the isostatic structures, the stiffness of the connections affects only the Serviceability Limit States (SLS), where the risks are limited to the amplification of the displacements. For the hyperstatic structures, the fixity of the end joints and the distribution of the loads between the structural elements strongly depend on the stiffness of the connections. Therefore, both the SLS and the Ultimate Limit States (ULS) are affected by excessive displacements leading to serious consequences and potential collapse.

In this study, the connections with the EPX showed, on average, a 10% higher stiffness and a 9% lower strength than the PUR at room temperature. The stiffness and strength decreased greatly for both adhesives at 40 °C, but the connections with the EPX were still 23% stiffer and 13% stronger than that of the PUR. Beyond this temperature, the losses were more dramatic for both adhesives. At 50 °C, the connections with the EPX had lost 87% of their initial stiffness, and 40% of their initial strength were 75% less stiffer, and nearly half as strong as the connections with the PUR. These losses of stiffness and strength near the limits of their certified service temperatures, 45 °C for EPX and 50 °C for PUR, warrant attention with respect to design implications. In what situations are the structural glued-in rod connections exposed to the temperatures that cause their degradation? The temperatures above 30 °C are not common in buildings, although they can be exceeded occasionally in the summer in the roof or in the case of a fire. The long-term effect of temperature on the performance of glued-in rod connections also raises questions.

Creep and service life

The viscosity of the adhesives affects the long-term behavior of glued-in rod connections. In SLS verifications, all of the displacements include part short-term and part long-term (creep) effects. Although not studied in this paper, creep tests and time-temperature superposition principles would be required to deal with this topic in depth. However, the influence of temperature on the performance of adhesives and glued-in rod connections is already evident from the DMA characterization of adhesives and from the instantaneous loading test results. Although the DMA tests repeated after a three-month delay did not reveal a significant influence on the storage modulus and loss modulus, the question about the reversed heating under load should be addressed. Creep experiments on the glued-in rod connections are currently underway.

CONCLUSIONS

1. In DMA tests, a very good repeatability of results was observed. The T_g values were 69 °C for the EPX and 86 °C for the PUR. For a normal service range of temperatures under 50 °C, the storage modulus of the EPX was two times higher than that of the PUR. However, the curves showed a significant drop for both adhesives at temperatures above 50 °C; *i.e.*, largely before the T_g.
2. The glued-in rod connections with the EPX adhesive showed, on average, a 10% higher stiffness and 9% lower strength than those with the PUR at 20 °C. However, at 40 °C the connections with the EPX were still 23% stiffer and 13% stronger than those with the PUR.
3. Based on the first two conclusions, no direct correlation was found between the T_g of the tested adhesives and the results of the connection tests. Most likely, other parameters, such as geometry and mechanical properties of the other connection components, also play an important role in the connection performance at elevated temperatures. It would be useful to isolate the effects of the temperature on the elastic and strength properties of wood in the future investigations and modeling of the connection performance.
4. The tested glued-in rod connections with the EPX and PUR adhesives demonstrated quasi-brittle behavior with a high stiffness up to the wood failure around the rods when loaded at temperatures up to 40 °C. Beyond this temperature, the behavior of the connections changed dramatically. They demonstrated a plastic failure of the adhesives, with significant losses of stiffness and resistance. The mechanical properties of the PUR decreased in near linear proportion to the temperature increase, whereas the EPX showed a fast nonlinear degradation of the properties at temperatures above 40 °C. The loss of stiffness and strength near the limits of their certified service temperatures warrant attention with respect to the design implications of glued-in rod connections. Further investigations would be required to extend and confirm these results for other connection configurations, for larger diameters and/or length of rods, *etc*.
5. The long-term effect of the temperature on the performance of glued-in rod connections raises questions. Creep tests and a time-temperature superposition principle would be required to deal with this topic in depth.

ACKNOWLEDGMENTS

This research was sponsored by the Canadian Natural Sciences and Engineering Research Council (NSERC) Industrial Research Chair on Ecoresponsible Construction in Wood (CIRCERB) at Laval University in Quebec City, in the province of Quebec. This work was also supported by the French National Research Agency (ANR) through the Xyloplate project, Equipex XYLOFOREST (ANR-10-EQPX-16), and the IDEX project (ANR-10-IDEX-03-02). The authors are grateful to the industrial partners of the CIRCERB for their support.

REFERENCES CITED

Aicher, S. and Dill-Langer, G. (2001). “Influence of moisture, temperature, and load duration on performance of glued-in rods,” in: *Rilem Symposium on Joints in Timber Structures*, Stuttgart, Germany, 383-392.

Aicher, S., Hofflin, L., and Wolf, M. (1998a). “Influence of specimen geometry on stress distributions in pull-out tests of glued-in steel rods in wood,” *Otto-Graf-Journal* 9, 205-217.

Aicher, S., Kalka, D., and Scherer, R. (2002). “Transient temperature evolution in glulam with hidden and non-hidden glued-in steel rods,” *Otto-Graf-Journal* 13, 199-214.

Aicher, S., Wolf, M., and Dill-Langer, G. (1998b). “Heat flow in a glulam joist with a glued-in steel rod subjected to variable ambient temperature,” *Otto-Graf-Journal* 9, 185-204.

Connolly, T. and Mettem, C. J. (2003). “Developement of Eurocode-type disign rules for axially loaded bonded-in rods,” Report for project LICONS.

CSA O86 (2014). “Engineering design in wood,” Canadian Standards Association, Mississauga, Ontario,Canada.

Cruz, H. and Custódio, J. (2006). “Thermal performance of epoxy adhesives in timber structural repair,” in: *Proceedings of the 9th World Conference on Timber Engineering*, Portland, OR, USA.

Custódio, J., Broughton, J., and Cruz, H. (2009). “A review of factors influencing the durability of structural bonded timber joints,” *International Journal of Adhesion and Adhesives* 29(2), 173-185. DOI: 10.1016/j.ijadhadh.2008.03.002

De la Cruz Sanchez, C. (2006). "Mesure des constantes élastiques du bois d'épinette noire (Picea mariana (Mill.) B.S.P.) dans des conditions d'équilibre du séchage à basse température," Mémoire de Maîtrise en sciences du bois. Université Laval, Québec, Canada.

EN 26891 (1991). “Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics,” European Committee for Standardization, Brussels, Belgium.

EN 1995-1 (2005). “Eurocode 5: Design of timber structures. Part 1-1: General Common rules and rules for buildings,” European Committee for Standardization, Brussels, Belgium.

EN 301 (2006). “Adhesives, phenolic, and aminoplastic, for load-bearing timber structures-Classification and performance requirements,” European Committee for Standardization, Brussels, Belgium.

EN 408 (2010). “Structures en bois-Bois de structure et bois lamellé-collé-Détermination de certaines propriétés physiques et mécaniques,” European Committee for Standardization, Brussels, Belgium.

Gerhards. C.C. (1982) "Effect of moisture content and temperature on the mechanical properties of wood. An analysis of immediate effects," *Wood & Fiber* 14(1), 4-36.

IRABOIS. (1999). “Guide professionnel. Assemblages bois: Tiges ou goujons collés de grande dimension,” Institut de recherches appliquées au bois, cahier n°11, Paris, France.

ISO 898-1 (2013). “Caractéristiques mécaniques des éléments de fixation en acier au carbone et en acier allié -- Partie 1: Vis, goujons et tiges filetées de classes de qualité spécifiées -- Filetages à pas gros et filetages à pas fin,” Organisation internationale de normalisation, Genève, Suisse.

Klapwijk, D. (1978). "Restoration and preservation of decayed timber structures and constructions with epoxies," Preprints of the contribution to the Oxford Congress, London, UK, pp. 75-76.

Lartigau, J., Coureau, J. -L., Morel, S., Galimard, P., and Maurin, E. (2015). "Effect of temperature on the mechanical performance of glued-in rods in timber structures," *International Journal of Adhesion and Adhesives* 57, 79-84. DOI: 10.1016/j.ijadhadh.2014.10.006

NDS (2014). National Design Specification® (NDS®) for Wood Construction, 2015, American Wood Council.

Richter, K. and Steiger, R. (2005). "Thermal stability of wood-wood and wood-FRP bonding with polyurethane and epoxy adhesives," *Advanced Engineering Materials* 7(5), 419-426. DOI: 10.1002/adem.200500062

Ross, R. J. (ed.) (2010). *Wood Handbook: Wood as an Engineering Material*, U.S. Department of Agriculture, Forest Products Laboratory, Madison, WI.

SIA 265 (2012). "Construction en bois," Société Suisse des Ingégnieurs et Architectes, Zurich, Suisse.

Steiger, R., Gehri, E., and Widmann, R. (2004). "Glued-in steel rods: A design approach for axially loaded single rods set parallel to the grain," in: *International Council for Research and Innovation in Building and Construction*, Edinburgh, Scotland, pp. 37-7-8.

Steiger, R., Serrano, E., Stepinac, M., Rajčić, V., O'Neill, C., McPolin, D., and Widmann, R. (2015). "Strengthening of timber structures with glued-in rods," *Construction and Building Materials* 97, 90-105. DOI: 10.1016/j.conbuildmat.2015.03.097

Taupin, J. (1980). "Restauration à la résine époxyde de planchers et charpentes au Monastère de la Grande Chartreuse," *Bulletin d'Informations Techniques* 92, 34-43.

Tlustochowicz, G., Serrano, E., and Steiger, R. (2011). "State-of-the-art review on timber connections with glued-in steel rods," *Materials and Structures* 44(5), 997-1020. DOI: 10.1617/s11527-010-9682-9

Article submitted: May 24, 2016; Peer review completed: July 22, 2016; Revised version received and accepted: July 26, 2016; Published: August 9, 2016.
DOI: 10.15376/biores.11.4.8200-8214