Final Report 1999-03

PB99-144784

Moisture Content Variations of Nail-Laminated Bridges in a Northern Climate

Minnesota Local Road Research Board

FUNDING ACKNOWLEDGEMENT

This project was conducted with funding provided by the Minnesota Local Road Research Board (LRRB). The LRRB's purpose is the develop and manage a program of research for county and municipal state aid road improvements. Funding for LRRB research projects comes from a designated fund equivalent to 1/2 of one percent of the annual state aid for county and city roads.

Technical Report Documentation Page

1. Report No. MN/RC - 1999-03	2.	3. Recipient's Accession No.
4. Title and Subtitle Moisture Content Variations of Nail-Laminated Timber Bridges in a Northern Climate		5. Report Date November 1998 6.
7. Author(s) Douglas A. Lange, Benjamin Wallace, Timothy D. Larson, Anthony Lukindo		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Minnesota Department of Wood & Paper Science 2004 Folwell Avenue St. Paul, Minnesota 55108		10. Project/Task/Work Unit No. 11. Contract (C) or Grant (G) No. (C) 74708 TOC # 66
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research Services 395 John Ireland Boulevard, Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report July 1995 - September 1998 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract (Limit: 200 words)

Timber in nail-laminated and stress-laminated bridges is often installed with moisture contents (MC) near the fiber saturation point. Post-installation moisture loss induces shrinkage in the timber components, which results in loosening of component fasteners. This research project sought to establish the equilibrium moisture content (EMC) of timber bridges in Minnesota.

Researchers took seasonal MC measurements on six nail-laminated timber bridges to determine annual MC variations and moisture gradients in individual bridge components: three bridges from northern Minnesota in St. Louis County and three from southern Minnesota in Sibley County. An electrical resistance meter measured moisture content, with oven-dry and toluene distillation methods of MC determination as controls.

The study found the average MC of bridge components in St. Louis County was 2 percent–11 percent higher than bridge components in Sibley. The study determined the average MC at a three-inch depth on three of the major bridge components as:

- deck laminations 18 percent (Sibley) to 28 percent (St. Louis)
- transverse stiffener beams 14 percent (Sibley) to 18 percent (St. Louis)
- deck supports 17 percent (Sibley) to 27 percent (St. Louis).

The results indicate that the regional microclimate may greatly affect MC. Results from this research will allow MC specifications to be determined before bridge installation, helping minimize post-installation moisture-related problems and optimize design calculations. In addition, results will provide necessary data for ongoing research on transverse load-sharing characteristics of longitudinally nail-laminated timber bridges. Finally, this information will provide a basis for inspecting MC in timber bridges.

17. Document Analysis/Descriptors timber bridge design wood transportation structures timber bridge moisture content		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 19	22. Price

Moisture Content Variations of Nail-Laminated Timber Bridges in a Northern Climate

Final Report

Prepared by

Douglas A. Lange

Timothy D. Larson

Benjamin Wallace

Anthony Lukindo

Wood & Paper Science Department
University of Minnesota

November 1998

Prepared for the

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail stop 330
117 University Avenue
St. Paul, MN 55155

Executive Summary

Timber in nail-laminated and stress-laminated bridges is often installed with a moisture content (MC) near the fiber saturation point (FSP), between 25% and 30%. Post-installation moisture loss induces shrinkage in the timber components. In nail-laminated bridges this results in loosening of the transverse stiffener beams and subsequent gap formation between deck laminae, while in stress-laminated bridges there occurs loss of tension bar forces, all of which reduce the transverse load distribution capacity of the bridge. These problems often manifest themselves in asphalt wear surface cracking. Moisture that infiltrates through these cracks can cause accelerated deterioration of affected bridge components.

The objective of this project was to establish the equilibrium moisture content (EMC) of timber bridges in Minnesota. Seasonal MC measurements were taken on six nail-laminated timber bridges to determine annual MC variations and moisture gradients in individual bridge components. The selected bridges ranged in age from 13 to 52 years old. Three bridges are from northern Minnesota in St. Louis County. The other three are from southern Minnesota in Sibley County. The two regions are separated by a distance of approximately 250 miles and differ in vegetation, annual temperature and precipitation.

Moisture content was measured by means of an electrical resistance meter. Oven-dry and toluene distillation methods of MC determination were used as controls. Bridge components measured for MC included the deck laminations, the supporting abutment and pier caps and, depending upon bridge design,

either the transverse stiffener beams or longitudinal support beams. The MC gradient was established from measurements taken at the surface and at a depth of ½", 1", 2" and 3". Approximately 480 total MC measurements were recorded from each bridge.

The average MC of bridge components in the north was found to be 2% – 11% higher than those in the south. Moisture content in any one bridge varied significantly between bridge components. The average MC at a 3 inch depth on three of the major bridge components measured are: deck laminations 18% (Sibley) to 28% (St. Louis); transverse stiffener beams 14% (Sibley) to 18% (St. Louis); and deck supports 17% (Sibley) to 27% (St. Louis). The results indicate that MC may be greatly affected by the regional microclimate.

Results from this research will allow MC specifications to be determined prior to bridge installation. This will help to minimize post-installation moisture related problems and optimize design calculations. In addition, results will provide necessary data for an on going research on transverse load sharing characteristics of longitudinally nail-laminated timber bridges. Finally, this information will provide a basis for inspecting MC in timber bridges.

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1- Introduction

Timber in nail-laminated and stress-laminated bridges is often installed with a moisture content (MC) near the fiber saturation point (FSP), between 25% and 30%. Post-installation moisture loss induces shrinkage of the timber components. In nail-laminated bridges there is loosening of transverse stiffener beams and subsequent gap formation between deck laminae, while in stress-laminated bridges there occurs loss of tension bar forces, all of which reduces the transverse load distribution capacity of the bridge. These problems often manifest themselves as asphalt wear surface cracking. Moisture that infiltrates through these cracks can cause accelerated deterioration of affected bridge components.

Given time, the MC of large timber bridge components should stabilize near an equilibrium moisture content (EMC). A study by McCutcheon et al (1986) found that the average MC of nail-laminated timber bridges across the northern United States is about 21%. This study also identified a significant variation of MC within nail-laminated bridges. Moisture content ranged from 26% in deck laminations adjacent to the bridge abutments to 17% in stringer beams. The higher MC of laminations near the abutments was attributed to wear surface cracks, which channel water to this location.

Based on values published by McCutcheon, components on a timber bridge are expected to shrink between 1% to 4%. If we consider a 25 ft wide timber deck and 4% shrinkage, then the effective bridge deck width will decrease 1 ft due to shrinkage from installation to equilibration. In a nail-laminated system this shrinkage would likely appear as gaps between laminae. However, in a stress-laminated bridge this shrinkage would have to be accommodated through additional tightening of the tension rods.

Another moisture related performance factor in timber bridges is the ultimate strength of the structure after wood components have attained EMC. Wood strength has an inverse logarithmic relationship to MC below FSP. Low MC is associated with higher strength and stiffness. Accurate regional EMC values should help to optimize design calculations for timber bridges.

The objectives of this research are to:

1) Find regional EMC of Minnesota timber bridges,
2) Develop a MC profile for structural timber bridge components,
3) Monitor annual variations of timber bridge MC.

Results from this research will allow MC specifications to be determined prior to bridge installation. This will help to minimize post-installation moisture related problems and optimize design calculations. In addition, results will provide necessary data for an on going research on transverse load sharing properties of longitudinally nail-laminated timber bridges. Finally, this information will provide guidelines for inspecting MC in timber bridge components.

2- Methods

The MC of six nail-laminated timber bridge structures in Minnesota was measured during the four annual seasons. The selected bridges were from northern and southern regions of Minnesota, three from northern in St. Louis County; and three southern southern in Sibley County. The bridges varied in age from 13 to 52 years old (Table 1). Four bridges were longitudinally nail-laminated (LNL) design. The other two were stringer bridges with transverse nail-laminated decks (TNL).

County	Inventory Number	Bridge Type	Age (Years)	Wear Surface
St. Louis	69563	LNL	12	Asphalt
	69561	LNL	14	Gravel over Asphalt
	7794	Stringer	51	Gravel over Asphalt
Sibley	6641	Stringer w/retrofit	48	Asphalt
	72501	LNL	37	Asphalt
	72520	LNL	19	Gravel

Table 1 - General timber bridge information

2.1. Moisture Measurements

Moisture content was measured by means of a Delmhorst model J-2000 conductance meter. The meter was a two-pin configuration. Pins used had the capacity to penetrate to a depth of 3" and were Teflon insulated. The Delmhorst meter had measurement controls for temperature and species correction. Measurements exceeding 30% MC were recorded as 30% because the moisture meter could not accurately measure moisture above the FSP. Moisture content was measured in accordance with ASTM D 4444-92.

Moisture content readings for the four seasonal replications were taken at the following locations on each LNL bridge (Figure 1) and on the two TNL bridges (Figure 2).

1-LNL) Abutment cap
2-LNL) Laminae at bridge abutment
3-LNL))Laminae at mid-span
4-LNL) Transverse stiffener beam (TSB)
5-LNL) Laminae over pier cap
6-LNL) Pier cap

1-TNL) Abutment cap
2-TNL) Laminae over abutment
3-TNL) Laminae at mid-span
4-TNL) Beam at mid-span
5-TNL) Laminae over pier cap
6-TNL) Pier cap

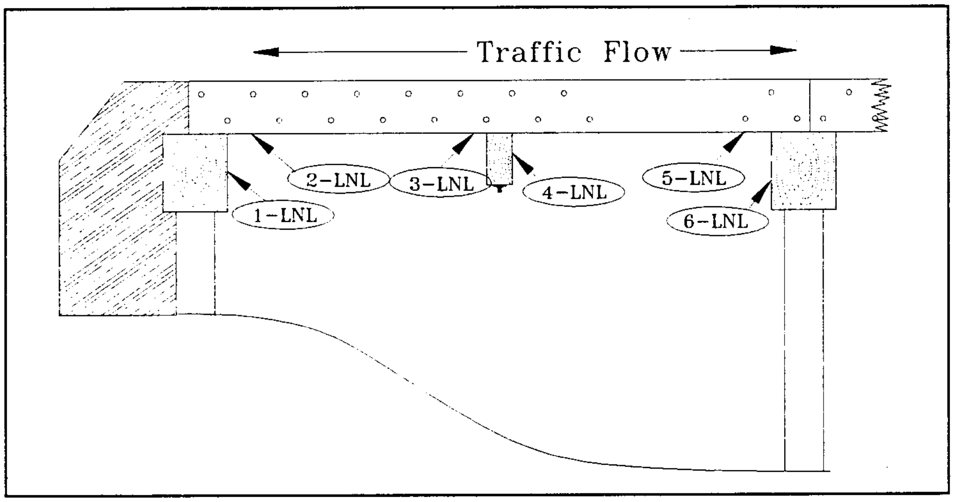

Figure 1 Moisture measurement locations on a longitudinally nail-laminated timber bridge.

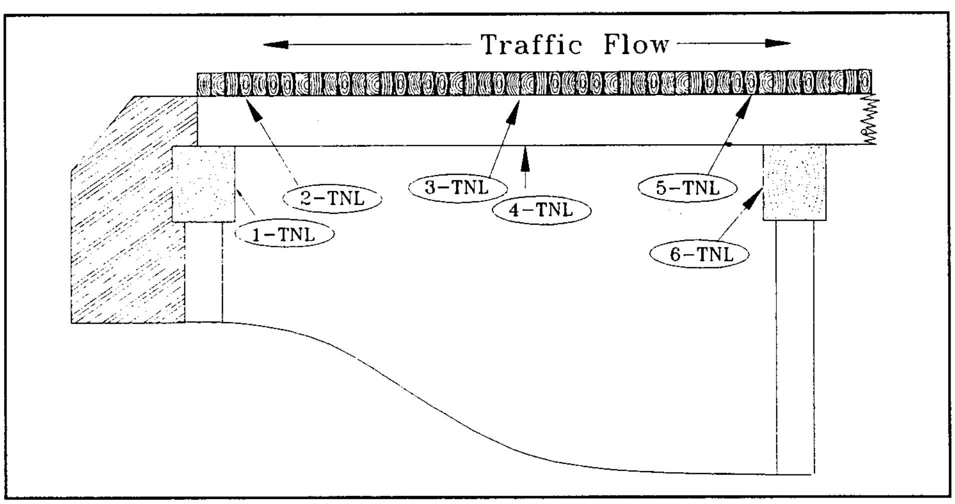

Figure 2 Moisture measurement locations on a transverse nail-laminated stringer bridge

Each bridge had 24 to 36 sites where the MC was recorded. Moisture content at each site was recorded at the wood surface and at depths of 0.5 inch, 1.0 inch, 2.0 inch and 3.0 inch. A total of 120 to 180 MC measurements were taken from each bridge during each seasonal visit.

Wood samples used for oven-dry and toluene distillation were collected using a calibrated increment bore (see ASTM D4442-92 for calibration method). Core samples where removed from five laminae adjacent to the abutments corresponding to the sites of MC conduction meter reading. The removed cores where ~4.0" long. The first 1.0" of each core was placed in a glass collection jar containing a porous ceramic thimble. The regions of 2.0" to 3.0" and 3.0" to 4.0" were separated and collected in pre-weighed plastic containers. Moisture content of cores from a depth >2.0" was determined by the oven-dry method. Toluene distillation was used for moisture determination of samples from the first 1" because creosote preservative was present in this region.

2.2. *Nominal EMC*

To help explain regional variations in MC the predicted nominal EMC of wood was calculated based on regional ambient temperatures and dew-point temperatures. An equation developed by Simpson (1971) was used to calculate the nominal EMC. Nominal EMC was calculated from an 18-year span of weather data (1978 to 1996) from the cities of International Falls and Minneapolis, which are in proximity to St. Louis County and Sibley County respectively (data was not available for cities within these counties). Data for the 18 years of monthly averaged ambient temperatures and dew-point temperatures was obtained from the Department of Soil, Water and Climate at the University of Minnesota.

First, the monthly average partial vapor pressure and saturated vapor pressure was calculated using Kirchoff's equation:

$$p_0 = \exp(53.421 - 6516.3/T - 4.125\ln T) \qquad \textit{Equation 2-1}$$

where:

p_0 = *saturation vapor pressure*
T = *temperature* (^{0}*K*)

Next, the mean monthly relative humidity was calculated using the partial vapor pressure and saturation vapor pressure:

$$h = \frac{p}{p_0} \qquad \textit{Equation 2-2}$$

where:

h = *relative humidity (fractional)*
p = p_0 *at the dew point temperature*

Finally, the monthly nominal equilibrium moisture content level was calculated using the following equation (Simpson 1971):

$$M = \frac{1800}{W}\left[\frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right] \qquad \textit{Equation 2-3}$$

where:

M = moisture content (%)
$W = 349 + 1.29T + 0.0134T^2$ *Equation 2-4*
$K = 0.805 + 0.000736T - 0.00000273T^2$ *Equation 2-5*
$K_1 = 6.27 - 0.00938T - 0.000303T^2$ *Equation 2-6*
$K_2 = 1.91 + 0.0407T - 0.000293T^2$ *Equation 2-7*

3- Results

3.1. Conduction Meter Readings

Average MC values versus depth of measurement were calculated based on bridge component, region and season. Moisture measurements of deck laminae on St. Louis County bridge # 7794 were excluded from averages of the region because they did not appear to be representative of the region. The moisture content deck laminae on bridge # 7794 was almost entirely above the FSP at all depths, whereas the MC of deck laminae from the other two northern region bridges increased with measurement depth from ~14% to ~30%. It was believed that the deck laminae MC measurements from bridge # 7794 were not representative of the region.

In general the winter measurements are observed to be higher than in other seasons. Possible reasons for this trend are presented in the section 4.

Values from the MC versus depth profile of bridge abutments in St. Louis Cty. (Figure 3) are approximately 3% higher than values in the Sibley County (Figure 4). St. Louis County measurements show a distinct separation of seasonal values at the 2" and a 3" depth, with summer values the lowest, and spring and winter values the highest.

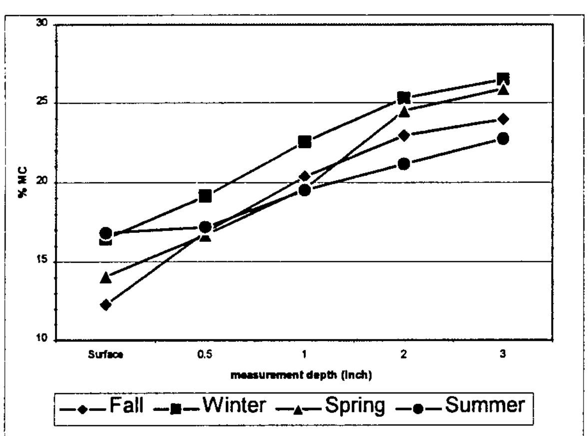

Figure 3 MC of Abutment -St. Louis Cty.

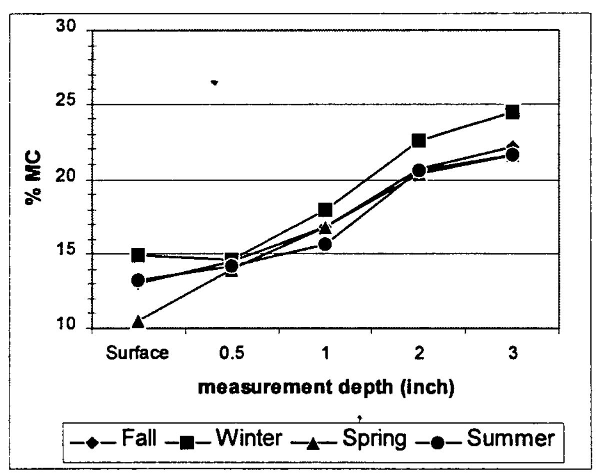

Figure 4 MC of Abutment -Sibley Cty.

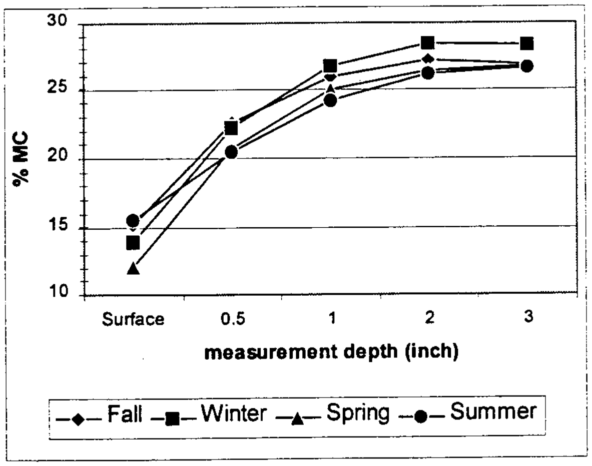

Figure 5 MC of Laminae over Abutment-St. Louis Cty.

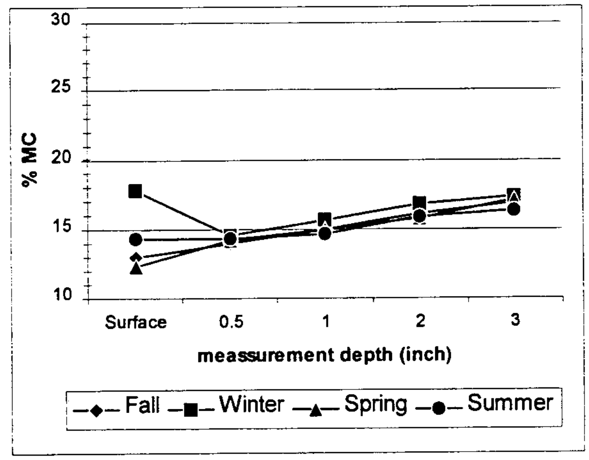

Figure 6 MC of Laminae over Abutment-Sibley Cty.

Laminae over the abutments in the two regions have very different MC versus depth profiles. In St. Louis County the MC profile is a smooth curve that levels off at ~27% between the 2" and 3" depth (Figure 5) [Note, the maximum values for laminae in St. Louis County are only relative since meter readings higher than 30% were expressed as 30]. Laminae over the abutments in Sibley County are ~10% lower than St. Louis County with a maximum value of about 17% (Figure 6). The MC depth profile in Sibley County is basically linear with a gradual slope that may continue to increase past the 3" depth.

Mid-span laminae MC measurements are similar to those for laminae over the abutments. Again, the profile for St. Louis County is a curve which levels off at ~27% (Figure 7) and the profile for Sibley County is linear with maximum values at ~17% (Figure 8). The 1" summer measurements in Sibley County are 1% to 2% lower between the depths of 1" and 3".

The MC depth profile for the TSB in St. Louis County is significantly lower than profiles components in this region (Figure 9). Excluding the winter measurements, this profile is linear up to the 2" depth and is levels to the 3" depth with a maximum MC of ~18%. The Sibley County TSB profile is also linear from 0.5" up to 2", it reaches a maximum MC of ~15% and then drops back to ~14% at the 3" depth (Figure 10).

The MC profiles for laminae over the pier cap are again similar in patterns to the profiles of the laminae over the abutments and laminae at mid-span. Measurements in St. Louis County produce curves which levels at ~28% MC (Figure 11). The profiles for the Sibley County measurements are fairly linear with a maximum MC of ~18% at the 3" depth (Figure 12).

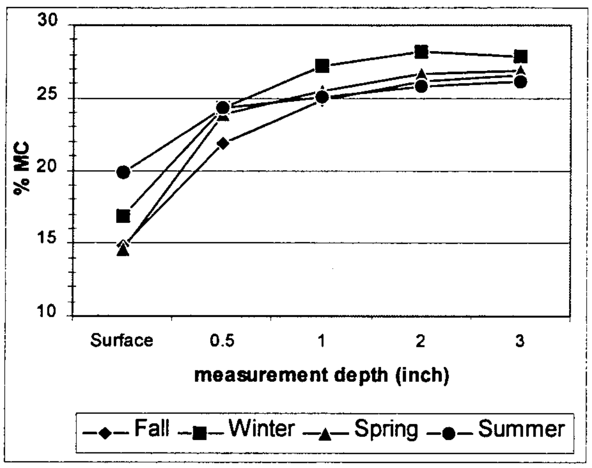

Figure 7 Laminae at Mid-Span-St. Louis Cty.

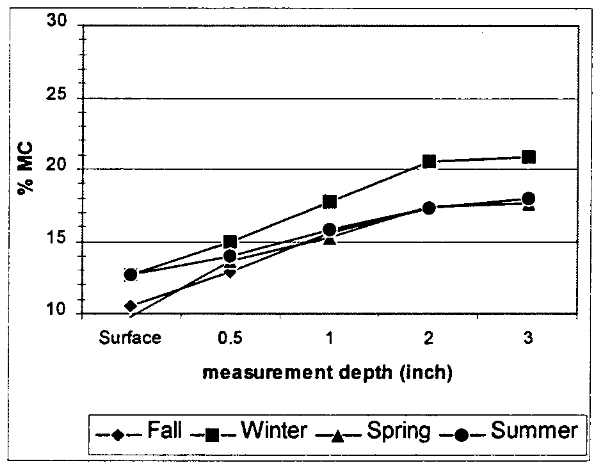

Figure 9 MC of TSB-St. Louis Cty.

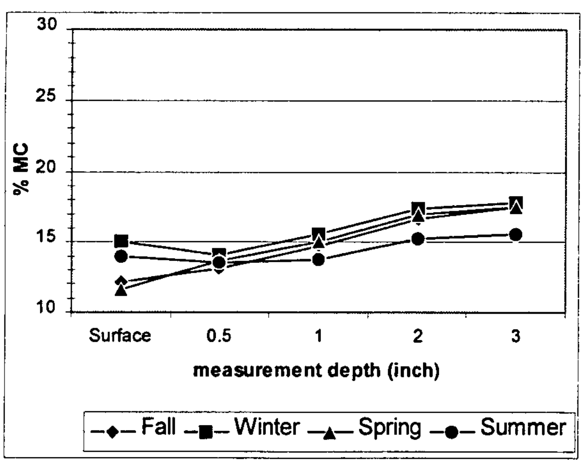

Figure 8 Laminae at Mid-Span-Sibley Cty.

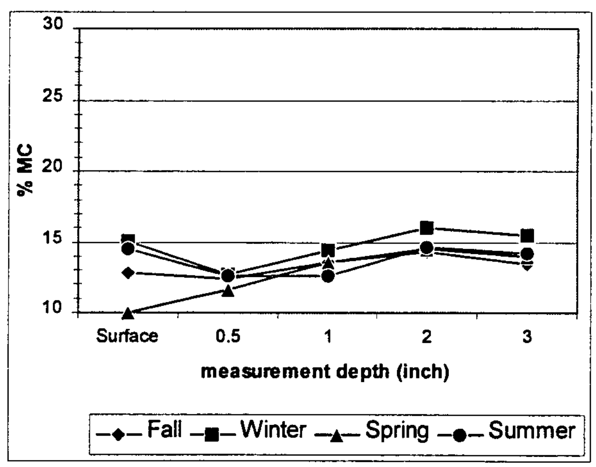

Figure 10 MC of TSB-Sibley Cty.

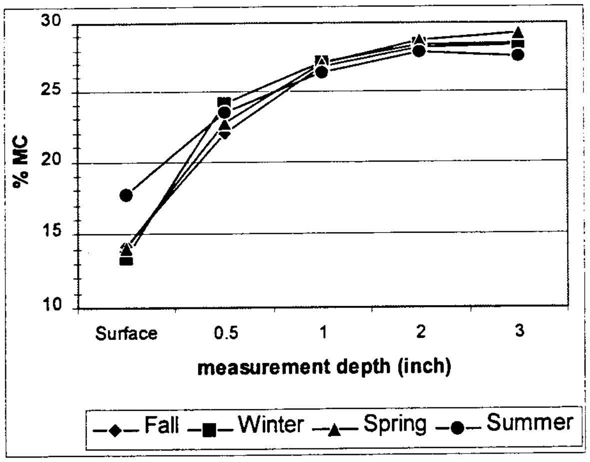

Figure 11 MC of Laminae Over Pier Caps – St. Louis Cty.

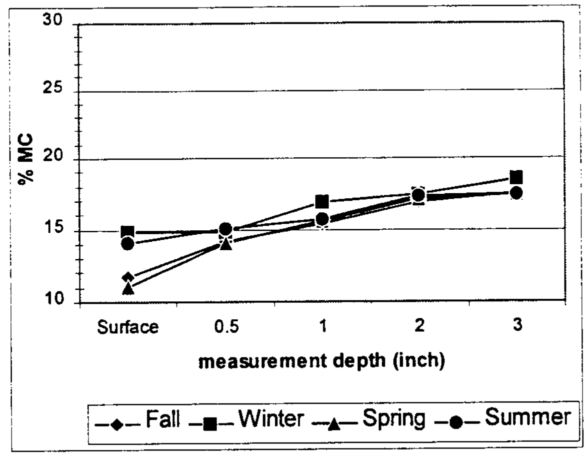

Figure 12 MC of Laminae Over Pier Caps-Sibley Cty.

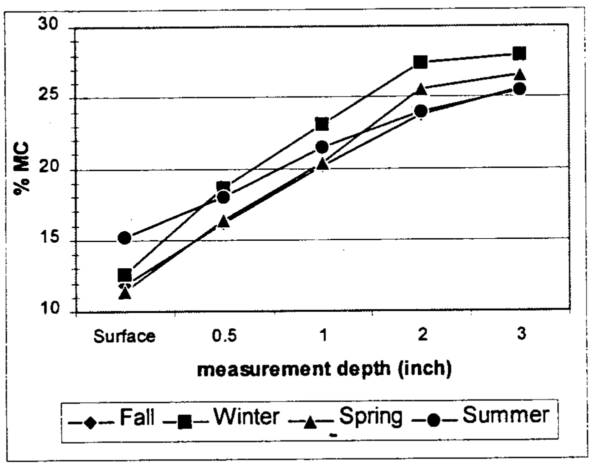

Figure 13 MC of Pier Caps-St Louis Cty.

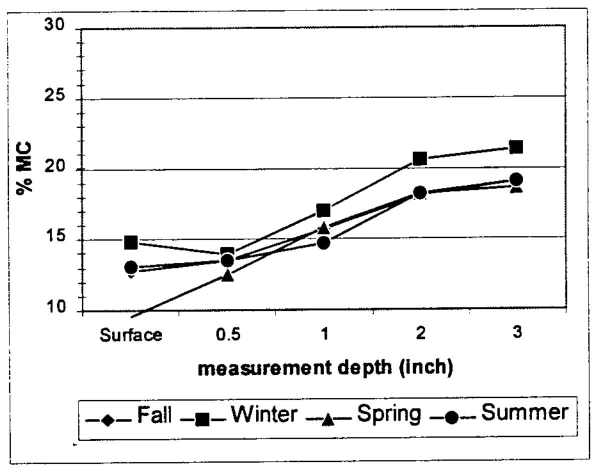

Figure 14 MC of Pier Caps-Sibley Cty.

The MC profiles for the pier caps in each region are similar to the profiles for the abutment caps. The profiles from St. Louis County are linear up to 2", then level off to ~26% at the 3" depth (Figure 13). Sibley County also has profiles which are roughly linear from 0.5" up to 2" and then level to ~19% at the 3" depth (Figure 14).

3.2. *Moisture Content of Core Retain Samples*

The MC of core retain samples was determined for St. Louis County bridges 69563 and 69561, and Sibley County bridge 72520. Only the summer season measurements provided usable results. Results are presented for core segments between 0-1" depth, 2"-3" depth and 3"-4" depth (Table 2). In addition, the corresponding moisture meter measurements are presented along with standard deviations. The MC of the 2"-3" core samples are essentially equal to the average between the 2" and 3" meter readings given the standard deviation associated with these meter measurements. Also notice that at depths >3" the oven-dry MC exceeds 30% in St. Louis County bridges 69563 and 69561

		69563		69561		72520	
		MC	Std Dev	MC	Std Dev	MC	Std Dev
Core Samples	0-1inch	16.5%		8.6%		16.5%	
	2-3 inch	29.1%		29.6%		16.4%	
	3-4 inch	41.0%		34.9%		17.4%	
Meter Readings	Surface	16.8 %	1.49	14.3 %	2.70	13.7 %	0.53
	0.5 inch	20.2 %	4.67	20.8 %	3.82	13.6 %	1.38
	1 inch	23.5 %	6.12	25.3 %	5.90	13.7 %	1.77
	2 inch	26.7 %	5.08	27.3 %	4.08	15.2 %	2.12
	3 inch	28.1 %	6.03	27.9 %	4.52	13.8 %	3.38

Table 2 MC of Core Retains and Corresponding Meter Readings

3.3. *Estimated EMC*

The estimated EMC for each bridge component is based on the 3" depth measurements. Again, MC values from St. Louis County bridge 7794 were excluded from these estimations. The estimated EMC is presented as an annual average for each component along with the variance based on a 90% level of confidence (Table 3).

Bridge Component	Estimated EMC	
	St. Louis County	Sibley County
1) Abutment Caps	24.7 +/- 1.0	22.5 +/- 0.8
2) Laminae over Abutments	27.1 +/- 1.0	17.0 +/- 1.2
3) Laminae at Mid-Span	26.9 +/- 1.3	17.1 +/- 1.5
4) Transverse Stiffener Beam/ Mid-Span Stringer	18.7 +/- 0.5	14.3 +/ 0.6
5) Laminae over Pier Caps	28.4 +/- NA	17.7 +/- 1.0
6) Pier Caps	26.4 +/- 0.9	19.5 +/- 0.9

Table 3 Estimated EMC

3.4. Nominal EMC

It is important to note that calculation of nominal EMC is based on sorption of moisture from the vapor phase and does not consider liquid moisture sorption. The annual nominal EMC for International Falls and Minneapolis respectively was approximately 13% and 11.5 % (Figure 15). The plotted linear regression trend for the 18-years indicates a 2.3% EMC increase for the northern region and a 7.8% increase for the southern region. While the nominal EMC does not directly correlate to the actual bridge EMC, it does support the observed higher EMC in the St. Louis County region.

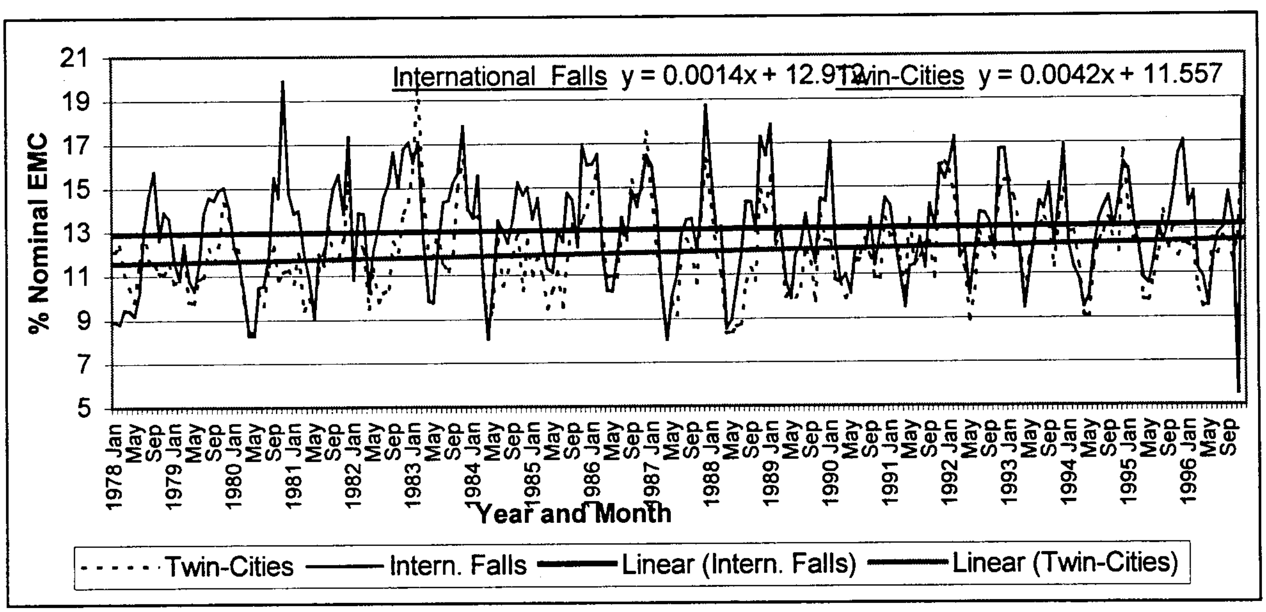

Figure 15 Calculated Nominal EMC for St. Louis and Sibley Counties

4- Discussion

The large difference of timber bridge MC between the two regions was unexpected. The initial assumption was a nominal EMC calculation would closely approximated the EMC for the two regions since the majority of the bridge components are concealed or protected from direct precipitation contact. The 1.5% difference in nominal EMC between the two regions does support some of the observed differences in MC measurements; however to what degree this variation impacts the ultimate EMC of the timber is not certain.

The equation used for calculating nominal EMC is insufficient for predicting the EMC of timber bridges because the equation only considers ambient temperature and dew point temperatures as variables and does not consider the influence of liquid water in the environment. We would propose the actual EMC of a timber bridges is affected by the much wider range of influential variables listed below, all of which may shift the actual MC away from predictable EMC conditions.

1) Diffusion rates of moisture in treated wood;
2) Precipitation;
3) Infiltration of moisture through the wear surface;
4) Surrounding microclimate, i.e. vegetation, wetting versus drying, season length, air flow, temperature and dew point temperature.

The wear surface type may also be a contributing factor, however this does not help to explain the much higher MC also observed in the St. Louis County bridge #

69563, which has a asphalt wear surface and is very comparable to the Sibley County bridges.

Generally, within each region the MC profiles for the different bridge components were complementary to one another. With the exception of the TSB, the average 3" measurements in St. Louis County were between 23-27%, and in Sibley County between 17-22%. The lower TSB MC of 17% and 14%, for St. Louis and Sibley respectively, is a factor of exposure and position. The TSB is exposed to air on three sides since it hangs below the bridge. The mid-span position of the TSB also places it away from the common areas of wear surface cracking, thus reducing direct contact with water that might infiltrate through the wear surface.

Several of the MC depth profiles display measurements for winter that are higher by ~2%. It does not seem likely that between autumn and winter some of the measured bridge components increased by 2% in MC at the 3" depth, then dropped back 2% MC during the spring. Rather there appears to have been some error in measurements at freezing temperatures despite the temperature-correcting feature of the moisture meter. One explanation for this variation is that frozen unbound moisture in the wood could have significantly changed the wood electrical conduction properties and thereby shifted the measurement values. If it can be assumed the winter reading were affected by low temperatures, then we find that all measurements taken at a half inch or deeper are within the tolerance of error from season-to-season. Furthermore, there is no obvious trend of moisture loss during the annual MC cycle suggesting that the measured components did not actually gain moisture during the winter months. Surface measurements appear to be the only seasonal values that vary significantly between seasons.

Shrinkage of bridge components should be considered an important factor of timber bridge construction. As was mentioned in the introduction, post-installation shrinkage will often necessitate corrective tightening of connectors. In addition, gap formation between laminae will introduce excessive force on nail connectors and allow independent movement of individual lamina.

Post-installation shrinkage can be calculated for the studied timber bridges using regional MC data and known percent shrinkage values for the species of wood used in construction. For example, we know coastal Douglas-Fir (*Psuedotsuga menziesii*) was used to build all of the bridges encountered in this study. The radial and tangential shrinkage values for Douglas-Fir are 4.8% and 7.6% respectively for a MC change from 30% to 0% (Encyclopedia of Wood or Wood Handbook). Fasteners in the bridge components may enter the timbers through either the radial or tangential direction. The following equation can be used to determine the percent shrinkage expected for both orientations:

$$S_m = S_o \frac{m_o - m}{30} \qquad \textit{Equation 4-1}$$

Where S_m is shrinkage in percent from m_o moisture content to the moisture content m, S_o is the total shrinkage percent. Two example calculations of shrinkage are presented below.

1) Shrinkage for TSB in Sibley County
   a) S_o = 7.6% The fasteners holding a TSB to the deck generally extend through the tangential direction of the TSB.
   b) m, = ~15% This is the EMC of a TSB in Sibley County (Figure 10).

c) m_o = 30% Bridge components are generally installed near 30% MC.

d) $S_m = 7.6\% \frac{30-15}{30} = 3.8\%$

e) The tangential dimension of the TSB is 12".

Total shrinkage: 12" x 3.8% = ~0.46" shrinkage

2) Shrinkage of the mid-span deck laminae in Sibley County.

a) S_o = 4.8% The fasteners holding deck lamina together generally extend through the radial direction of the laminae.

b) m_t = ~17% This is the EMC of mid-span laminae in Sibley County (Figure 8).

c) m_o = 30% Bridge components are generally installed near 30% MC.

d) $S_m = 4.8\% \frac{30-17}{30} = 2.08\%$

e) Individual lamina are 3" wide. In a 40' wide deck there are 160 laminae.

Total shrinkage: 3" x 2.08%x160 = ~10" loss of deck width.

The loss of lamina width in a nail-laminated bridge appears as gaps between adjacent lamina, whereas it appears as loss of deck width in a stress-laminated bridge.

5- Conclusions

1) The selected bridges have reached an EMC within the given regions.

2) Microclimate does have a substantial effect on timber bridge EMC.

3) In Minnesota, timber bridge components may experience up to a 4% dimension loss or shrinkage after installation. Pre-drying of bridge timbers to a MC comparable to regional EMC should greatly reduce post-installation dimension loss, but will be costly.

6- References:

1) McCutcheon, W.J., Gutkowski, R.M. and Moody, R.C. 1986. Performance and Rehabilitation of Timber Bridges. Transportation Research Record 1053. Pp. 65-69.

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