Determining the impact of sensor orientation on moisture content measurements in eastern white pine

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Abstract. As buildings become more airtight and insulated, the movement and accumulation of moisture within building envelopes become paramount in determining its resiliency. Current methods for quantifying the moisture content (MC) of wood species involve the measurement of electrical resistance between two installed electrodes and the use of existing empirical correlations to evaluate the MC. However, these correlations do not adequately consider the impact of sensor orientation within wall assemblies. The objective of this paper is to determine the impact of MC readings within a wood sample due to sensor orientation. A total of 126 eastern white pine samples were tested with electrodes placed along the grain of the wood (longitudinal), across the grain of the wood (tangential), and in a diamond pattern, using six different fasteners as electrodes. The samples were placed in a controlled environmental chamber until steady state was achieved at approximately 18% MC. Electrical resistances of the samples were measured in both directions at temperatures ranging from -10°C to 40°C. It was found that the tangential-to-longitudinal resistance ratio is 1.1-1.35 depending on the electrode type.

1. Introduction

Increasing demand of occupant and thermal comfort has led to the increase of insulation in many new buildings. As high R-value walls become more extensively researched and building enclosure designs become more airtight, the need for more accurate moisture content (MC) sensors is paramount. By adding insulation to the outside of structural wall sheathing, while also using new materials with very low vapour permeances, a greater potential for moisture accumulation can arise. This accumulation may lead to mould, mildew, health-related problems, and in extreme cases, cause wood components to rot, leading to structural failures. Several techniques exist today for measuring MC in wall assemblies, but these methods have high uncertainties when implemented during long-term field testing due to sensor drift and external sources of damage such as dust, rust, corrosion, etc.

The electrical resistance technique is commonly used today to measure MC in wood-frame buildings. A current is run between two metal electrodes installed in lumber or engineered wood, and the measured resistance across the wood is then correlated to MC using existing empirical equations. However, this technique has a lack of focus on examining the effects of using different electrode types and the impact of sensor orientation relative to grain direction on the resistance readings. Existing international standards [1,2] recommend installing these electrodes in an orientation where current flows parallel to the grain of the wood; however, these recommendations are supported by outdated literature that is generalized for all wood species. Additionally, this is not always possible when used in actual in-situ measurements based on the geometry being evaluated. This paper examines the impact of sensor orientation on electrical resistance to study the effect of electrical conductivity anisotropy in eastern white pine (Pinus strobus) by installing electrodes along the grain of wood (longitudinal) and across the grain of the wood (tangential).
2. Literature review

Through a review of current literature, two gaps were observed: 1) There is a lack of attention in literature with regards to examining how conductivity behaves in different directions in different species of wood and; 2) From the studies that did look into this, some have shown that electrical conductivity is an isotropic physical property, while others have showed that it varies with direction of current flow. This section identifies and reviews the studies under both categories.

2.1. Isotropic electrical conductivity

Forsén & Tarvainen [3] measured the electrical resistance of pine and spruce samples in the longitudinal and tangential directions over MCs ranging from 7% to 25% and found no difference in resistance readings. Their findings also agreed with Apneseth & Hay [4]. Samuelsson [5] measured electrical resistance of pine and fir samples in the longitudinal, tangential and radial directions over the entire MC range and also found no difference in readings.

Fernandez-Folfin et al. [6] measured electrical resistance of multiple wood species (oak, beech, cherry, ash) across both directions and reported that the bulk of their errors was within ±0.5% MC, showing that these species are isotropic with regards to electrical conductivity.

2.2. Anisotropic electrical conductivity

James [7] reported that grain direction is negligible at moisture levels below 15% MC, but at moisture levels above 20%, ratios of resistances to the longitudinal direction can be 1.8 times for radial and 2.0 times for tangential directions. The study reported that moisture readings may be as much as 2 percentage points lower if readings were taken in the tangential direction. The US Forest Product Lab Wood Handbook [8] also reported the same values.

Dai and Ahmet [9] measured the MC for moisture levels of 6% to 30% MC by using cylindrical wood buffers to measure resistance in both directions in several wood species. The study reported that the ratio of tangential-to-longitudinal resistance increases with moisture levels from 1.2 at 6% MC to 2.0 at 22% MC.

Stamm [10,11] focused on relating structural orientation to electrical conductivity of wood. The study has reported that the ratio of tangential-to-longitudinal resistance can range from 2.1 to 3.9 and ratio of radial-to-longitudinal resistance can range from 1.9 to 3.2. Kuroda and Tsutsumi [11,12] also reported that the MC in wood affects the degree of anisotropy. This study examined a commonly used species of wood in Japan (Sugi wood) and reported that the ratio of tangential-to-longitudinal resistance varies with MC. As MC increases from oven-dry to ~8% MC, the ratio decreases to ~2.0 and it starts increasing again after ~8% MC up to a moisture level of ~20%.

The electrical conductivity anisotropy property in wood still appears to have a degree of uncertainty, thus, it is crucial to improve the understanding of this property in wood. This is done in the paper by examining the effects of resistances in different directions in eastern white pine.

3. Methodology

A methodology was established based on the international standards and reviewed literature to determine the relationship between electrical resistance along and across the wood grain for eastern white pine. This section outlines how the test samples were prepared, conditioned to a specific temperature and relative humidity, and how electrical resistances were recorded.

3.1. Specimen preparation

Boards of eastern white pine species with a nominal thickness of 1.9 cm (3/4”) were collected from multiple suppliers to ensure sample randomization. A total of 126 samples with dimensions of 63.5 mm (longitudinal) x 63.5 mm (tangential) x 19 mm (radial) were cut from these boards. The samples were free of visible irregularities such as knots, decay and resin concentrations as dictated by ASTM D4444 [2]. To measure electrical resistance in the wood, six sets of different electrodes were used for this procedure: (1) #10 stainless steel wood screws, (2) #8 zinc-plated steel wood screws, (3) #4 zinc-plated steel wood screws, (4) 2.1 mm stainless steel finishing nails, (5) 3.5 mm aluminum galvanized roofing nails, and (6) #6 brass wood/metal screws. The total sample size was divided into three sets for testing,
where the first set had two electrodes installed in the longitudinal direction relative to the wood grain, the second set had two electrodes installed in the tangential direction relative to the wood grain and the third set had four electrodes installed (two in each direction) in a diamond orientation. The three sets were further divided into 6 subsets for the use of different electrode types. For example, the #10 stainless steel screws were installed in 21 samples, where 7 samples had screws implemented in the longitudinal direction, 7 in the tangential direction and 7 in a diamond orientation. This was the case for the rest of the fasteners used. The overall experimental setup is summarized in Figure 1.

Prior to electrode installation, pilot holes were drilled to reduce crack formation along the grain. Diameters for each fastener type can be seen in Table 1 below.

**Table 1.** Pilot hole sizes for each fastener type.

| Fastener diameter (mm) | Stainless steel screw | #4 Zinc screw | #8 Zinc screw | Stainless steel nail | Roofing nail | Brass screw |
|------------------------|-----------------------|----------------|---------------|---------------------|-------------|-------------|
| 4.76                   | 3.97                  | 2.78           | 2.11          | 3.56                | 3.57        |
| Pilot hole (mm)        | 3.18                  | 2.38           | 1.59          | 1.19                | 2.38        | 1.59        |

It is worth noting that a method was implemented to prevent moisture from entering or leaving the wood samples as they were exposed to different temperatures and vapour pressures. By changing the ambient temperature, wood becomes susceptible to different vapour pressures causing mass changes. To mitigate these changes, the wood samples were placed in low-density polyethylene bags which had slits small enough for fasteners to penetrate through. After which, the fasteners were inserted through the bags into the samples at a depth of approximately 9.5 mm at 0.5H (H = sample thickness). The electrodes were centered with respect to the sample and installed at a spacing of 23 mm from the center of the first electrode to the center of the second electrode for all 126 samples. To make the polyethylene bags airtight, an industrial-grade adhesive tape was placed around every fastener where wood was permeable to moisture due to the slits in the bags. A non-conductive bonding putty was then placed over the tape patches, specifically along the circumference of each fastener. This was done to ensure that the interface between each fastener and tape patch was sealed to prevent moisture transport in or out. The entire step-by-step process can be seen in Figure 2.
3.2. Conditioning Regimen
All 126 samples were placed in a temperature-and-humidity-controlled climate chamber. The model used was a BINDER KMF 720 (E6) which has a 720 L volumetric capacity. The large volume made it so that sufficient space was provided between each sample in the chamber and that homogenous conditioning was ensured for all samples on all sides. With the polyethylene bags open, the samples were placed in the climate chamber at conditions of T = 20°C and 85% RH to reach a target MC of 18% based on the equilibrium moisture content (EMC) criteria found in [8]. The samples accumulated moisture within the chamber and reached steady state conditions in 74 days. Constant mass criteria was further dictated by ISO 12571 [13] and was measured regularly by a OHAUS EX1103 balance with a 1.0 mg resolution.

After recording the electrical resistances at T = 20°C, the samples in the chamber were sealed with the polyethylene bags and electrical resistances were recorded at different temperatures of T = -10°C, T = 0°C, T = 10°C, T = 30°C and T = 40°C. Values were recorded when temperatures stabilized at ±0.1°C. Upon recording the EMC values for each temperature, it was ensured that the samples remained within a constant mass tolerance of ±0.2% as ambient temperatures changed within the chamber.

3.3. Data Logging
A PXIe-4081 Digital multimeter (DMM) and a PXIe-2525 multiplexer switch module for routing automated signals were both used in measuring the resistance in each wood sample during the conditioning regimen. 24 AWG wires connected the DMM to all the electrodes within the samples using crimped-on alligator clips. To record the electrical resistance, a current ran through each wood sample using the 24 AWG channels and the resistance in turn across the wood was recorded. Specific channels were dedicated for measuring resistance in the longitudinal (R\text{L}), tangential (R\text{T}), and in both directions. One of the challenges faced with measuring resistances at low moisture levels and low temperatures in wood is quantifying the associated electrical resistances, which tend to fall in the high ohmic range. For this reason, a DMM with a high resistance reading specification was selected to measure the wood’s resistance. The DMM can read up to a resistance of 5×10\textsuperscript{9} Ω (5 GΩ) which is able to measure electrical resistance of relatively dry wood samples at low temperatures.

4. Results and discussion
4.1. Overall trend
Electrical resistances were plotted against the tested temperatures for each type of fastener used. Although variations in readings existed between each fastener, looking at the overall relationship showed a strong linear correlation (R\textsuperscript{2}=0.98) between the logarithm of resistance and temperature at the target MC of 18%. Figure 3 shows R\text{L} as a function of wood temperature for all six types of fasteners used. It should also be noted that R\text{T} as a function of wood temperature for all six fasteners showed a similar trend but the resistances at every temperature were not shown to avoid redundancy.

Figure 3 shows that as wood’s temperature increases, the resistance decreases. The data in the figure is intended to both verify that the experimental results are consistent, and to provide the readers with a better understanding of the range of resistance values recorded at each temperature at a target MC of 18%. Although all fasteners follow the same trend, it is observed that stainless steel nails stand out in Figure 3 as they generally show the largest readings in both longitudinal and tangential directions. This is further discussed in section 4.2. All the mean values are within the 25\textsuperscript{th} and 75\textsuperscript{th} percentiles and are fairly close to the median.
4.2. Comparison of resistances in the longitudinal and tangential grain directions

To investigate the existence of a trend between $R_L$ and $R_T$, a comparative analysis was done between 42 wood samples containing two screws inserted in the longitudinal direction and a second set of 42 wood samples containing two screws inserted in the tangential direction. Since different wood boards were used to obtain these samples, it was intended to show that a relationship exists between resistances in both directions without needing to take measurements from the same wood board, thereby removing a sampling bias. Figure 4 shows a comparison of this data.

As seen in Figure 4, it is evident that the mean value of $R_T$ is higher than the mean value of $R_L$ for every fastener at every tested temperature. Stainless steel nails had the highest resistance readings out of all six fastener types, which is due to the lower surface contact it has with wood in comparison to threaded...
screws which promote electrical conductivity. Regardless, resistance in the tangential direction was still larger for the stainless steel nails, showing that there is a consistent relationship between resistance measurements and grain direction. It should be noted that y-axes were scaled differently for each temperature in Figure 4 to illustrate the trend in resistance rather than the magnitude.

To accurately quantify the resistance ratios within eastern white pine, an analysis was done using the wood samples containing four electrodes installed in both longitudinal and tangential directions. This was done to compare resistances within the same samples rather than between samples. The ratios of resistances measured across the grain to ones measured along the grain were quantified for all temperatures and fastener types tested and are seen in Figure 5. Due to the general trend of tangential resistances being larger, \( R_T \) was normalized with respect to \( R_L \).

![Figure 5. Ratios of \( R_T/R_L \) for different fastener types in eastern white pine over different wood temperatures.](image)

With exception to the outlier of the #8 zinc screw at \( T = 40^\circ C \), the remaining fastener types display a fairly consistent resistance ratio at every wood temperature. As ratios for each fastener type show < \( \pm 5\% \) deviation in ratios between different wood temperatures, it was established that temperature has no impact on grain orientation as resistance measurements are taken. Table 2 shows mean ratios for each fastener type that are independent of temperature.

| Fastener Type          | \( R_T/R_L \) Ratio |
|------------------------|---------------------|
| Stainless Steel Screw  | 1.325               |
| #8 Zinc Screw          | 1.137               |
| #4 Zinc Screw          | 1.286               |
| Stainless Steel Nail   | 1.138               |
| Roofing Nail           | 1.305               |
| Brass Screw            | 1.283               |

The different ratios found in Table 2 prove that electrode type is important when it comes to measuring MC in wood. Although Figure 4 proves that \( R_T \) is greater than \( R_L \) when MC measurements are taken, it should be noted what type of electrode is used. The appropriate correction factor may then be applied in the case where electrodes are installed in wood in the tangential direction. Implementing this in guidelines can reduce reading errors depending on the type of empirical correlation used to obtain MC. A general observation can be made that a mean ratio of 1.3 was calculated for stainless-steel screws, #4 zinc screws, roofing nails and brass screws and a mean ratio of 1.14 was calculated for #8 zinc screws and stainless-steel nails.

The impact of sensor orientation on MC measurements at a nominal MC of 18% was assessed. The %MC error was determined by using the empirical equation developed by Pfaff & Garrahan [14] with the species correction factors for eastern white pine. The error percentage did not exceed ±1.0% MC.
across all the wood samples and the average % error values ranged between ±0.15% MC to ±0.65% MC for each fastener type across all tested temperatures. For the mean resistance ratios of 1.3 and 1.14, the %MC error was found to be ±0.50% MC and ±0.25% MC, respectively. Based on these values, it was determined that measuring the resistance along the tangential direction underestimates the MC of the sample and should be considered when assessing the overall accuracy of the reported MC.

Several studies that have quantified the effect of grain orientation on MC measurements used electrical conductance rather than electrical resistance to evaluate wood’s anisotropy for electrical conductivity. To complete a numerical comparison of this study with others, resistance (R) can be yielded from conductance (G) by taking the reciprocal, which is done in Table 3 using equation (1).

\[ R = \frac{1}{G} \]  

A comparative analysis was done between studies which have examined the impact of sensor orientation on resistance/conductance measurements. As mentioned in the literature review, some of these studies found that grain orientation had no (or negligible) effect on resistance readings (Forsén & Tarvainen [3], Apneseth & Hay [4], Samuelsson [5], Fernandez-Folfin et al. [6]), while other studies disputed this claim and were able to quantify ratios of R_T/R_L. Table 3 shows the differences in findings for these ratios. It should be noted that results of the studies in Table 3 were obtained using different experimental testing parameters, and for that reason, the wood species and electrode type were identified for each study. There is a gap in the moisture content research area regarding sensor orientation. In this regard, more extensive research is needed using different wood species and fastener types to reduce error margins on readings and establish more conclusive results.

The ratios found in literature are not quite comparable as they all examine different wood species using different electrodes. However, one common result found between all the studies is that resistance in the tangential direction is always larger than in the longitudinal. This can be attributed to the ease of moisture to conduct electricity along the fibers of wood rather than across the tightly packed fibers in the tangential direction.

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| Wood species | This study | James [7], Wood Handbook [8] | Dai & Ahmet [9] | Stamm [10,11] | Kuroda & Tsutsumi [11,12] |
|---------------|------------|-------------------------------|----------------|----------------|-------------------------|
| Electrodes used | Stainless steel screws | Not specified | Silver-painted brass screws | Unknown | Unknown |
| Ratio | 1.325 | 2.0 | 1.2 @ 6% MC | 2.1 – 3.9 | ~3.5 @ 18%MC |

* Specific parameter inaccessible

5. Conclusion and future work
The goal of this study was to examine how resistance varies in different directions of eastern white pine using different fastener types. It was determined that at a target of 18% MC, the impact of temperature on sensor orientation is insignificant and therefore was not considered a factor. It was also determined that the ratio of tangential-to-longitudinal resistances is affected by electrode type. As such, a mean ratio of 1.3 was calculated for the #10 stainless-steel screws, #4 zinc-plated steel screws, 3.5mm aluminum roofing nails and the #6 brass screws, and a mean ratio of 1.14 was calculated for the #8 zinc-plated steel screws and the 2.1 mm stainless-steel nails. Knowledge of these ratios is useful for determining the MC regardless of which orientation the sensor is installed relative to the grain. When used, these ratios will further contribute to more accurately quantifying MC in wood and reducing overall measurement errors. For mean resistance ratios of 1.3 and 1.14, it was determined that an average %MC
error of -0.5% and -0.25%, respectively, occurs by measuring the resistance along the tangential direction if the MC correlation being used is intended for use along the longitudinal direction for eastern white pine. The large variation in $R_T/R_L$ ratios, calculated in this study and in literature, shows the need for more research on electrical conductivity anisotropy. By industrial standards, the more species studied over a broader range of moisture levels and electrode types, the more confidence one can have in generating in-situ MC readings. Considering these factors, one step closer to prevention of moisture-related problems in building envelopes is taken.

Based on the results shown in this study for eastern white pine at a target MC of 18%, it is important to continue this work and examine the impact of grain sensor orientation over a wider MC range. This effort should also extend to other materials used in North America in wooden frame buildings such as construction lumber, oriented strand board (OSB) sheathing and plywood. Following these research ideas, it would be beneficial to investigate the relationship of electrical resistance between the two directions. One way to examine this relationship is to implement the same methodology as in this paper and measure the resistance in a third direction (±45° relative to the grain), providing further insight on the electrical conductivity anisotropy in wood.

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