In-situ Testing of Field Diagnostic Methods for the Wood Components at Taliesin West

Zhen Ni

Follow this and additional works at: https://repository.upenn.edu/hp_theses
Part of the Historic Preservation and Conservation Commons

https://repository.upenn.edu/hp_theses/726

This paper is posted at ScholarlyCommons. https://repository.upenn.edu/hp_theses/726
For more information, please contact repository@pobox.upenn.edu.
In-situ Testing of Field Diagnostic Methods for the Wood Components at Taliesin West

Abstract
Situated within the desert of Scottsdale, Arizona, Taliesin West served as Frank Lloyd Wright’s winter home and school for the Taliesin Fellows from 1938 to 1959. As an experimental design laboratory, Wright trained apprentices by enlisting them to construct and continually modify the site over the course of twenty years. The complex today continues to operate as a museum under the stewardship of The Frank Lloyd Wright Foundation who is currently in partnership with The University of Pennsylvania to study and address problems of wood deterioration seen throughout the site. This thesis seeks to document the efficacy and limitations of different in-situ diagnostic methods for detecting wood decay, including resistograph drilling, moisture content mapping, thermography and hand probing. The instrument field testing was conducted at three locations that contain Wright’s iconic whirling arrow design as part of both structural and ornamental wood components of the office, drafting studio and Garden Room. Data sets of each of these metrics have been overlaid and evaluated with the intent to provide a sequence of combined diagnostics for future assessment and monitoring of the site. This research aims to service the sustainability of the compound by informed stewardship while providing new insights and means of field diagnostics for the conservation of wooden built heritage.

Keywords
Frank Lloyd Wright, wood diagnostics, Taliesin West, resistograph, comparable analysis

Disciplines
Historic Preservation and Conservation

This thesis or dissertation is available at ScholarlyCommons: https://repository.upenn.edu/hp_theses/726
IN-SITU TESTING OF FIELD DIAGNOSTIC METHODS FOR THE WOOD COMPONENTS AT TALIESIN WEST

Zhen Ni

A THESIS

In

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Science

2020

Andrew Fearon
Advisor
Lecturer in Historic Preservation

Frank G. Matero
Department Chair
Professor
ACKNOWLEDGMENTS

Thank you to my advisor, Andrew Fearon, for his passion, knowledge, guidance and invaluable advice, especially in English academic writing. My completion of this thesis could not have been accomplished without you.

Thank you to Frank G. Matero, Professor and Chair of the Historic Preservation Department, for making this thesis a reality and for his support throughout the process.

Thank you to Emily Butler, Fred Pozzillo, and all others associated with the Frank Lloyd Wright Foundation and Taliesin West who made this thesis possible. The time I spent at Taliesin West was precious and unforgettable.

Thank you to Laura Keim at Stenton, and Morris Arboretum of the University of Pennsylvania, for partnering in the purchase of the Resistograph Drill and for providing the opportunity for preliminary tests.

Besides, thank you to my parents, who have been supporting me both financially and emotionally in the past two years; thank you to my girlfriend Yifan Jiang, who makes me happy every day; thank you to my friends at Penn, who have been sharing happiness and sorrow with me.
# TABLE OF CONTENTS

LIST OF FIGURES........................................................................................................................................ iv

1. Introduction ........................................................................................................................................... 1

2. Methodology & Materials .................................................................................................................. 5
   2.1. Methodology .................................................................................................................................... 6
   2.2. Comparing Logic .......................................................................................................................... 6
   2.3. Materials ....................................................................................................................................... 7
   2.4. Methods ....................................................................................................................................... 9
       2.4.1. Infrared Thermography ....................................................................................................... 9
       2.4.2. Surface Temperature ........................................................................................................... 9
       2.4.3. Moisture Content ............................................................................................................... 10
       2.4.4. Physical Hand-Probing with Awl ....................................................................................... 10
       2.4.5. Resistograph Drilling .......................................................................................................... 11
   2.5. Data Interpretation & Graphic Format ......................................................................................... 13
       2.5.1. Point-based Data Interpolated ............................................................................................ 13
       2.5.2. Infrared Thermography ....................................................................................................... 13
       2.5.3. Resistograph Drilling .......................................................................................................... 14

3. Results & Discussion ............................................................................................................................ 14
   3.1. Individual Results of Each Method ............................................................................................. 14
       3.1.1. Infrared Thermography ....................................................................................................... 14
       3.1.2. Surface Temperature ........................................................................................................... 14
       3.1.3. Moisture Content ............................................................................................................... 15
       3.1.4. Physical Hand-Probing with Awl ....................................................................................... 15
       3.1.5. Resistograph Drilling .......................................................................................................... 16
   3.2. Comparable Analysis & Discussion ............................................................................................. 22
       3.2.1. Three Point-based Data Sets ............................................................................................... 22
       3.2.2. Thermography & Surface Temperature .............................................................................. 28
       3.2.3. Resistograph & Comparable Analysis ............................................................................... 31

4. Conclusions & Recommendations ..................................................................................................... 37
   4.1. Methods & Recommendations ..................................................................................................... 39
   4.2. Recommendations for Future Work ............................................................................................. 41

Bibliography ............................................................................................................................................ 44
Appendix .................................................................................................................................................. 48
Index ....................................................................................................................................................... 75
LIST OF FIGURES

Figure 1: View of the original Office from the southeast. (Ni) ......................................................... 3
Figure 2: The View of the drafting studio form the south. (Ni) ....................................................... 3
Figure 3: The view of the Garden Room from the southwest. (Ni) ................................................. 4
Figure 4: The axonometric view of the model ................................................................................ 8
Figure 5: The outer elevation of the model ...................................................................................... 8
Figure 6: The grid system made at the Office and its diagram. (Ni) ................................................ 8
Figure 7: FLIR E60 Infrared Camera ............................................................................................... 11
Figure 8: Milwaukee 10:1 Infrared Temperature Gun .................................................................... 11
Figure 9: WAGNER MMC-210 Pinless Moisture meter ................................................................. 12
Figure 10: MALCO AO Scratch Awl ............................................................................................... 12
Figure 11: IML-RESI PD-400 Digital Wood Inspection Drill ............................................................ 12
Figure 12: Thermal Images from three locations ........................................................................... 17
Figure 13: Surface temperature readings from three locations .................................................... 18
Figure 14: Moisture content readings from three locations ............................................................ 19
Figure 15: Probing readings from three locations ........................................................................ 20
Figure 16: Resistographs from three locations ............................................................................. 21
Figure 17: Point-based data collected from the Office ................................................................. 25
Figure 18: Point-based data collected from the Garden Room ...................................................... 26
Figure 19: Point-based data collected from the Drafting Studio ..................................................... 27
Figure 20: Thermal image and surface temperature distribution at the Drafting Studio ............. 30
Figure 21: Resistograph and thermal image of the Office .............................................................. 34
Figure 22: Resistograph, moisture content readings and probing readings of the Drafting Studio ....................................................................................................................................................... 35
Figure 23: Resistograph, moisture content readings and probing readings at the Office ............ 36
Figure 24: Roof structure of the Garden Room. (Ni) ..................................................................... 43

Table 1: Assessment and Recommendation Table for Wood Diagnostics Methods ................... 38
1. Introduction

Taliesin West, located in Scottsdale Arizona, was designed by Frank Lloyd Wright in 1938 as a winter camp for his Taliesin Fellowship school based in Wisconsin known as Taliesin East. Construction of the compound followed over a period 20 years under Wright’s direction and continued to evolve after his death up until the present day. The use of wood components seen throughout the site was a result of both Wright’s ideology of organic architecture and influence of Japanese construction.\(^1\) This material was integrated as a prominent feature at Taliesin West seen in the iconic whirling arrow design that functions both structurally and ornamentally in three buildings constructed during the recognized period of significance (1938-1959) at Taliesin West [Figure 1-3].

The Drafting Studio and Wright’s Office, together with the Kitchen, the Original Dining Room, Wes and Svetlana Peters’ and Gene Masselink’s Rooms, the Loggia and the Kiva comprised the Historic Core of Taliesin West.\(^2\) Began in 1938, this campaign of the main core of the camp continued each Winter and Spring season at Taliesin West until 1941 with the addition of the Garden Room. The Garden Room first served as the Wright’s living room then became a shared space for all the Fellowship where some formal and entertaining events were often held.\(^3\)

The Redwood (*Sequoia sempervirens*) whirling arrows that originally supported a canvas roof represents Wright’s exploration of wood and fabric as seasonal tent-like structures. The design was altered almost annually not only because of Wright’s desire to further explore design

---

\(^2\) Harboe Architects, PC. *Taliesin West Preservation Master Plan*, 11
\(^3\) Ibid, 13
possibilities, but inevitably because the wood and canvas were vulnerable to the harsh desert climate.\textsuperscript{4} During the period following Wright's death in 1959, several building campaigns proceeded. In 1991, deteriorated wood framing members of these buildings were replaced with Douglas-Fir (\textit{Pseudotsugma enziesii}) and the roof systems were rebuilt and glazed in with acrylic panels.\textsuperscript{5} As of January 2020, this roof system was still in place.

As part of the evolution of Taliesin West, the established site management of the Frank Lloyd Wright Foundation has invested in the careful stewardship of the compound since the death of Wright. The most recent and comprehensive planning document that has outlined future conservation goals is the Taliesin West Preservation Master Plan authored by Harboe Architects in October 2015. The plan covers the history, evolution and current condition of Taliesin West providing recommendations and prioritization of future preservation work, including wood elements. It is noted in the Condition Assessment section that there are deteriorated wood elements and suggests repairing and replacing all damaged and decayed wood components; both structural and non-structural.

The conservation management of Taliesin West is currently recognized as a continually evolving endeavor that is central in the sustainability of the UNESCO World Heritage Site. The objective of this research is to determine the best means and methods to identify the extent of wood fungal deterioration at Taliesin West. The results of the in-situ testing program has been tailored to serve as guidelines for the employment of wood diagnostics for future monitoring of the compound. Additionally, the exercise also provides an opportunity to explore and document

\textsuperscript{4} Harboe Architects, PC. Taliesin West Preservation Master Plan, 14
\textsuperscript{5} Ibid, 17
the performance of practical diagnostics technologies used in combinations that help to address the universal problems studied within the broader field of wooden heritage conservation.

Figure 1: View of the original Office from the southeast. (Ni)

Figure 2: The View of the drafting studio form the south. (Ni)
Figure 3: The view of the Garden Room from the southwest. (NI)
2. Methodology & Materials

There is a clear interconnection among various wood diagnostic technologies that measure moisture content, surface temperature and density; all of which indicate wood decay in direct or indirect ways. In many cases, resources and access are limited restricting complex instrumental surveys by diagnostic specialists. An understanding of the collective and individual accuracy of the studied field diagnostics provide information towards alternative and reliable means for practical assessment.

Past published work concerning the evaluation of wood diagnostics tools have served as a useful reference in reviewing the methods studied. For example, Morales-Conde, Roderiguez-Linan and Rubio de Hita (2013) applied thermography, ultrasound and resistography to a wooden roof of a historic building to conclude that these inspection techniques could locate, with a fair degree of accuracy, zones of deterioration, but also recommended the combined use of non-destructive techniques to aid visual inspection in the identification of defects. In other papers among the same group of authors (2012), examined infrared thermography applied to wood in a laboratory environment and found that thermography could detect zones with distinct moisture content, but not so by means of passive thermography in the absence of sufficient moisture content. Tomasz, Jerzy and Katarzyna (2016) confirmed the usefulness of resistance drilling method to estimate the depth of wood decay and suggested it be treated as a qualitative assessment. They then strongly recommended that a combination of non-destructive

---


methods be used in assessment of one single building, along with visual strength grading. Pang and Jeong (2019) conducted a similar study to investigate the effects of density, temperature, size, and grain direction in measuring moisture content of wood materials non-destructively. They found that when other factors were the same, the lower the density, the larger the size and the more parallel the meter to the grain direction, the higher the moisture content reading observed.9

2.1. Methodology

One goal of this research is to document and test the efficacy and limitations of different in-situ diagnostic methods for detecting wood decay. A comparable analysis which includes resistograph drilling, moisture content mapping, thermography (surface temperature and infrared photography) and hand probing was conducted on three different elements of the whirling arrow design at Taliesin West. The study takes different aspects of each metric into account including instrument expense, ease of application, accuracy and degree of destructiveness.

2.2. Comparing Logic

Each of the diagnostic methods included within the scope of the testing program provides data in different forms. The objective of the study is to explore and understand what comparisons are feasible and meaningful. Through this exercise, moisture content mapping, surface temperature mapping and hand probing can be enlisted under one easily comparable group because each shares point-based data with a close relationship between temperature,

---


moisture content and absorption of water. Infrared photography or thermography can also be
directly linked to moisture content and surface temperature for this reason. Resistograph
drilling, the most quantitative of all methods studied, has been utilized as a baseline reference
to identify zones of decay by measuring changes in densities across the section of a wooden
member.

2.3. Materials

The whirling arrows tested in this research all follow the same construction but vary slightly
in dimensions. The construction assembly is comprised of three wood members mitered
perpendicular to one another returning the central horizontal roof member to vertical planes
that enclose the interior spaces. In section, each assembly is built from two smaller pieces; the
thinner one being the outer element and the thicker member at the center with a central core
of a mounted steel sheet that supports the roof structure [Figure 4, 5].

Before conducting the contact diagnostics, each of the three whirling arrows examples studied were documented using a Nikon D300 DSLR camera under normal light conditions. Additionally, the necessary dimensions were measured in order to create 2-D drawings in AutoCAD and 3-D models in SketchUp also utilizing existing HABS drawings. These drawings and models served as base documents upon which all test data was recorded and presented. A grid and alpha-numeric recording system in which the top edge of the whirling arrow functions as the X axis (starting from 1) and the outermost edge as Y axis (starting from A) was graphed directly on the painted surface of the wood in pencil at a spacing of either 10 cm or 20 cm squares depending upon the size of the whirling arrow [Figure 6].
Figure 4: The axonometric view of the model.

Figure 5: The outer elevation of the model.

Figure 6: The grid system made at the Office and its diagram. (Ni)
2.4. Methods

2.4.1. Infrared Thermography

Infrared thermography is the science of detecting infrared energy emitted from an object, converting it to apparent temperature then displaying the result as an infrared image.\(^{10}\) Images of the whirling arrow were captured by a FLIR E60 infrared camera with a ±3.6°F accuracy for ambient temperatures of 50°F to 95°F. The camera provides an infrared image in gradient colors representing different temperatures on the wood surface after inputting the environmental and climate data. The application method here is passive thermography which means the sun is the only energy source.\(^{11}\) The images provides a qualitative assessment of which areas are cooler or warmer than other areas indicated by a color-coded scale, also manually showing the temperature of a given point as selected by the cursor on a display screen [Figure 7].

2.4.2. Surface Temperature

To complement and verify the thermographic range, surface temperature readings of all the points on the grid system were recorded using a Milwaukee 10:1 Infrared Temperature Gun with an operating temperature range from 32°F to 122°F. The instrument has an accuracy of ±4°F or 2% and a repeatability of ±0.8% or ±2°F. It shows the temperature instantly when the laser detector reaches the subject surface [Figure 8].


2.4.3. Moisture Content

A Wagner MMC-210 Pinless Moisture meter was used to record moisture content in the field testing at each of the grid points. Pinless meters of this type emit electromagnetic waves to measure moisture from the surface of a given wooden member. These emitted wavelengths are sent and returned to a sensor that when interrupted by the presence of moisture in the material are translated to standard percentage content. The instrument is influenced by substrate densities and must calibrated for different wood species specific gravities, in this case 0.49 for Douglas-fir (Pseudotsuga menziessi) the species documented for all of the three subject areas. Measurements are taken through a scanning area of 1.5’ (3.8cm)’ by 2.5’’(5.1cm) from a 0.75’’ (1.9cm) depth beneath the wood surface. The readings are displayed from 5% to 32% with 0.1% increments [Figure 9].

2.4.4. Physical Hand-Probing with Awl

Physical probing with a scratch awl, knife, screwdriver or similar instrument is a basic testing method that can yield very definite and accurate results with little effort or investment. Advance stages of decay that reduced the densities of the outer area of a given member are readily detectable. The instrument used in this study was a MALCO AO Scratch Awl with a 10cm steel probe of 2mm diameter with a tapered point. Knowing that it is a tool relying on the subjective feeling of the user, one individual was selected for conducting all testing points to help ensure relative consistency. In terms of readings, a scale from 1 to 10 was defined, with 1 as wood exhibiting maximum resistance or the highest impenetrability and 10 as no resistance, or the most readily penetrable [Figure 10].
2.4.5. Resistograph Drilling

The wood inspection drill used in this testing is the IML-RESI PD-400 Digital Wood Inspection Drill. It operates by sending a rotating needle with a diameter of 2 mm into the wood to up to 400 mm in depth. By detecting the resistant force it receives from the wood grain, it will simultaneously generate a depth-amplitude graph throughout the whole process. It is nearly minimally destructive, leaving a 2mm-diameter hole. In our field testing, the needle speed was set at 4000 r/min and the feed speed at 102cm/min, which are suggested settings according to the manufacturer. The depth was set to the width of the respective testing piece [Figure 11].

One drilling test for every horizontal axis of all three whirling arrows was conducted crossing as many vertical axes as possible since the positioning of the instrument was limited due to the short distance between the bottom-most member of wood and the ground.

---

Figure 9: WAGNER MMC-210 Pinless Moisture meter (www.wagnermeters.com)

Figure 10: MALCO AO Scratch Awl (www.malcoproducts.com)

Figure 11: IML-RESI PD-400 Digital Wood Inspection Drill (www.iml-na.com)
**2.5. Data Interpretation & Graphic Format**

In order to present the data in a clear, visually digestible format, all the readings collected were translated from numeric readings to colored diagrams overlaid onto the base architectural graphics of the whirling arrows.

**2.5.1. Point-based Data Interpolated**

The data collected by the surface temperature meter, the moisture content meter and the scratch awl can be grouped together as point-based data, due to their shared method of collecting data from area points or regions. As it would be impractical and destructive to yield point base data for the entire surface area of the subject, the following adjustments were provided. Every intersection at grid points tested was used to represent the average value of its surrounding area, in this case either 10cm or 20cm square regions. The numbers were then transformed into color gradations using Excel’s conditional formatting to make it visually easy to recognize the potential zones of fungal decay. Monochromatic gray-scale diagrams were also created based on colored values to allow a second comparison with less variables to process visually.

**2.5.2. Infrared Thermography**

The original image file exported from the IR camera is multi-colored. The colors range from white to red, yellow, green, blue, purple and then black to represent temperature readings from high to low. To unify with other data, the thermal images were converted to a gray-scale format so that it may be easily compared with other metrics also illustrated monochromatically.
2.5.3. Resistograph Drilling

The amplitude-depth graph generated by the resistograph drill is a visually intuitive interpretation of density change and distribution throughout the drilling path represented as high and low peaks on a graph of density vs distance. In order to compare these graphs with other methods, each was scaled and placed at the exact location where they were created on the same elevation drawing. By this method, the exact loss of the wood density as a result of decay could be identified and checked against other collected data sets to understand the degree of accuracy of each instrument tested.

3. Results & Discussion

3.1. Individual Results of Each Method

3.1.1. Infrared Thermography

The thermal images showed some similar patterns among the three testing locations [Figure 12]. One observation is that in general, the outer members of the assembly sections appeared warmer than the central members. Areas of shade from plants or adjacent architectural features also registered in the subject elevation as cool regions. Of significance, the area of the lower miter showed the coolest ranges indicating high moisture content suggesting areas of absorption related to increase in porosity and result water retention characteristic of advanced fungal decay.

3.1.2. Surface Temperature

The results also revealed areas of cooler surface temperature at the end-grain of miters, especially the lower member [Figure 13]. The temperature difference was not dramatic however the range was useful enough to differentiate regions consistent with changes in moisture
content. One obvious problem of this tool is the sensitivity to changes in the environment such as the movement of clouds or the sun. Once the testing area was cast in shade, the temperature readings would suddenly drop. To ensure the reliability of the data, effort was made to complete a single round of testing under stable environmental conditions.

3.1.3. Moisture Content

The moisture content pattern also indicated that at the end-grain of the two miters [Figure 14], the readings were significantly high and some points even reached the maximum instrument reading of 32%, whereas in other areas, most readings were below 10%. The reason for this pattern may be explained by the inherent problem of the architectural detail that allowed rain water, and roof runoff to absorb into the end grain of the wood miter joints. Areas of metal bolts and screws similarly served as vulnerable entry points for water, inferring micro-zones of decay.

3.1.4. Physical Hand-Probing with Awl

The results turned out to be very similar across all three whirling arrows with the area at the miters and particularly areas of the lower miters that could be easily penetrated with the scratch awl [Figure 15]. Conversely areas of sound wood were impenetrable with little variation or range between the two opposite phenomena. It is of importance to note that the probing was limited to detecting decay that reached near the surface of the member and if the outer surface was free of decay than any underlying deterioration could be missed by use of this method alone.
3.1.5. Resistograph Drilling

In the amplitude-depth graphs digitally produced by the drill, a consistent pattern of micro-peak was observed indicating the abrupt density changes in late wood to early wood [Figure 16]. The difference in the amplitudes seen in a more macro scale indicated areas of low density across a given member. The graph indicated a strength loss caused by deterioration when an abnormally low amplitude within the regular wave pattern occurred, also felt by the operator when holding the drill similar to hand probing. Strength loss can be attributed to defects in the wood structure including insect damage or mechanical loss so effort was made to isolate only those changes related decay that characteristically appeared as more gradual transitions in contrast to a more abrupt transition of a crack or check. This method proved to be very useful and accurate when trying to identify and pinpoint zones of decay.
Figure 12: Thermal Images from three locations
Figure 13: Surface temperature readings from three locations
Figure 14: Moisture content readings from three locations
Figure 15: Probing readings from three locations
Figure 16: Resistographs from three locations
3.2. Comparable Analysis & Discussion

3.2.1. Three Point-based Data Sets

In wood pathology, parameters of moisture content, temperature, density, porosity and absorption are all properties that have strong interrelationships among them.\(^{13}\) Moisture content often functions as an internal condition or cause factor with independent variables, whereas temperature and density may be considered dependent variables, or result factors. When exposed to the environment, wood absorbs water related to absorption routes and porosity which may increase or decrease moisture content rapidly in response. If the high moisture content is sustained over a period of time, the areas that retain water in will remain cooler than other areas since they require more energy to warm them to the ambient temperature of the exterior environment. Additionally, areas of sustained water absorption create a micro-environment for the propagation of decay fungi that consumes the mass of the wood zone resulting in both a decrease in density and an increase of absorption and further water retention.\(^{14}\) Theoretically, as a result, a higher moisture content percentage indicated by a cooler temperature may translate to less density, more porosity as a function of absorption and the presence of mass loss by decay fungi or conditions that may propagate decay. Additionally, even in the absence of decay fungi, higher moisture contents may compromise the strength of wood.\(^{15}\) On the basis of these known relationships, we may combine multiple qualitative data sets of temperature, moisture content and density to more accurately, more quantitatively, predict zones of decay [Figure 17-19].

\(^{13}\) Brian Ridout, Timber Decay in Buildings: The Conservation Approach to Treatment (Taylor & Francis, 2000).
\(^{15}\) Ibid
For the drafting studio, areas that have higher moisture content percentage are the inner wood piece and two miters. This overall pattern can also be observed from the physical probe diagram, where the greenest area is at the lowermost miter joint. The surface temperature diagram shows that the inner piece of wood is overall cooler than the outer piece, and that both miter joints have cooler surfaces. The whole bottom member of wood appears cooler than the other areas of the whirling arrow however moisture content percentage probing readings do not support evidence of a decay zone. The probable reason for this phenomenon is that the bottom piece is partly in the shade of the studio, which can make a significant temperature difference especially when the sun is out and warms the adjacent surfaces deferentially.

The other two sets of data gathered from the Garden Room and the Office show similar results. The areas of high moisture content percentage still appear at the two joints and the upper piece of wood, where the surface temperature is also cooler than other areas. However, the results of physical probing do not align in perfect symmetry with the other two testing methods. Despite the color blocks at exactly where the joints are shown in darker green in the Garden Room diagram, the whole of remaining areas are the same lighter green shade.

To conclude, these methods can greatly improve the accuracy and reliability when used in combination, but through testing, significant limitations of each instrument have been identified. The moisture content meter is relatively reliable in comparison with others in that the measuring sensor is designed not to be influenced by external environmental factors such as surface moisture. One potential source of inaccurate data occurs when there are metal fasteners near around the testing area, or other anomalies of density are encounter that may influence obtained readings. The surface temperature meter is also a reliable method to confirm and more accurately identify cool spots seen in thermography, however, the fact that it only
measures a small area of surface it is greatly sensitive to shifts in environmental temperature that may occur when taking multiple readings. These measurements, like thermography can shift dramatically high if the wood surface is exposed to the sun for a long period, which may provide misleading inaccurate data that does not indicate the actual presence of moisture. The scratch awl is an ideal tool providing the user a rough and qualitative reading of positive or negative with little or no gradient between the two. Attempts to assign a scale to the probe did not enhance the effectiveness of this method, which is limited to exposing only advance stages of decay that have reached the surface of the wooden member.
Figure 17: Point-based data collected from the Office
Figure 18: Point-based data collected from the Garden Room
Figure 19: Point-based data collected from the Drafting Studio
3.2.2. Thermography & Surface Temperature

Thermal cameras and surface temperature meters are the two devices used to measure the same index of temperature. The following comparison explores the differences between the two methods and the advantages and disadvantages of each.

The first problem identified from the two data sets is that these two methods are both highly sensitive to the environment. For the thermal camera, the pre-testing settings of environmental temperature, relative humidity, wind compensation and distance make results more accurate and reliable when operating in a controlled laboratory but have limited value when applied to in-situ testing in a constantly shifting exterior environment. Additionally, the camera set up was time consuming to focus and to set the temperature range. This shift in environment also diminishes the usefulness of the surface temperature meter which is even more sensitive due to its point-based detector. The location of the sun and clouds will make a 20°F’s degrees difference in a few seconds along with shadows from immovable elements such as trees or adjacent built features.

Data at three locations shared common information. For this comparison, we can observe the data at the Drafting Studio as an example [Figure 20]. The thermal images and surface temperature measurements at the Drafting Studio were taken at 2 p.m. on January 3rd. The environmental temperature was 60°F; the RH was 27%. The two diagrams show a similar pattern at most areas, but also demonstrate differences in terms of specific readings.

Qualitatively, the thermal image shows a temperature range from approximately 59°F (light blue areas) to 85°F (white areas), which gives a clear understanding of what the temperature distribution is throughout the entire picture plane. Quantitatively, it is relatively difficult and
unnecessary to get the temperature reading for a certain point from thermal images in this case. The first reason is the inherent weakness of the thermal camera unit employed in that it only produces 320*240 resolution, meaning the pixels are all very large and coarse with a level of detail that cannot fully satisfy the accuracy requirements even when the image is zoomed in upon.

The surface temperature meter exhibits the inverse problem of thermographic imaging where readings at grid points are more reliable than the distribution, because the pattern between two points are unknown. With a highly sensitive sensor, temperature readings will change instantly as environmental factors shift i.e. wind and shade. This can be easily tested when taking multiple readings from the same point over the course of one minute. In conclusion, these two devices or methods when used together, can provide a more comprehensive understanding of temperature of the tested object features. The ultimate application of the surface temperature meter is to complement the infrared photography in providing more accurate readings at the time of photography.
Figure 20: Thermal image and surface temperature distribution at the Drafting Studio
3.2.3. Resistograph & Comparable Analysis

The resistograph proved to be the most definitive instrument for identifying zones of decay across a given section of the wooden members, consistently and complementary to other diagnostics, however some notable limitations are important to acknowledge.

The testing area of resistograph drilling could not extend across the whole surface of the whirling arrow because some accessibility problems: the bottom piece was too close to the ground; the upper piece was too far to reach; the inner piece had too little contact area so that the drill couldn’t be placed parallel to the grain. Therefore, this comparison is limited to these areas that were successfully tested by the resistograph drill.

Another source of potential error when interpreting the resistograph data relates to the orientation of the annual rings across a given member particularly relevant for a species with dramatic densities of early to late wood transitions such as Douglas-fir. For example, from the data collected at the Office location, a repeated pattern of the resistographs of all the horizontal drills at the outer piece was observed. The pattern records a drop at approximately 10 cm from the edge that appeared consistently at the same location along the member [Figure 21]. One plausible explanation would offer that there might be some decay in that section. However thermal images and moisture content readings showed that the outer piece was relatively warmer and dryer and the patterns were evenly distributed from top to bottom, which indicated that it was in fact a sudden change of the transition between the early-wood and late-wood as the board was typically flat cut with large volumes of early softer wood in the drill path. At the lower part of this whirling arrow, several low amplitude areas in the graphs was observed especially at the lower miter and the bottom edge where the inner and the outer pieces met, which indicated they might be hollow parts with no resistant strength at all. These
results align with the thermal images where the same areas showed the coolest temperature. In summary, the amplitude of resistograph requires interpretation and understanding. Once the degree of deterioration reached a certain point, it will completely lose all material resulting in a hollow void of which will retain no density or moisture content therefore may create misleading results when looking at thermographic or moisture content readings.

Additionally, when comparing the resistrographs with other point-based data sets, it was often found that the surrounding and adjacent areas of the decayed zone indicated by the resistograph alone revealed inconsistencies in accurate data recording. For example from the data collected at the Drafting Studio location [Figure 23], the upper part showed relatively high moisture content along the drilling paths, but in the resistographs only a few of these areas showed low density. Similar patterns can also be observed at the lower miter of the data collected from the Office location. A possible explanation for that would suggest that the presence of water in the wood where the assemble receives the highest exposure to environment such as roof run-off, increases moisture content and lowers the temperature which is in this instance definitive for determining if the wood is wet, but not necessarily definitive for determining if the wood is decayed.

Finally, when comparing the resistographs with diagrams created from scratch awl tests [Figure 22, 23], consistent findings indicate every location an awl easily penetrated the surface, a resistograph curve demonstrated symmetrical readings with flattened amplitudes. However, the presence of the flattened peaks in resistrographs did not always indicate that surface was penetrable with the awl. This suggests that hand-probing with scratch awls can provide accurate information but is limited to penetrable advance stages of decay that have affected the surface.
or near the surface of the member. Both instruments function on same principles but represent opposite ends of the scale for accessibility, ease of use and depth of information.

The summary of these comparisons helps to demonstrate that there is a necessity to use different diagnostics in combination with one another. Among them, thermography and resistograph drilling can be especially complementary.
Figure 21: Resistograph and thermal image of the Office
Figure 22: Resistograph, moisture content readings and probing readings of the Drafting Studio
Figure 23: Resistograph, moisture content readings and probing readings at the Office
4. Conclusions & Recommendations

By applying different diagnostics methods to the site and comparing their results side by side, the advantages and disadvantages of these methods were observed. To summarize all the data and information assessed for each diagnostic method including pros, cons, range, accuracy, training requirements, access requirements, degree of destructiveness and price was drafted into a table [Table 1].

Each diagnostic method tested demonstrates unique features that are useful and not easily substituted for, but each also demonstrates vulnerabilities and flaws influenced by internal and external factors. The objective of the testing program is not to rank a preference of all or any of the methods examined but rather to explore or narrow a combination of them that together may compensate for limitations of the individual tools. In the diagrams where all the testing results are put together, it is clear that each diagnostic method helps to determine the accuracy of another. A combination of any two diagnostic methods would provide more information than applying either one of them alone. These tests that were carried out at Taliesin West have already provided much information about the diagnostic methods, but it is just the beginning of the needed future monitoring anticipating the refining and development of all the technologies studied. Other diagnostic tools will become available and should be tested for future work with more testing locations incorporated at Taliesin west. The more information obtained and documented, the more the site and the greater field of wooden heritage conservation will benefit.
## Table 1: Assessment and Recommendation Table for Wood Diagnostic Methods

<table>
<thead>
<tr>
<th>Diagnostic Methods</th>
<th>Pros</th>
<th>Cons</th>
<th>Training Requirement</th>
<th>Service Range</th>
<th>Accuracy</th>
<th>Price</th>
<th>Access Requirements</th>
<th>Degree of Destructiveness</th>
<th>Room for Progress</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectified Photography</td>
<td>Easily implemented, necessary for baseline documentation, easy to identify visual deterioration</td>
<td>Only detects surface defects related to advanced stages decay</td>
<td>Minimal</td>
<td>Medium to high, depending on lens</td>
<td>High for surface detail, low to none for internal</td>
<td>Low to moderate</td>
<td>Easy</td>
<td>Non-destructive</td>
<td>Higher quality when used with Agisoft</td>
<td></td>
</tr>
<tr>
<td>Thermography with IR Camera</td>
<td>Easily implemented, fast accurate results under right conditions</td>
<td>Requires even external conditions, can lead to false positives; output image is in low resolution</td>
<td>Moderate</td>
<td>Medium</td>
<td>High for relative accuracy in tested area, moderate to low for absolute accuracy. Limited for internal temperature</td>
<td>Moderate to high</td>
<td>Easy</td>
<td>Non-destructive</td>
<td>Higher-end types provide higher-quality images</td>
<td></td>
</tr>
<tr>
<td>Moisture Content Mapping</td>
<td>Easily implemented, fast accurate results indicating presence or potential for decay</td>
<td>Requires moisture present and multiple readings; requires decay present in a limited testing depth</td>
<td>Minimal</td>
<td>Low, require contact</td>
<td>Moderate to high for surface, require deep probe accessories for readings beyond 3/4&quot; in depth</td>
<td>Low to moderate</td>
<td>Moderate to difficult</td>
<td>Non-destructive for pinless types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Temperature Readings</td>
<td>Easily implemented, fast accurate readings for surface temperature with a laser point accuracy</td>
<td>Highly sensitive to environmental factors; hard to get readings for larger area beyond laser point</td>
<td>Minimal</td>
<td>Medium</td>
<td>High for temporary surface temperature</td>
<td>Low to moderate</td>
<td>Easy to moderate</td>
<td>Non-destructive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scratch Awl Probing</td>
<td>Easily implemented, fast direct feedback of the density</td>
<td>Limited to decay reaching surface, hard to form systematic data</td>
<td>Minimal</td>
<td>Low, require contact</td>
<td>Positive and negative only with no gradation between</td>
<td>Low</td>
<td>Easy to moderate</td>
<td>Destructive; leave holes on surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistograph Drilling</td>
<td>Gives direct density indexes through the whole drilling path; can get data from locations that cannot be seen and accessed normally</td>
<td>Hard and time-consuming to operate; requires much operating space; limited accessibility to the tested piece</td>
<td>Moderate to high</td>
<td>Low, require contact</td>
<td>High if operated correctly</td>
<td>High</td>
<td>Moderate to difficult</td>
<td>Destructive; leave tunnels in wood</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.1. Methods & Recommendations

The resistograph drill is the most quantitative device among all the equipment tested and it also provides the most accurate results with the least possibility of error, if operated correctly. With the amplitude – depth curve created after each drill, the area of decay can be pinpointed easily by reading the graph. But as a general statement, it is not an instrument that is strongly recommended to purchase, because of its price and other maintenance costs. It takes a relatively long time to operate one drill, so it is not efficient if the goal is to understand the overall condition of a large area of wooden elements required as part of requisite frequent cycles of site monitoring. In addition to its price as very expensive, it also requires the greatest amount of training time. Although some in the field of conservation categorizes it as a non-destructive method, it still leaves holes in wood. It is best left to be employed by a professional with expertise in wood diagnostics on a periodic basis or to investigate specific structural questions.

IR camera is a device that can be used in many different ways. Although the thermal images it produces has quantitative temperature readings, it is more reliable when considered as a qualitative method, especially when employed in-situ. The reason may be attributed to; (A) the calibration needs time and it requires other equipment to know exact environmental data, and (B) the low resolution of the output image limits the level of detail of the data. The price of an IR camera varies depending on its type, but one sufficient model can be obtained for much less than a Resistograph Drill. Therefore, the recommendation here is to purchase an IR camera as first measure to monitor potential zones of decay.

Moisture Content Meters and Surface Temperature Meters are two similar devices that are very easy to recommend for the site. They are both inexpensive and easily applied with little
training requirements. Each of results data sets were decent in the comparison and in most cases, they were complementary diagnostics. It should be noted that the moisture content meters requires substrates present to detect moisture content, which means it can malfunction when detecting a hollow area with heavy deterioration and give a low reading, and that the surface temperature meter is extremely sensitive to the weather, especially to the sun; one solution in response is to operate it when conditions are overcast and to minimize the testing duration.

In wood conservation, a scratch awl to a conservator is like tape measure to an architect. It serves as an extremely handy tool and should be the first tool and most essential tool for wood diagnostics, so the recommendation is to definitely add several of these to the toolbox. It can quickly give a direct and accurate evidence for those areas that are heavily deteriorated and have affected the surface of the member. However, due to its limitations to the surface, it is more reliable when used as a supplemental or first measure investigative tool with other devices mentioned above.

To conclude, first it is highly recommended for the site to have a medium-to-high end IR camera to serve as a quick survey diagnostic for visual understanding of the conditions of wooden components. The IR camera can not only function as an examination method, but can also be used as a monitoring system, especially in different weather conditions so that a dynamic process can be observed and help better understand the deterioration mechanisms present. The IR camera does not need to be used on frequent basis given its qualitative results and long debugging and preparation time. Once a month would be an appropriate cycle for the site to identify decay or potential areas for decay by surveying within in a two day period after a light rain, early in the morning before intense direct sunlight.
Second, it is also highly recommended for the site to be equipped with at high quality moisture content meter, a surface temperature meter and several scratch awls, to serve as first measure tools for general monitoring of decay. The data accuracy of these three methods are in fact higher than the IR camera when conducting in-situ tests. They can be used on a more frequent basis without the IR camera and are a means to “ground truth” the imaging of the IR camera when used together in combination.

Third, based on previous comparisons, a resistograph is not essential to predict zones of decay since the combination of other methods can adequately accomplish the goal. It is not strongly recommended for the site to be equipped with one due to its high expense and relatively high training cost. However, the instrument will required to carry out more in-depth investigations on wood as the resistograph is still the most definitive, quantitative diagnostic available. It not only provides evidence necessary in locating the zone of decay when used with methods mentioned above at the same time, but also reveals properties of the tested wood pieces, for example the transition of early and late wood, potential locations of knots, cracks, insect damage and on other defects not related to moisture content. As the University of Pennsylvania owns this instrument, it is ideal for Taliesin to schedule a site visit with instructors and students annually to as a means to employ this more advanced diagnostic and to maintain field-training of this type within the curriculum.

4.2. Recommendations for Future Work

Architectural conservation can be divided into three phases: documentation, assessment (diagnosis) and treatment, with this research limited to the phase of diagnostics and some of its methods, which should in turn serve as the basis for treatment formulation. As for the site
management at Taliesin West, only the means to identify decay has been provided with this study, which leaves much space for future work.

For a historic site like Taliesin West, the limitation of this testing has been to identify the problem but not necessarily the source or combination of environmental factors that have created the problem. Better roof detailing, better construction detailing, better sealing of end grain, preventive topical preservatives, better replacement species are all areas that must be addressed for the sustainability of wooden elements at the site [Figure 25]. Wright made use of the sloped roof of these structures to function as a gutter to guide the rain along the ridge of these whirling arrows. When water reaches the edge of the roof, instead of dripping to the ground, it keeps running along the direction of the slope into the wood pieces, of which the end grains are not sealed. If this problem can be treated in a system, for example monitoring the environment, finding the travel path of water, it is possible to reduce the impact of water on the wooden components. Treatment of the material itself and intervention of the system from a broader perspective should be closely examined with input by specialists.

In field of wooden heritage conservation, there is also much to continue regarding the comparative study of these methods. Laboratory-based tests could provide a more objective and reliable results of how accurately these methods can perform in a controlled, environment, which can serve as a base line when moving from laboratory to in-situ environments. More in-situ data can also be collected from each of these methods in the future to minimize error as much as possible, and to gradually switch from a visual and qualitative comparison such as this research to more quantitative comparison where more precise and mathematical correlations between the data may be found and interpreted. This field testing only reviews current technologies. As future technologies develop, a more comprehensive understanding of wood
diagnostics methodology will evolve that will depend upon further field testing and more advanced means for testing them.

Figure 24: Roof structure of the Garden Room. (Ni)
Bibliography


45


APPENDIX A
Diagnosis Diagrams
A Comparable Analysis of Field Diagnostics for Wooden Elements at Taliesin West
Graduate Program in Historic Preservation
Weitzman School of Design
The University of Pennsylvania
A Comparable Analysis of Field Diagnostics for Wooden Elements at Taliesin West
Graduate Program in Historic Preservation
Weltman School of Design
The University of Pennsylvania

Infrared Thermography Photo

Surface Temperature Distribution
APPENDIX B
Resistographs Examples
Appendix C: Field Photos

My advisor, Andrew Fearon, conducting Resistograph drilling test at the Drafting Studio. (Ni)
Zhen Ni (myself) conducting Resistograph drilling test at the Garden Room. (Fearon)
Index

A
accessibility, 31, 33, 38
accuracy, 5, 6, 9, 14, 23, 29, 37, 38, 41
amplitude, 14

C
comparison, 13, 23, 28, 31, 40, 43
complementary, 31, 33, 40

D
decay, 5, 6, 7, 10, 13, 14, 15, 16, 22, 23, 24, 31, 33, 38, 39, 41, 42
density, 5, 6, 14, 16, 22, 23, 32
destructive, 5, 11, 13, 38, 39
deterioration, 2, 5, 15, 16, 32, 38, 40
Douglas Fir, 2

E
early wood, 16

F
fungal, 2, 13, 14
fungi, 22

I
infrared, 5, 6, 9, 29, 44
in-situ, 2, 6, 28, 39, 41, 42

L
late wood, 16, 31, 41
level of detail, 29, 39

M
miter, 14, 15, 23, 31, 32
moisture content, iv, 5, 6, 10, 13, 14, 15, 22, 23, 31, 32, 40, 41
monitor, 39

P
porosity, 14, 22
probing, iii, iv, 10, 15, 38

Q
qualitative, 5, 9, 22, 24, 39, 40, 43
quantitative, 7, 39, 41, 43

R
Redwood, 1
resistance, 5, 10
resistant, 11, 32
resistograph, 5, 6, 14, 31, 32, 33, 39, 41

S
strength, 6, 16, 22, 32, 38
subjective, 10, 38
surface temperature, iv, 5, 6, 9, 13, 14, 23, 24, 28, 29, 38, 40, 41

T
thermography, iii, 5, 9, 13, 14, 28, 38, 44, 45, 46, 47

W
water, 7, 14, 15, 22, 32, 42
whirling arrow, 1, 6, 7, 9, 23, 31