Thermography in the identification of pathologies in ancient building wood

Termografia na identificação de patologias em madeira de edifícios antigos

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ABSTRACT

The present study aims to investigate the degradation of wood in historic buildings through the application of thermography, a non-destructive technique. In order to comprehend the potential of this approach, representative samples of different wood species were selected, exhibiting fissures, holes, and other damages caused by xylophagous organisms. The experimental process involved subjecting the wood samples to controlled thermal stimulation, reaching a temperature of 150°C. Using a high-resolution thermal camera (FLIR T460), images were captured that highlighted temperature variations on the wood surfaces. The meticulous analysis of these images allowed for the precise and detailed identification of fissures, holes, and areas affected by xylophagous organisms, providing valuable insights into the state of degradation. The obtained results clearly demonstrate the effectiveness of thermography as a tool for the identification and characterization of pathologies in wood from ancient buildings. The ability to non-invasively visualize thermal variations on wood surfaces offers a highly sensitive approach for detecting problematic areas. Furthermore, the utilization of this technique can contribute to more accurate diagnoses and informed decisions regarding preservation and restoration interventions.

Keywords: Thermography; Historic wood; Xylophagous organisms; Heritage conservation; Non-destructive testing.
RESUMO

O presente estudo se propõe a investigar a degradação da madeira presente em edificações históricas através da aplicação da termografia, uma técnica não destrutiva. Com o intuito de compreender as potencialidades dessa abordagem, foram selecionadas amostras representativas de diferentes espécies de madeira, que apresentavam fissuras, orifícios e outros danos decorrentes da ação de organismos xilófagos. O processo experimental envolveu a submissão das amostras de madeira a um estímulo térmico controlado, alcançando uma temperatura de 150°C. Utilizando uma câmera termográfica de alta resolução (FLIR T460), capturaram-se imagens que destacaram as variações de temperatura nas superfícies da madeira. A análise minuciosa dessas imagens permitiu a identificação precisa e detalhada das fissuras, orifícios e áreas afetadas pelos organismos xilófagos, fornecendo informações valiosas sobre o estado de degradação. Os resultados obtidos demonstram claramente a eficácia da termografia como ferramenta para a identificação e caracterização de patologias na madeira de edificações antigas. A habilidade de visualizar de forma não invasiva as variações térmicas nas superfícies da madeira fornece uma abordagem altamente sensível para detecção de áreas problemáticas. Além disso, a utilização dessa técnica pode contribuir para diagnósticos mais precisos e tomadas de decisões embasadas em intervenções de preservação e restauração.

Palavras-chave: Termografia; Madeira histórica; Organismos xilófagos; Conservação do patrimônio; Ensaios não destrutivos.

INTRODUCTION

The conservation of wooden structural elements in historical buildings plays a pivotal role in their stability and maintenance. A significant portion of wooden structures within historical edifices is situated in their rooftops, rendering their preservation of utmost importance. Roofs not only shield the buildings from the elements but also provide structural cohesion between masonry and beams, contributing to the safety and integrity of occupants. Moreover, roofs constitute an intrinsic part of cultural heritage.

Given their significance and the challenges in maintenance access, roof structures are often among the first to undergo restoration. When selecting intervention techniques, designers must be aware of the implications for the monument's cultural value. The chosen technique can yield both detrimental and beneficial outcomes, affecting not only historical and cultural value but also technical aspects of durability and safety. Despite the existence of significant manuals and technical guides on the restoration of roof structures, published by organizations like IPHAN, it is imperative to investigate the origins of pathologies and explore less invasive intervention methods.

This article emerges as an integral component of a research project within the Postgraduate Program in Built Environment and Sustainable Heritage, offering an innovative approach to characterizing wood degradation. The focus lies on utilizing
thermography as a non-destructive method for detecting pathologies. The research presents preliminary results obtained through the application of thermographic techniques on various wood species, utilizing thermal excitation at temperatures up to 150°C. Thermal analysis facilitated the identification of cracks and voids within wood structures based on observed temperature variations.

By shedding light on thermography as an effective tool for identifying pathologies in historical buildings, this study seeks to expand the repertoire of non-invasive approaches, minimizing interference with original construction systems. The capacity of thermography to provide valuable insights into the preservation and restoration of wooden structures in ancient buildings is meticulously examined, with the primary aim of enriching the field of architectural and cultural heritage preservation.

**THEORETICAL FOUNDATION**

Brazil proudly boasts nineteen historical sites recognized as World Heritage Sites, a remarkable selection from the UNESCO's globally elected six hundred. Among these sites, notable examples include the Historic Center of Goiás (GO), Diamantina (MG), Olinda (PE), Ouro Preto (MG), and the Historic Centers of São Luís (MA) and Salvador (BA), all containing buildings with wooden structures, prominently in their roofs.

Roof structures with wooden elements were introduced in Brazil during the colonial period, accompanying the earliest explorers. The constructions of that era harnessed locally available resources. A substantial portion of the rich collection of culturally significant buildings preserved in Brazil is characterized by the use of wooden structures, particularly in roofs. The importance of preserving traditional carpentry is underscored, where dovetail serve as a crucial element. As per Gonzaga (2006), the technical knowledge of cuts and carvings held by Portuguese colonizers merged with the indigenous wisdom regarding the properties of native woods, culminating in a distinctive construction culture.

It is noteworthy that, over the years, guidelines concerning preservation and intervention in historical buildings have consistently emphasized the retention of traditional construction systems. The adoption of minimally invasive interventions is recommended, preserving original materials and technical solutions whenever feasible. It is essential for repair and restoration techniques applied to wooden structures to be reversible, and for the species used to be meticulously documented in cases of reinforcement or replacement of components. In general, the approach encompasses a
methodology spanning analysis, recording, inspection, diagnosis, and a detailed study of potential interventions on ancient roofs (ZYBAŁA et al., 2021; CHENWEI et al., 2021; SANTINI; BAGGIO; SGUERRI, 2023).

The International Council on Monuments and Sites (ICOMOS) has developed three specific documents addressing methodologies for the conservation and restoration of wooden structures. The following sections (Tables 1-3) summarize the content of these documents.

Table 1 – Principles for the Preservation of Historical Wooden Structures (ICOMOS-1999).

<table>
<thead>
<tr>
<th>Principles (ICOMOS-1999)</th>
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<tbody>
<tr>
<td><strong>Inspection, Recording, and Documentation</strong></td>
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<tr>
<td>1. Emphasizes the importance of documenting the structure’s condition before intervention and the materials used in treatments. All documentation and samples of removed parts from the structure should be cataloged, including information about the traditional technology used and justification for the choice of material and technique in the intervention.</td>
</tr>
<tr>
<td>2. Document the causes of degradation and structural ruin through in-depth diagnosis, which may include documentary evidence, physical inspections, and non-destructive analysis methods. This might involve emergency measures with specific interventions;</td>
</tr>
<tr>
<td><strong>Interventions</strong></td>
</tr>
<tr>
<td>3. The primary goal of preservation and conservation is to maintain historical authenticity and the integrity of cultural heritage.</td>
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<tr>
<td>4. Proposed interventions should preferably use traditional means, be reversible if technically possible, or at least not hinder future preservation efforts when required, and should not hinder access to structural modifications.</td>
</tr>
<tr>
<td>5. Adopt the principle of minimal intervention, which, if necessary, may involve disassembly and reassembly for repair.</td>
</tr>
<tr>
<td>6. Consider the historical structure as a whole and preserve as much existing material as possible, including surface finishes. If necessary, reproduce original materials, techniques, and textures.</td>
</tr>
<tr>
<td>7. The aim of restoration is to conserve the historical structure, its load-bearing capacity, and to reveal its cultural values, enhancing the understanding of its historical integrity, its previous state, and its design, as indicated in Articles 9-13 of the Venice Charter. Removed elements and other components of the historical structure should be cataloged, with characteristic samples kept in storage as part of the documentation;</td>
</tr>
<tr>
<td><strong>Repair and Replacement</strong></td>
</tr>
<tr>
<td>8. When the replacement of deteriorated or damaged members is necessary, substitution wood may be used as long as the new members are of the same or better quality and possess similar natural characteristics. Construction technology and manufacturing should ideally match the originals, including reproducing nails and secondary materials.</td>
</tr>
<tr>
<td>9. New members or parts of members should be distinguishable from existing ones. The natural degradation or deformation of replaced members should not be reproduced. Traditional or modern methods can be used to match the color of old and new materials, provided they do not harm or degrade the wood’s surface.</td>
</tr>
<tr>
<td>10. New members or parts of members should be discreetly marked on the wood for identification;</td>
</tr>
<tr>
<td><strong>Contemporary Materials and Technologies</strong></td>
</tr>
<tr>
<td>11. Contemporary materials like epoxy resins and techniques such as structural steel reinforcement should be chosen and used with maximum care only in cases where durability and structural behavior have been satisfactorily proven over long periods. Installations such as heating and fire prevention systems should be installed with due respect to the historical and aesthetic importance of the structure or site.</td>
</tr>
<tr>
<td>12. The use of chemical preservatives should be carefully controlled and monitored, and should only be used when there are guarantees of benefit, when public and environmental safety is not compromised, and when long-term effectiveness is likely;</td>
</tr>
<tr>
<td><strong>Monitoring and Maintenance</strong></td>
</tr>
<tr>
<td>13. Adopt a monitoring and maintenance strategy for historical wooden structures.</td>
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</tbody>
</table>

Fonte: The authors, 2023
Table 2 – Recommendations for analysis, conservation, and structural restoration of architectural heritage (ICOMOS-2001).

<table>
<thead>
<tr>
<th>Recommendations (ICOMOS-1999)</th>
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<tbody>
<tr>
<td><strong>General Principles:</strong></td>
</tr>
<tr>
<td>1. Structural restoration in architectural heritage is not an end in itself but a means for preserving the building as a whole.</td>
</tr>
<tr>
<td>2. No action should be undertaken without first assessing the potential benefits and harms to architectural heritage, except in cases where urgent safeguarding measures are needed to prevent imminent structural collapse. These urgent measures, however, should, whenever possible, avoid irreversibly modifying the structure.</td>
</tr>
<tr>
<td>3. Deteriorated structures should be repaired rather than replaced whenever possible.</td>
</tr>
<tr>
<td><strong>Guidelines - Corrective Measures in Structural Restoration of Wood:</strong></td>
</tr>
<tr>
<td>4. Preliminary operations should identify species that are differently susceptible to biological attacks and assess the load-bearing capacity of individual elements.</td>
</tr>
<tr>
<td>5. When reinforcement or consolidation materials are introduced, their compatibility with the wood structure should be verified. For example, steel connections are susceptible to corrosion in association with some wood species and should be made using stainless steel. Interventions should not obstruct wood’s natural breathability.</td>
</tr>
<tr>
<td>6. As many wood structures were originally prefabricated, partial or complete disassembly can facilitate effective repair.</td>
</tr>
<tr>
<td>7. Wood is mostly used to form frame or truss structures where major problems are generally related to local failures at nodes. Common repair measures involve reinforcing nodes or adding additional diagonal elements as needed to enhance lateral stability;</td>
</tr>
</tbody>
</table>

Fonte: The authors, 2023

Table 3 – Summary of Recommendations for Intervention in Wood Structures.

<table>
<thead>
<tr>
<th>ICOMOS Documents’ Recommendations for Wood Structures</th>
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<tbody>
<tr>
<td>1. Importance of recording and documentation.</td>
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<tr>
<td>2. Importance of diagnosis and inspection.</td>
</tr>
<tr>
<td>3. Replacement with equal or better quality wood - durability.</td>
</tr>
<tr>
<td>4. Contemporary techniques with careful use and proven durability.</td>
</tr>
<tr>
<td>5. Control of preservative chemicals with beneficial and effective use.</td>
</tr>
<tr>
<td>6. Importance of maintenance and monitoring of structures.</td>
</tr>
<tr>
<td>8. Possibility of disassembly and reassembly.</td>
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<tr>
<td>10. Didactic character.</td>
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</table>

<table>
<thead>
<tr>
<th>ICOMOS Documents’ Principles for Wood Structures:</th>
</tr>
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<tbody>
<tr>
<td>I. Authenticity.</td>
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<tr>
<td>II. Preference for traditional techniques.</td>
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<tr>
<td>III. Harmonious distinction with marking new parts.</td>
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<tr>
<td>IV. Reversibility.</td>
</tr>
<tr>
<td>V. Minimal intervention.</td>
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<tr>
<td>VI. Compatibility.</td>
</tr>
</tbody>
</table>

Fonte: The authors, 2023

The Conservation and Restoration activity is meticulously conceived, planned, developed, and executed with the aim of preserving both the substance and memory of works of historical, artistic, and cultural significance (BRODA, 2021). According to authors like BRAGA (2013); SANTINI et al. (2022) and TERLIKOWSKI (2023), "indirect intervention" measures in works are intended to extend their lifespan, delay aging, reduce risks, maintain original features, and preserve physical and functional integrity. The effectiveness of these measures depends on comprehensive knowledge of
the work from its creation to the intervention, the surrounding context, the underlying causes of pathology, and appropriate technical means to prevent alterations.

Any intervention in the roofs of ancient buildings should begin with a thorough analysis of the condition of the wooden structures. It is preferable to employ non-destructive and minimally invasive techniques to avoid causing or exacerbating damage to the structure (SANTINI; BAGGIO; SGUERRI, 2023). The use of such techniques, including infrared thermography, is relatively new and less common due to high equipment costs and complexity of application (TERLIKOWSKI et al., 2021; SZYMCZAK-GRACZYK et al., 2022, ZIELIŃSKA; RUCKA, 2023).

This article focuses on exploring infrared thermography as a Non-Destructive Testing (NDT) technique. In the construction field, this technique is used in leak detection, thermal inspection of areas around new constructions, and thermal evaluation for building preservation. Here, we propose the use of thermography to identify pathologies in wooden structures, offering a novel and reliable application of the technique in the context of architectural heritage.

Numerous material and component pathologies in buildings are associated with temperature. Thermal measurement contributes to understanding the underlying phenomena of these anomalies. Thermography offers advantages such as detecting invisible objects, non-contact operation, real-time analysis, and non-destructive approach (BARREIRA, 2004; XIN et al., 2021; FRANÇOIS et al., 2021; PENG et al., 2023). According to the technical manual of the thermal camera, the technique is limited to detecting only surface temperature variations, unable to penetrate walls or detect damage below the surface.

In Brazil, Cortizo (2007) pioneered the use of thermography in diagnosing pathologies in historical heritage. Globally, significant studies, such as those by CARLOMAGNO; MEOLA (2001); CLARK; McCANN; FORDE (2003), DORREGO; LUXÁN; DORREGO (2003), GRINZATO; BISON; MARINETTI (2002), MALDAGUE (2001), and ROSINA; GRINZATO (2001), analyzed the use of thermography for diagnosing hidden pathologies in buildings. LEMASTER (2007), LO; CHOI (2004), LI et al. (2022), XU et al. (2021), and RIPPA et al. (2021) investigated thermography for detecting wood problems.

The thermography technique involves color imaging of surface temperature, allowing for the detection of thermal variations indicative of pathological issues (PENG et al., 2023). Maldague (2001), Xin et al. (2021), and François et al. (2021) discuss two
approaches to non-destructive thermal imaging: passive and active. The passive technique relies on heat stored internally in materials or stimulated by natural sources such as solar energy. The active approach, on the other hand, involves heating or cooling materials to induce the necessary heat flow and thermal gradient. Passive thermography is qualitative in nature, indicating anomalies, while the active technique tends to generate quantitative results, enabling more precise measurements and control of events (source, duration, intensity, and distance).

According to Barreira (2004) and Rippa et al. (2021), bodies emit or absorb electromagnetic radiation due to internal matter agitation. When radiation strikes real objects, part of it is absorbed, and the rest is reflected or transmitted.

In this scenario, the objective of this work is to evaluate the technical feasibility of infrared thermography as a method for detecting pathologies in ancient wooden structures.

METHODOLOGY

As emphasized by Råberg; Terziev; Land (2009), the lack of agile and effective methods for identifying and quantifying wood deterioration is one of the obstacles compromising prognosis in structures. These authors stress that the key to the success of these methods lies in the analysis of measurable characteristics of deterioration and their correlation with material strength.

In this context, an experiment was conducted to investigate the feasibility of infrared thermography in detecting defects in wood. Three distinct wood samples were selected, originating from different Brazilian species, each displaying different apparent defects. The aim of this experiment is to validate the applicability of thermography on woods with diverse defects. The chosen samples exhibited evident flaws: sample 1 displayed holes with a diameter of approximately 0.5 cm, indicative of loss of section area or attack by wood-boring organisms; the second sample had a crack originating from the collapse of a sample subjected to compression testing, representing a structural element that had experienced severe structural failure, potentially leading to building collapse; the third sample showed an irregularity on the surface, altering the cross-sectional area and revealing loss of resistant section.

The samples were heated at constant intervals and temperatures, reaching up to 153°C (Figure 1), within a controlled chamber in terms of temperature and relative air
humidity (Figure 2). When the temperature reached 150°C, the pieces were kept in the chamber for a period of 30 minutes, with the time recorded. Subsequently, thermal images were captured to identify, through temperature variations, the regions of cracking and pathologies. The image capture process was repeated at fixed intervals of 5 minutes, allowing monitoring of sample cooling and evaluating evidence of defects based on thermal contrast. The images were captured from a distance of 30 cm between the thermal camera and the samples.

**Figure 1** – Detail of the chamber control panel and temperature and relative air humidity control.

![Figure 1](image)

Fonte: The authors, 2023

The equipment used for the test was a FLIR T460 thermal camera, illustrated in Figure 2. For its use, it is necessary to input the object's emissivity, ambient temperature, and distance to the object. The camera captures infrared rays and calculates surface temperature based on the input data. The camera's operating range varies from -20°C to 1200°C. The images generated by the camera display surface temperatures in colors. The equipment also has a laser target for identification of the analyzed point. Other characteristics are described in Table 4. In the test, the emissivity (E) of the woods was set at 0.80 (PENG et al., 2023).

**Figure 2** – FLIR T460 thermal camera.

![Figure 2](image)

Fonte: The authors, 2023
RESULTS AND DISCUSSION

After conducting the experiment, the resulting thermograms provided valuable information about defect detection in different wood samples. In this section, the obtained results from infrared thermography will be presented and discussed.

In Figure 3, the thermograms of Sample 01 are presented. In these thermograms, the presence of two 0.5 cm diameter holes can be clearly distinguished. Through the temperature contrast, evidenced by the various colors, it is observed that the holes exhibit higher temperatures compared to the rest of the sample body, even during the cooling process. This characteristic suggests that the holes retain heat more effectively, possibly due to differences in the thermal conductivity of the affected wood compared to the surrounding region.

The thermograms of Sample 02 are presented in Figure 4. In these thermograms, the presence of a crack on the sample’s surface can be identified. Similar to Sample 01, the temperature contrast indicated by the colors reveals that the crack maintains a higher temperature compared to the rest of the sample, even during the cooling process. This temperature elevation may indicate that the crack is retaining heat due to changes in its thermal properties, which is an indication of pathology.
Figure 3 – Cooling thermograms of Sample 01.

Figure 4 – Cooling thermograms of Sample 02.

Figure 5 presents the thermograms of Sample 03. These thermograms reveal the presence of a fault on the sample's surface, representing an irregularity in its cross-
sectional area. Through the temperature contrast, it can be perceived that the region where
the irregularity occurs presents a lower temperature compared to the rest of the sample.
This observation suggests that the area affected by the irregularity conducts heat
differently, possibly due to variations in the thermal properties of the wood.

**Figure 5** – Cooling thermograms of Sample 03

Based on the obtained results, it can be highlighted that at elevated temperatures,
the color contrast in the thermal scale is more pronounced in areas of apparent defects.
Defects resulting in section loss, such as holes and cracks, exhibit higher temperatures
than unaffected areas. This temperature discrepancy evidenced in the thermographic
images points to the feasibility of using infrared thermography as an effective tool for
non-intrusive detection of wood pathologies.

The thermography approach has proven promising for the early identification of
structural failures and defects in wooden components, thus contributing to the
conservation and restoration of historical and cultural structures. However, it is important
to consider that accurate interpretation of thermographic images requires solid technical
knowledge and a deep understanding of the thermal characteristics of the materials in
question. Therefore, the application of thermography should be complemented with more
in-depth analyses to ensure a comprehensive and accurate assessment of wood structure conditions.

CONCLUSIONS

This experimental research study aimed primarily to obtain relevant information for the analysis of the conservation state of wooden buildings and structures, using woods commonly found in Brazil and widely employed in construction. The results obtained from the tests demonstrated the viability of using infrared thermography for on-site evaluation of ancient wood structures to diagnose their state of conservation. These tests open promising prospects for the application of thermography as a non-destructive technique for analyzing historical wood structures.

When assessing the effectiveness of using thermography in identifying pathological manifestations in woods, it was observed that the thermal camera detected temperature changes on the surface at certain points. These changes may be related to cracks, splits, holes, or variations in the wood pieces' cross-sections.

However, it was not possible to identify internal defects in the samples or determine the depth of the defects solely based on surface temperature. It was observed that visualization by temperature contrast improves significantly at higher temperatures (above 100°C). So far, the interference of hole temperatures on sample surface temperature has not been observed.

Despite the initial considerable cost of the thermal camera, it is an agile tool and can be used remotely. It does not replace existing traditional techniques, such as visual analysis and tests like percussion, resistography, tomography, or other employed methodologies. However, thermography can be integrated as an additional tool to verify the presence of pathologies in ancient structures. For a more comprehensive and accurate assessment, in-situ tests using the technique are recommended, allowing for result comparison and evaluation of the influence of variables such as relative humidity, distance, ambient temperature, and thermal excitation of the structure.

In summary, the results of this study suggest that infrared thermography has the potential to be a valuable tool in the field of conservation and restoration of wooden structures in historic buildings, providing complementary information for informed decision-making and contributing to the preservation of architectural and cultural heritage.
ACKNOWLEDGMENTS

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