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Infrared thermography (IRT) to detect internal defects caused by xylophagous insects in bamboo culms

Termografía infrarroja (TI) para detectar los defectos internos causados por los insectos xilófagos en los culmos de bambú

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Abstract

Infrared Thermography (IRT) is a technique used in the inspection of constructive elements in buildings. It has a great potential for the investigation of pathological manifestations because it is a strictly non-destructive procedure that could be rapidly applied in fieldwork. This research analyzes the possibility of using active IRT to detect internal defects caused by xylophagous insects in bamboo culms, in order to apply it in the fieldwork for the inspection of pathological manifestations in buildings. In laboratory, samples of bamboo culms of Bambusa tuldoides and Phyllostachys bambusoides species were submitted to a thermographic experiment using a thermographic camera and FLIR B400 software. Subsequently, the potential for using this technique in the fieldwork was evaluated. The results point the limitations of both, technique and method used, to identify perforations of diameter less than or equal to 3 mm located in the inner wall of the bamboo culms.

Keywords: *Infrared thermography, bamboo, detection of internal defects, insect decay, non-destructive testing*

Resumen

La Termografía Infrarroja (TI) es una técnica usada para inspeccionar los elementos constructivos en las edificaciones. Posee un enorme potencial para la investigación de las manifestaciones patológicas porque es un procedimiento estrictamente no destructivo que se podría aplicar fácilmente en el trabajo de campo. Esta investigación analiza la posibilidad de usar la termografía infrarroja activa para detectar los defectos internos causados por insectos xilófagos en las cañas de bambú, con el fin de aplicarla en terreno en la inspección de las manifestaciones patológicas de las construcciones. En el laboratorio, muestras de cañas de bambú de las especies Bambusa tuldoides y Phyllostachys bambusoides se sometieron a un experimento termográfico usando una cámara termográfica y software FLIR B400. Luego, se evaluó el potencial de esta técnica para ser usada en terreno. Los resultados señalan las limitaciones, tanto de la técnica como del método usado, para identificar las perforaciones menores o igual a 3mm de diámetro ubicadas en la pared interior de los culmos de bambú.

Palabras clave: Termografía infrarroja, bambú, detección de defectos internos, deterioro por insectos, ensayo no destructivo

1. Introduction

The utilization of bamboo in the civil construction might become a sustainable alternative considering its potential for renovation, abundance, and fast growth. However, bamboo is an organic material and consequently, susceptible to deterioration caused by biotic agents, among them, the xylophagous organisms (Gupta and Kumar, 2008); (Jaramillo, 2019).

The durability of a construction and its constructive components is a requirement of users regarding the performance (International Organization for Standardization, 2011); (Associação Brasileira de Normas Técnicas, 2013). In this sense, the study of the condition and conservation of bamboo elements used in buildings contributes to increase the knowledge on this subject that has been little explored and, consequently, to make possible to determine its durability.

Visual inspection is a non-destructive method used to inspect buildings constructive elements; it is widely used to detect irregularities in building components. However, it is limited to the outside aspect and does not identify the interior integrity state of the components. Considering this, to inspect bamboo elements, it is necessary to complement it with other inspection procedures to identify the state of internal impairment parts that show signs of deterioration, facilitating the decision-making related to preventive or palliative treatments (Jaramillo and Librelotto, 2018); (Jaramillo, 2019).

The Infrared Thermography (IRT) is a strictly non-destructive inspection method that works with a thermographic camera, measuring the radiation emitted by the sample surfaces at a given moment and shows it in the form of thermograms. A fast execution technique that can be applied in the fieldwork (Gayo et al., 1992); (Rodríguez-Liñán et al., 2012). In construction, it is often used to detect regions with different humidity, air infiltrations, also to inspect electrical installations and to analyze thermal performance of buildings in order to determinate the energy efficiency (Bagavathiappan et al., 2013).

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After performing a systematic research about IRT in several databases, it was found a scientific paper (Tuli et al., 2009) that describes specifically the application of an active IRT in bamboo. That research explored the possibility of using the technique to study defects and damages in this material; modulating different heating frequencies and simulating hole type defects, with diameters between 3-10 mm, in samples of half bamboo culms (bamboo cut in half lengthwise) for the tests.

Previously, in a fieldwork performed linked to this study, it were made a few visual inspections of bamboo constructions and it was possible to observe and record the presence of surface holes of approximately 3 mm in diameter in some culms (Jaramillo et al., 2018), caused by dinoderus minutus and other insects. Therefore, due to these typical anomalies and insects attack, the focus was the application of the thermography technique to identify and analyze the pathological manifestations with diameter until 3 mm.

Thus, the objective of this study was to analyze the potential of using active IRT to detect internal defects (holes) caused by xylophagous insects in bamboo culms, exploring the application of this technique in current studies, and also guiding future researches about subject.

2. Theoretical framework

The pioneering IRT applications happened in 1800, when William Herschell identified the existence of infrared rays. During the 19th century, some researches were held in as an attempt to design devices to detect and quantify this type of radiation. In the 20th century, the development of this technology was substantial and its application was mainly for military purposes. Only after the end of World War II, the application was set for engineering intents. (López, 2010)

The radiation emitted by most bodies is mainly concentrated in the infrared spectrum, with wavelengths between 2 and 5.6 μ (Gayo et al., 1992). The thermographic camera can detect measure and capture images of this radiation, which allows calculating and processing these images to make the temperatures of the emitting body visible on a map (thermogram). This is possible because the detectors of a thermographic camera convert the radiant energy of the infrared spectrum into an electrical signal and then into a visible temperature image. (López, 2010)

In this sense, thermography is a technique based on the detection of infrared radiation emitted by objects, allowing the measurement of temperatures and the observation of patterns of heat distribution in a given system (Altoé and Oliveira, 2012) and can be used in the inspection of pathological manifestations in buildings and as a preventive engineering instrument.

The existence of a defect in a constructive element reduces the rate of heat diffusion, for this reason when observing temperature of the surface with a thermographic camera; the defects appear as zones of distinct temperature regarding the surrounding area. To see the deeper defects, a longer observation time is needed and so it will appear in reduced contrast. (Maldague, 2000)

In order to understand properly the inspection of constructive elements through the use of IRT application, it was necessary to achieve a bibliographic survey regarding its working principles on identifying wood defects and then later, to adapt and apply them in bamboo samples, in the laboratory. This experimental research aims a future application of this technique in the fieldwork, inspecting constructions made of bamboo.

To use IRT to inspect wood pieces, the identification of internal defects occurs due to the variations of density combined with irregularities in the material: the defects are related to density reduction and the singularities to the increase (López et al., 2012). These density changes modify the material's thermal behavior, causing a variation of temperature in the surface of the sample. It is because thermal diffusivity is inversely proportional to density (López et al., 2014). The identification of a temperature modification captured by the infrared camera suggests the occurrence of a defect or singularities in the wood. This same operation principle and identification can be applied to bamboo.

Some studies (Rodríguez-Liñan et al., 2012); (López et al., 2014); (López et al., 2012) have noted the possibilities of applying IRT in wood pieces to detect differences of humidity content, internal density loss as well as illustration of deterioration processes in various stages.

IRT essays are classified in two types: passive and active. In the first one, the thermographic record is obtained without the use of thermal excitation in the sample. In the other hand, active thermography type exposes the object of study to an artificial source of heat. In general, the passive IRT does not present perceptible thermal differences in wood samples, regardless both size or depth of the internal defect regarding the surface (Rodríguez-Liñan et al., 2012). For this reason, it is necessary to use active IRT to obtain visible results.

There are some types of active IRT based on the type and duration of thermal excitation (López, 2010): pulsed thermography, long pulsed thermography, lock-in thermography, vibro-thermography. In the first three types it is necessary to apply heat to the analyzed object face, whereas in the last a mechanical vibration is applied.

The pulsed thermography has three main characteristics: inspection speed, possibility of application in components in service and prevention of damage to the system rehearsed due to the use of low intensity stimulus. (Oshiro, 2011) This technique has been applied for detection of internal defects in wood (Rodríguez-Liñan et al., 2012) as well as the long pulse thermography (López, 2010); (López et al., 2012).

The method tested in the detection of internal defects in bamboo samples was the Frequency Modulated Thermal Wave Imaging (FMTWI) (Tuli et al., 2009), which can be referred as a type of lock-in thermography (Chatterjee et al., 2011). (Tuli et al., 2009) pointed to the application of this technique in four bamboo culms of two different species, split in the middle longitudinal direction, with blind hole perforations made of various diameters. To the thermal excitation of the samples it was used two halogen lamps of 300W placed each one side by side of the sample being tested for twenty minutes, in order to heat the surface, considering it was flawless and testing frequencies between 1 - 100 mHz. The results of the previous mentioned study, pointed to the possibility to identify holes with diameters bigger than 5 mm located among 2-6 mm depth regarding the surface of the cortex and the feasibility of observing defects at 2 mm depth with frequencies similar to 100 mHz.

Based on these experiments, the purpose of this study is to test pulsed active IRT to inspect bamboo culms with hole defects, in samples having hole diameters made up to a *maximum 3 mm in diameter, similar to those caused by xylophagous insects.*

Xylophagous insects cause the most destructive attacks on bamboo, principally in dry culms. Drills and termites are the most common, their attack is characterized by the presence of galleries in the culms walls and circular or oval holes in the cortex. Field inspections of bamboo structures, identified that the diameter of this kind of holes is approximately 2 – 3 cm (Jaramillo and Librelotto, 2018); (Jaramillo, 2019) and (Kaminski et al., 2016) pointed that Powderpost beetles are the most common insects that attacks bamboo culms and they make 1 – 2 mm diameter exit holes.

3. Materials and methods

The camera used in this study was a FLIR (brand) model B400 infrared camera, that counts with a spatial resolution of 320 x 240 pixels, with a thermal sensitivity of 50 mK (0.05 ° C) allowing to the inspected object a temperature range among -20 and 350 ° C with an accuracy of +/- 2 ° C.

Previously, it was inserted in the camera the following parameters: ambient temperature, air humidity, camera/object distance, reflected temperature and emissivity. Through the use of a thermo hygrometer it was possible to record the ambient temperature and air humidity. The distance between camera and the sample was 80 cm. Before each test, the reflected temperature was set by the method described in ASTM E1862-97 (ASTM, 2010). Also, to determine the emissivity of the samples, it was used the method described in ASTM E1933-99a (ASTM, 1999). The bamboo emissivity value obtained was ε = 0.95.

The samples were heated by two different forms. At the beginning, a transportable type of heating source was used, aiming it to be replicable in fieldwork procedures - specifically when the procedure would be in bamboo constructions. Thus, two Phillips 150W infrared lamps with 50 Hz frequency each were used. These lamps were put near the samples, being 30cm distant from the culm surface, on the same face of the image catchment. (Figure 1).

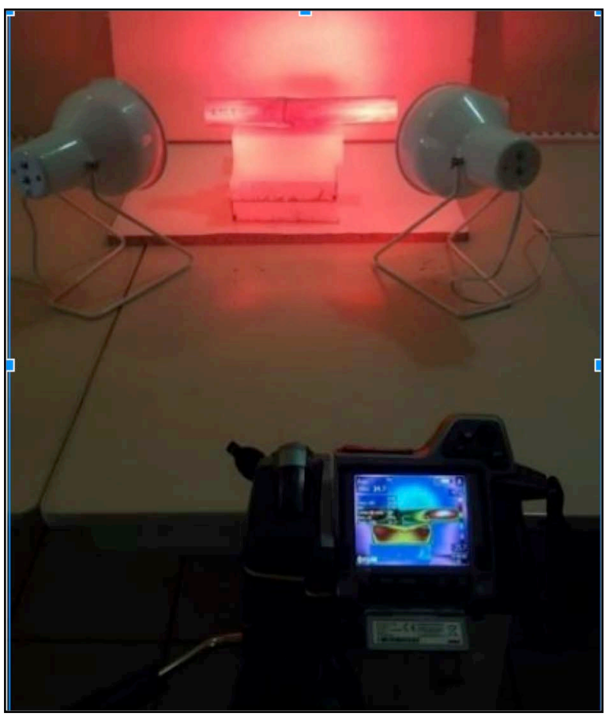

Figure 1. *Test equipment arrangement*

The other heating form used was an Olidef Cz (brand) drying and sterilization laboratory oven, having the following internal dimensions: 31.5 cm x 31.5 cm x 31.5 cm. The oven option was used in order to achieve a greater uniformity heating comparing to that one the lamps could provide. The samples, at this stage were heated in groups of three, considering that each group was composed by samples of the same bamboo species and also holes or integrity - similar characteristics. The (Figure 2) demonstrates the arrangement of the samples inside the oven.

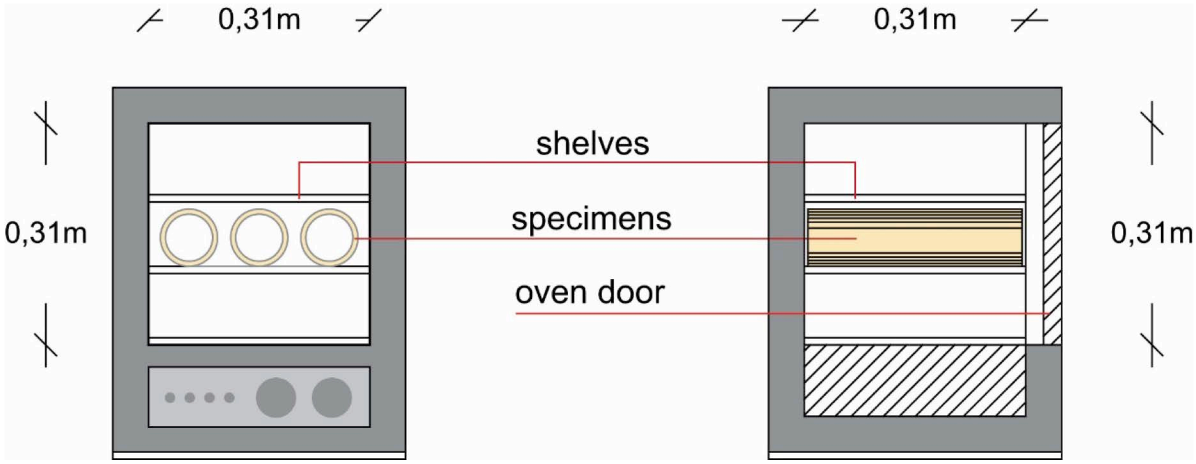

Figure 2. *Disposition of the samples inside the oven*

3.1 Samples

The samples were extracted from culms of Bambusa tuldoides and Phyllostachys bambusoides (as known as bamboo Madake) species. In total, twenty four samples were tested. The general characteristics of each one are summarized in the (Table 1):

Table 1. *General characteristics of tested samples*

Species	*Origin and treatment*	*Description*	*Number of samples*	*Code*
Bambusa tuldoides	*Origin of bamboo: Florianópolis / UFSC campus (2016). Treatment: immersion in a pentaborate solution at the laboratory.*	*Round bamboo with or without node/30 cm length*	*6*	*RT* (Round Tuldoides)*
		Half bamboo culms/30 cm length	*6*	*MT* (Half Tuldoides)*
Phyllostachys bambusoides	*Origin of bamboo: São Paulo Treatment: boiling water (performed by the supplier)*	*Round bamboo with or without node/30 cm length*	*6*	*RM* (Round Madake)*
		Half bamboo culms/30 cm length	*6*	*MM* (Half Madake)*

*****NOTE:*** *each group of sample was identified with the letters "S" and "C", to distinguish the samples of* ***Without Holes (S)*** *and* ***With Holes (C)***

Each group were composed by six bamboo samples, three of them were used intact (without defects) for the tests. Other three samples were perforated in different ways, to simulate defects similar to the galleries left by xylophagous insects. In samples with simulated defects, the perforations were made with a portable drilling machine on perpendicular direction in relation to the fibers, using four different diameters of wood drills: 1.5 mm; 2.0 mm; 2.5 and 3.0 mm respectively, and penetration depth of 2 mm in relation to the surface of the culms cortex. It was made as well perforations in the longitudinally direction in culms with a wall bigger or equal to 3 mm, with 15 mm depth and diameters of 1.5 mm and 2 mm. (Figure 3) demonstrates the characteristics and arrangement of perforations in samples with defects.

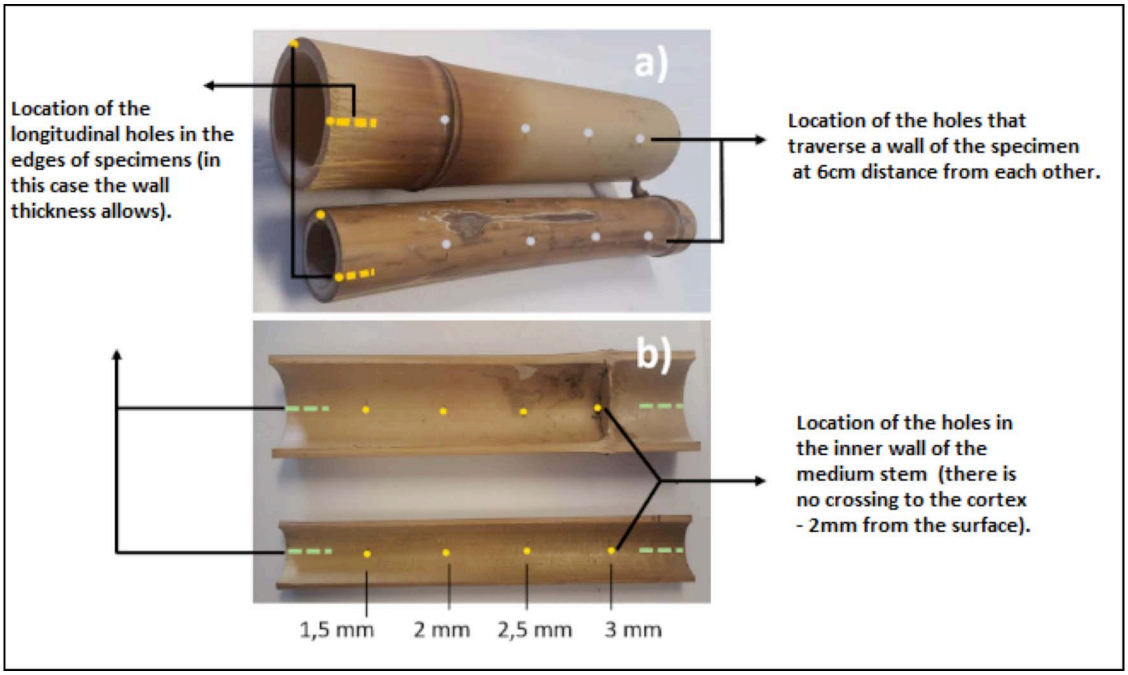

Figure 3. *Diameters and location of perforations in the round (a) and half-culm (b) samples*

3.2 Experimental procedure

To execute the lamps heating procedure - in all cases - the sample was placed horizontally above a Styrofoam surface, in a 90 cm distance from the thermographic camera. Each lamp was positioned in a 30 cm distance close to the borders of the sample.

After 25 min of heating, the lamps were switched off and the cooling process started. During both phases, heating and cooling, from five to five minutes interval the images were recorded. In the cooling period, the time elapsed until the last recording was 30 minutes, at this moment the thermal imager of the camera was showing that the sample was practically in thermal equilibrium with the ambient temperature.

After the execution of these tests, the results obtained showed the need to perform an adjustment in the samples heating process. All the thermograms presented by the camera showed higher temperature records at the points closest to the location of the infrared lamps, evidencing the occurrence of lack of uniformity in the heating process. This condition influenced the generated thermograms and, consequently, the obtained results.

In order to improve uniformity temperature in the samples heating process, it was decided to heat them in an oven at 90˚C temperature for 30 min. The decision about the temperature degree was based on the temperature and time used in a similar research with wood (Rodríguez-Liñán et al., 2012) and also considering that the bamboos physical properties would not be affected, which happens above 160 °C (Brito, 2013).

Once the heating was done, the samples were removed from the oven and remained at ambient temperature for 30 min, until the cooling was complete. During this stage, in every 30 seconds the thermographic records were taken. During the cooling process, this interval among the records of samples was reduced comparing to the ones heated with lamps, in order to increase the numbers of temperature variations records.

3.3 Analysis of the results

The thermograms obtained in the previous heating phases of samples were quantitatively analyzed using the FLIR Tools software, which allows to create points, lines or areas in the images and determinate the temperature in each single pixel of the image. After the quantitative analysis, the information was exported to an electronic spreadsheet to be used in the elaboration of the graphics.

During the analyses stage, in addition to the identification of the defects and singularities in the tested samples, a comparison was made based on the thermograms and graphics obtained from a same sample first heated with lamps and then in the oven. The graphics and thermograms were also compared regarding the sample condition being it intact or defective.

4. Results and discussion

At the end of the tests, 754 thermograms were obtained: 270 of samples heated with lamps and 484 of heated in the oven. In samples heated with lamps, it was possible to observe the maximum temperature on the surface was 71.56 ° C. In those ones heated in the oven, although its temperature was set at 90 ° C, the reached by the samples at the end of the heating was 87.67 ° C. (Table 2) It can be seen, through the comparison of the coefficient of variation of maximum temperature, the existence diminishing of the temperature variation in samples heated in the oven. This fact occurred because with this procedure was obtained a more uniform heating than in the one with lamps.

Table 2. *The average maximum temperatures reached in the samples heated with lamps*

	Group of samples	**Number of samples in the group**	**Average maximum temperature by culms group (° C)**	**Coefficient of variation (CV) of maximum temperature**	**Average maximum temperature by heating method (°C)**
Heating through the lamps	RTS	3	62,675	6%	71,56
	RTC	3	69,67	10%	
	RMS	3	71,77	5%	
	RMC	3	74,5	3%	
	MTS	3	70,9	3%	
	MTC	3	68,77	5%	
	MMS	3	76,6	5%	
	MMC	3	77,63	8%	
Heating through the oven	RTS	3	80,33	0,3%	87,67
	RTC	3	78,7	2%	
	RMS	3	91,6	1%	
	RMC	3	87,16	3%	
	MTS	3	91,46	1%	
	MTC	3	86,57	1%	
	MMS	3	92,9	0,4%	
	MMC	3	92,6	0,5%	

4.1 Influence of the heating type in the samples

The thermographic tests using lamps for thermal excitation did not provide a uniform heating in the samples, which lead to a difficult interpretation of the results. The thermal excitation obtained in the oven, however, allowed a great heating uniformity of the samples, making possible to observe clearly the defects. This fact can be verified comparing (Figure 4a) which shows an image of lamp-heated 'RMC2' sample, with (Figure 4b), which shows the same sample heated in the oven. Both images were taken immediately after the heating

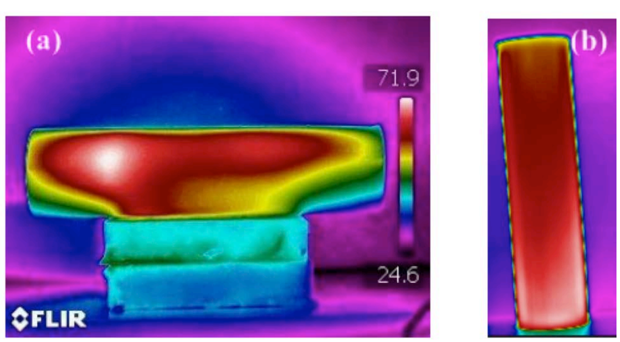

Figure 4. *The thermograms differences showing the heating of the RMC2 sample with lamps (a) and in the oven (b)*

These first observations show the necessity to test some alternatives to provide thermal excitation of bamboo culms. Thus, in the future it may be possible the use of IRT application in the fieldwork, during the inspection of a building. It is important to mention at this point the necessity to observe that, during the procedure adopted, the temperatures reached should not change the properties of the material.

In this study, only the results obtained from samples heated in the oven were considered to analyze the thermograms of bamboo surface culms, in order to facilitate the identification of temperature differences from its visible singularities.

4.2 Observations regarding the intact samples

Through the obtained thermograms, it was possible to visualize different temperatures on the sample's surface. It is possible to observe in (Figure 5a) the photograph of RTS1, RTS2 and RTS3 samples and just beside are their thermograms obtained in minute four of the cooling phase (Figure 5b). It can be seen the chromatic differences in the samples indicating various temperatures. In RMS samples the differences weren´t as perceptible as in these.

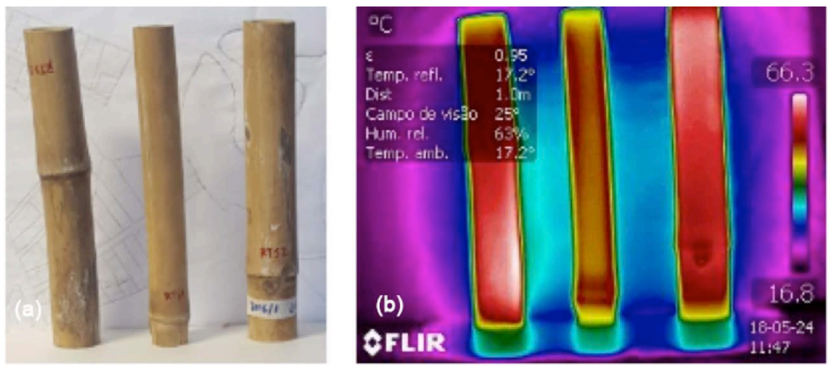

Figure 5. *Photograph (a) and thermogram (b) of RTS1, RTS2 and RTS3 samples*

A thermogram showing the minute two of the cooling phase of samples MMS1, MMS2 and MMS3 can be seen in (Figure 6). In all cases occur evident variations of temperatures among the pixels near to the node region. In the same image also appears near to the samples superior edges, the splinters irregularities produced in the cortex during the cutting process.

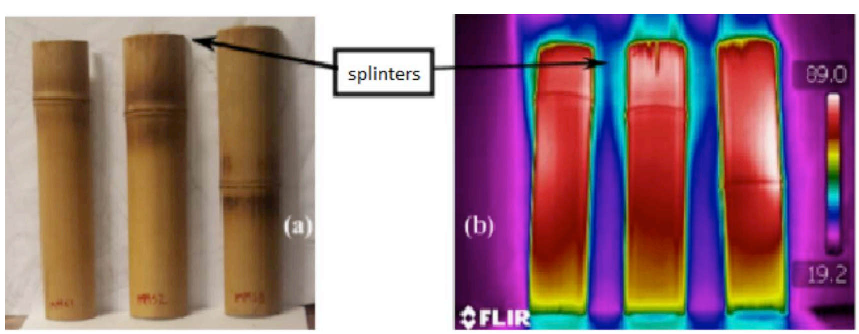

Figure 6. *Photograph (a) and thermogram (b) of the samples MMS1, MMS2 and MMS3 in minute two of the cooling phase*

In cases such as the samples surface had some singularity on the visible surface to the naked eye, such as stains or some perforation in the cortex, the irregularity appears as a different temperature (color) from the closest pixels in the sample thermogram. (Figure 7a) shows a photograph of MTS1, MTS2 and MTS3 and (Figure 7b) is the therrmogram captured at the beginning of the cooling phase.

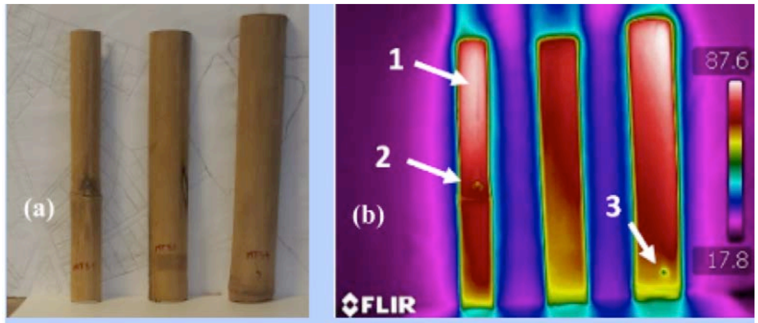

Figure 7. *Longitudinal stain of the culm (1), gem and node (2) and existing perforation passing through wall (3) in samples MTS1, MTS2 and MTS3*

4.3 Round samples and half- culms with holes (internal defects)

When analyzing thermograms of samples with manufactured internal holes that do not reach the surface (cortex) - RTC, RMC, MTC and MMC groups, in no case it was possible to observe temperature differences on the specific areas where the defects were located.

As an example of the defective round bamboo group, (Figure 8) shows the thermograms and temperature difference graphs of the RMC samples group, in the minutes 5 and 22 of the cooling phase. The obtained thermograms were similar to those flawless samples (RMS); therefore, only visible external defects appear in the cortex of the culm. It can be observed in the highlighted regions with dotted lines in the thermograms, where the thermal differences of the manufactured defects specific points supposed to be appearing, there are no changes in the temperature that could evidence internal holes and it is even more notable in the analysis graphs (which show the temperature in each image pixel).

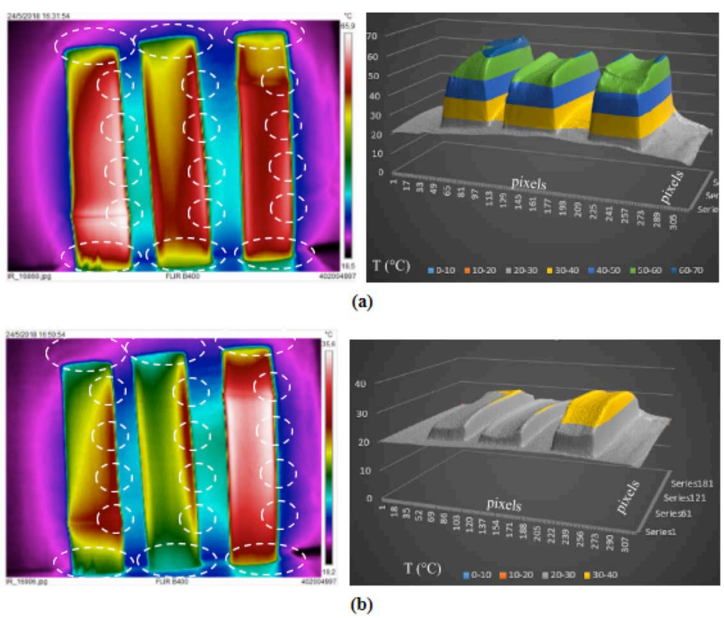

Figure 8. *Thermograms and temperature difference graphs of RMC1, RMC2 and RMC3 samples in minute five (a) and minute twenty-two (b) of the cooling phase*

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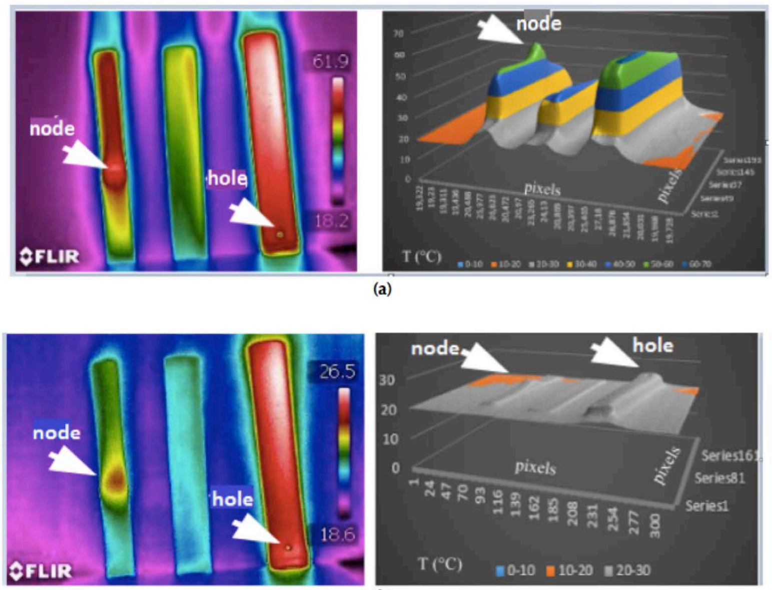
Similarly, to exemplify the thermograms of the half-culm defective bamboo group, (Figure 9) shows the thermograms and temperature difference graphs of the samples MTC1, MTC2 and MTC3 in minutes five and twenty-five of the cooling phase. Similar to the observed in the round samples, the thermograms obtained were similar to the flawless ones (MTS). In the sample's central longitudinal axis, it were expected thermal differences at the defect points, though there were are no changes in temperature that could give some evidence of internal defects. The only defect that stands out is the hole, which goes through the inferior part of one of the samples and the singularity of the sample MTC1 node.



(a) (b)

Figure 9. *Thermograms and temperature difference graphs of MTC1, MTC2 and MTC3 samples in minute five (a) and minute twenty five (b) of the cooling phase*

Through a compared analysis between the used method in this study with the one applied for (Tuli et al., 2009). It is possible to observe that those authors detected defects at 2 mm depth with diameters close to 10 mm, while in the present study the largest diameter simulated at the same depth was 3 mm, in order to resemble defects observed in the fieldwork. Additionally, unlike that method, for this research no frequency modulation was used, trying to work with thermal excitation sources with constant frequency.

4.4 Another general observations

During the tests, it was possible to observe that in the sample wall with thin thickness the heating and cooling process were faster than the thick ones. It was also noted that the culms nodal regions (more dense than the rest of the culm) took longer to warm up and also to cool. This should be considered during a test with another heating source.

Considering relevant the material density variations, within a thermographic and samples surface characteristics analysis, the increasing density in the radial direction of the bamboo wall, which generates a very dense cortex, would influence and make it difficult to observe the defects on its inner layer, which is less dense. In future researches, it could be tested bamboo laminated samples, to observe if these density variations across the culm wall make impossible the identification of defects inside it with this technique.

5. Conclusions and recommendations

By considering the limitations and characteristics of this research as bamboo species, types and direction of heating used, distance between the camera and the samples, time of heating, deep and diameter of the holes, at the end of this study and its data analysis, it was observed the following points:

- *IRT is a non-destructive technique which allows us to identify the natural singularities of bamboo culms like nodes and buds, as well as stains and splinters in the cortex. This is visible because the density surface changes in the different parts of the samples, which influences its temperature, and:*

- *By pulsed active IRT, it was not possible to identify defects with a diameter less or equal to 3 mm, with a depth of 2 mm in relation to the cortex, neither on the wall of the round bamboo culms, nor the half-culms samples, considering the bamboo species, the equipment specifications and the methodology applied in this study.*

However, the existent relation between material density and temperature in the thermograms show the potential of the technique regarding the defect detection. It is necessary to continue with more specific and in-depth research on this topic, changing some variables. In the future, it is suggested to extend the tests to a bigger quantity of bamboo species and samples, to test as well other temperature ranges for thermal excitation and test various heating methods, use a thermographic camera with higher resolution - which makes possible to analyze a bigger number of points in the samples.

6. Acknowledgments

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