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ORIGINAL

Advanced wireless sensors for termite detection in wood constructions

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Abstract Considering the decay risk of wood structures in temperate regions and the need to implement environmentally sound and healthy safe integrated pest management strategies, the main objective of this research was to detect xylophagous insects (especially termites) at an early stage as well as to relate the wood conditions in buildings (moisture content and temperature) to the infestation risk of the main wood-rotting fungi. To do this, an advanced sensor was developed. It sends a wireless alarm with the indication of termite activity inside the wood or with the warning signal that the conditions in the wood make it vulnerable to fungal settlement. After investigating the main detection parameters and testing different prototypes under varying laboratory conditions, a final sensor was developed for use in real conditions. Furthermore, a wireless network of these biodegradation sensors was developed and installed in three representative buildings for their automatic monitoring, forming an integral alarm system for wood degradation activity supported by an advanced remote sensing management.

Introduction

Wood is a natural material and, therefore, it has the risk to be attacked and deteriorated by xylophagous insects and fungi. In regions with temperate climates, both in urban and rural areas, it becomes more and more necessary to monitor the timber structural conditions in order to allow early detection of its biodegradation in

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such a way that costly chemical curative treatments can be prevented (Lewis 2001; Unger et al. 2001). Moreover, many historical wooden buildings belong to cultural inheritance and need to be preserved from decay (Cymorek 1984; Moreno et al. 2009).

In these constructions, wood is exposed to insect attacks of the families Cossidae (carpenter moths), Siricidae (wood wasps), Termitidae (termites), Bostrichidae (false powderpost beetles), Curculionidae (weevils), Lyctidae (true powderpost beetles), Anobiidae (furniture beetles), Cerambycidae (longhorn beetles), Scolytidae (bark beetle) and Platypodidae (ambrosia beetles). These insects all feed on wood resulting in biodeterioration of the cell wall and consequently significant reduction of the mechanical strength (Creffield 1996). Many of them attack wood with moisture content higher than 20 %, especially termites (Krishna and Weesner 1970). Termites, in particular subterranean termites (*Reticulitermes* ssp.), are the most dangerous insects for wooden buildings in temperate regions, for example, in Mediterranean Europe. Each year, subterranean termites cause over €700 million in damage, treatments and repair of damage to wooden structures in Europe (UNEP 2000). Termites can cause major damage to buildings in a relatively short time and may gain access to the interior of a building through cracks or construction joints, which are concealed from view (Ahmed and French 2008b), making it difficult to detect (Moreno et al. 2009). Additionally, in higher ranges of humidity, wood structures are also exposed to rot (Grosser 1985). This multiagent attack is a key reason for the lack of image of wood as construction material under Mediterranean conditions (Gutiérrez Oliva et al. 1984; Przewloka et al. 2007).

Termites prefer to attack humid wood, but in case of dry wood, they are able to transport water from the soil (Weidner 1970). On the other hand, the two influencing parameters on fungal biodegradation are temperature and moisture. In terms of temperature, the optimum growth rate of most decay fungi (Basidiomycota) is between 24 and 35 °C. Decay fungi require a wood moisture content of at least 20 % to sustain any growth and higher moisture contents (over 29 %) for initial spore germination (Weiss et al. 2000).

Preventive and remedial treatments are normally based on chemical products, mostly containing persistent organic pollutants. Monitoring of pests and circumstances that influence them is a key prerequisite for implementing IPM (Integrated Pest Management) strategies. The advantage of using IPM is sustainability by reducing dependence on (persistent) pesticides and damage to the environment (including natural enemies) and health is prevented. Termite pesticides can contaminate water systems and enter the food chain (Lewis 2001).

Visual inspection is the normal procedure to evaluate the biodegradation level in timber structures. Nevertheless, the detection of termite activity by routine visual inspection has to be considered as an unreliable method (French et al. 2010). Other detection methods are based on bait systems and acoustical technologies (Ahmed and French 2008b). Bait systems are efficient for the treatments, but need to be open to control and monitor the termite activity. This represents a high logistic and cost factor. Acoustic devices are useful for the detection in situ, but are unable to be used as a permanent monitoring factor due to the interferences on the ultrasound termite activity spectrum (Moreno et al. 2009).

Considering the limits of the actual detection methods, the high decay risks of wood structures especially in temperate regions and the need to implement IPM strategies, it has been considered necessary to develop an innovative wireless detection methodology for insects (especially termites) in the wood at an early stage as well as to relate the wood conditions in buildings (moisture content and temperature) to the entrance risk of the main wood-rotting fungi. To achieve this main goal, the operative objective of the research has been the development of a sensor that sends a wireless alarm with the indication of insect appearance inside the wood or with the warning signal that the conditions in the wood make it vulnerable to fungi settlement. This represents an important breakthrough in the field of non-destructive quality assessment and evaluation of timber structures. Furthermore, a wireless network of these biodegradation sensors can be installed in an entire house or building for automatic monitoring of wooden elements, both structural and decorative, forming an integral alarm system for wood degradation activity supported by an advanced remote sensing management system.

Materials and methods

Figure 1 shows a scheme of the multistep research approach to develop the advanced wireless detection sensor.

Preliminary development of sensors and testing material

The first methodological approach was to develop a preliminary sensor based on the principle of emission of light (LED—light emitting diode) and the recapture of the

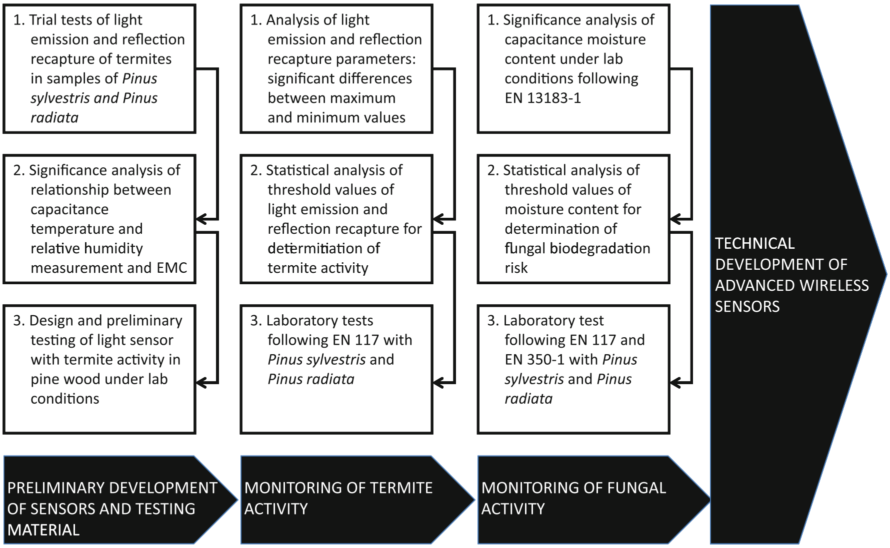

Fig. 1 Scheme of the multistep research approach to develop the advanced wireless sensor

reflection. Since the reflected light varies when it impinges on a termite, its detection is done when it interferes with the reflected light signals. Trial tests of light emission and reflection recapture of termites in samples of *Pinus sylvestris* and *Pinus radiata* were performed.

The sensor should calculate the risk of fungal infestation by measurement of the moisture content. To do so, the preliminary sensor included a temperature sensor and a relative humidity sensor for the air inside the wood. These two sensors are connected to the microcontroller, which includes a system for calculating the EMC of wood from the temperature and air humidity following the algorithm developed by Simpson (1998). A significance analysis of the relationship between capacitive and resistive measurements of wood moisture and EMC was performed.

The preliminary sensor was developed with all its electronic parts inside a dark wooden housing with cylindrical form (diameter = 27 mm, length = 41 mm) in order to be inserted inside the wood samples simulating the main entrance routes for the termites in the building (pillars or vertical elements with ground contact, beams or other elements close to moisture sources etc.). The hole was blocked up in order to prevent the entrance of direct air. The black colour of the open wooden housing allows the necessary light reflection of the LED emitter (Fig. 2).

Laboratory tests for termite activity analysis

Each sensor is endowed with a microcontroller connected to at least one insect detector; this insect detector comprises a LED emitter and a light detector connected to the microcontroller. The microcontroller generates an electrical signal proportional to the light reflected in the housing of the sensor, which varies depending on whether or not insects are present, and its exact value depends on the termite colour and size. The light emitter generates pulses during a previously first period of time, which is interrupted during a second period of time, likewise pre-established (e.g.

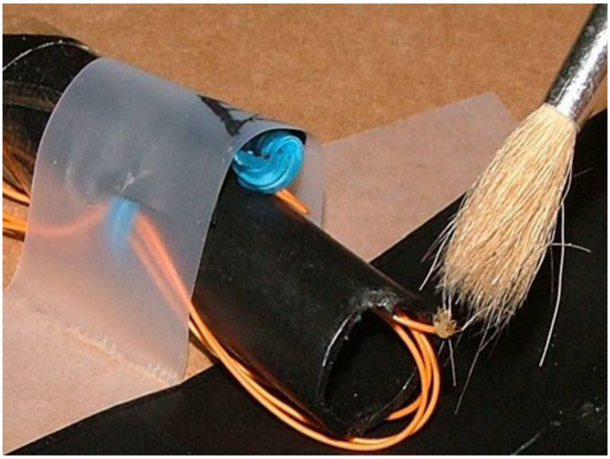

Fig. 2 Introduction of termites in the first sensor prototype

1 s), with the two periods being repeated sequentially. For a certain interval of time (e.g. 5 min), the microcontroller was programmed to detect the maximum and minimum value of the electric signal generated by the light detector, which corresponds to the maximum and minimum values of the reflected light in the housing of the sensor and then calculates the significant difference between the two values. A statistical analysis determines threshold values of light emission and reflection recapture.

The next laboratory test was the manual introduction of termite workers in the sensor prototype, in order to measure the LED interruptions by single termites. Additionally, according to EN 117 (2007) and the methodology described by Ahmed and French (2008a), the preliminary sensors were tested in termite colonies with constant substrate under controlled climatic conditions. Samples of *P. sylvestris* and *P. radiata* were pre-bored in order to facilitate termite entrance.

Laboratory tests for fungal infestation risk analysis

The preliminary sensors also included an air temperature and relative humidity capacitive sensor in order to calculate the EMC. To evaluate the accuracy of the moisture content measurement, a parallel test was carried out comparing the values obtained by the sensor with a calibrated GANN xylohygrometer and a laboratory test of the same samples following EN 13183-1 (2002).

The calculated wood moisture was compared with a threshold value stored in the microcontroller. The microcontroller had to generate an alarm when the moisture content of the wood exceeds the pre-defined threshold (e.g. >20 %).

Results and discussion

Monitoring of termite activity

The results of the laboratory tests show that the programmed threshold is exceeded when an insect interferes with the reflected light, that is, when the difference between the minimum and maximum values is highly significant. Then, a warning signal can be generated.

Figure 3 shows the interruptions of LED light by one termite within 1 h. Figure 4 shows an example of the termite activity detection data during a day measured with the sensor prototype. The results demonstrate that the microcontroller was able to detect individual termites as well as the movement of the testing colonies under laboratory conditions.

At certain intervals of time programmed in the sensor (between 24 h and 1 week), the microcontroller stores the arithmetic mean of the values of the electrical signal from the light detector during a period of time (e.g. 1 h) and then compares it to the arithmetic mean of the values obtained in several following periods in order to determine whether there are any significant differences between them. By updating these values and removing the old ones cyclically, this algorithm was able to act like a system of temperature and electronic noise compensation, so that the sensor does

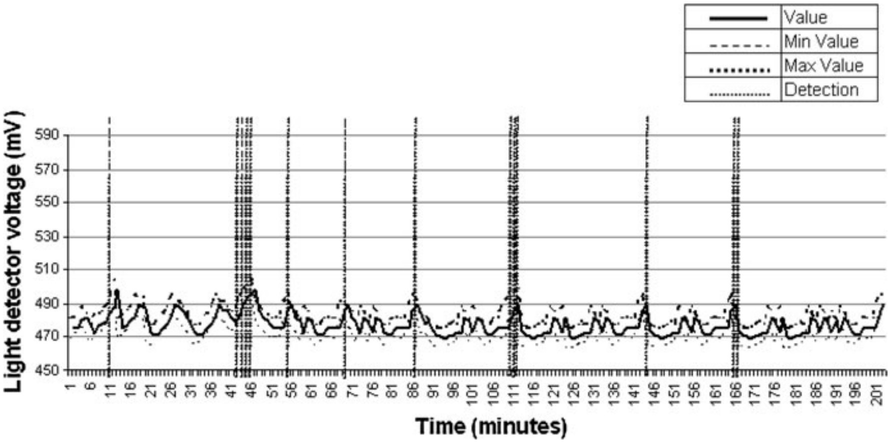

Fig. 3 Interruptions of LED light by one termite in the sensor prototype during 1 h

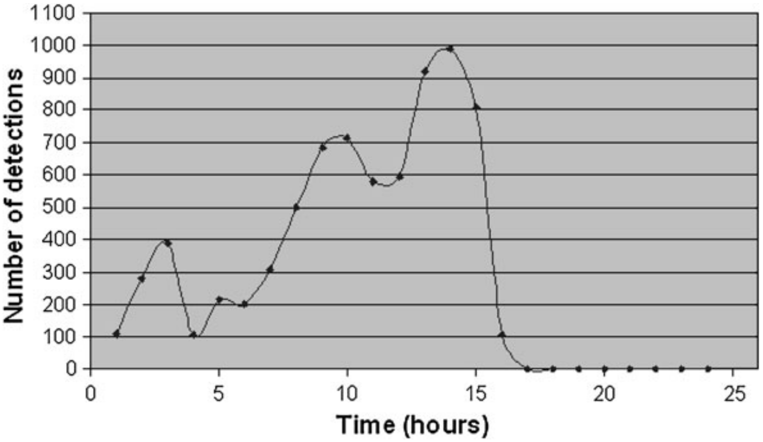

Fig. 4 Termite activity detection during a day with sensor prototype in termite colonies (50 workers + 5 soldiers, *Reticulitermes* spp.) in climatic chamber

not need any initial tuning. Thus, the sensor is expected to be insensitive to the ageing of the electronic parts, to small dust or dirt accumulations in the light emitter or in the light detector, to thermal drift and to electronic noise.

Figure 5 shows the results of an example of measurement sequences with significant differences. In case of significant differences, the microcontroller generates a signal indicating that a malfunction has occurred between two periods of time, such as, for example, the power supply battery has run out or there is an accumulation of residues between the light emitter and detector. It is crucial that any accumulation of residues can be detected, because termites build mud trails in order to gain access to the interior of a building. Under laboratory conditions, it was observed that the termite colonies have not only entered the sensor after few hours;

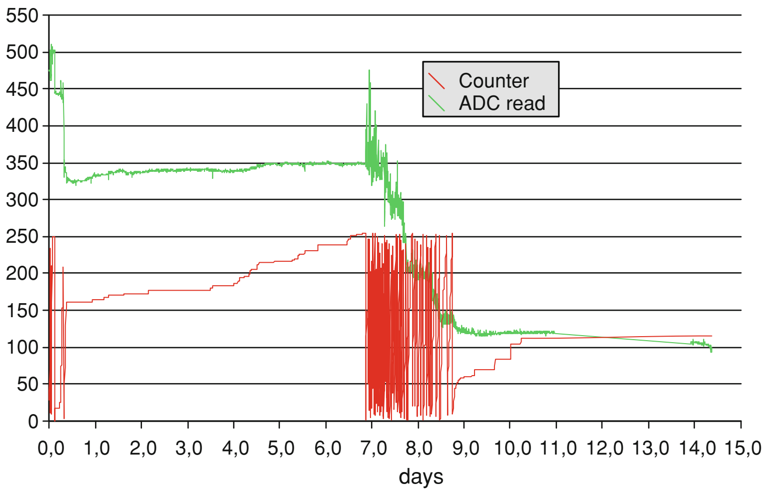

Fig. 5 Example of LED light signal conversion in mV (*top curve*) and number of termite detections (*bottom curve*) with final sensor during a measurement sequence of 15 days

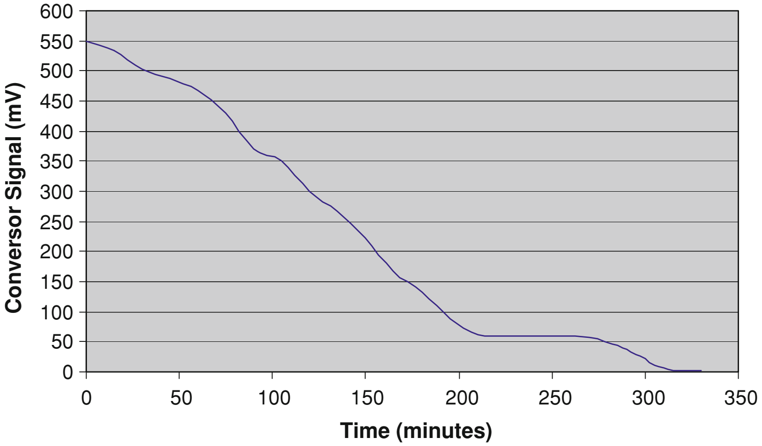

Fig. 6 Example of signal reduction of the light convertor during the building period of the mud trail in the final sensor

moreover, they have built mud trails into the sensors in order to block the LED emitter. Figure 6 shows the process of shadowing the light emission and reception during the building period of the mud trail in the sensor. It can be assumed that the light impulses disturb the biological cycles in the colony. In fact, the termite workers react rapidly creating mud trials in the sensor to block the light impulses. In consequence, the light emission has acted as an additional attraction source for the termites and not as a barrier.

Monitoring of fungal infestation risk

As the sensor comprises an air temperature sensor, the date on the wood moisture content is complemented by the temperature, which allows the microcontroller not to send alarms signals unnecessarily when the moisture content is right for wood-rotting fungi, but the temperature is too high (>49 °C) or low for their development (<1 °C). This is especially important for outdoor use of the sensors. Additionally, the means for determining the wood moisture content starting from the temperature and relative humidity of the air comprise conversion tables for different types of wood. These tables are based on the principle that under stable conditions (like the sensor inserted inside wood and the hole blocked up), wood tends towards the EMC, which is related to the temperature and relative humidity of the air around the wooden element (Simpson 1998).

The first results have shown that the measurement of the wood moisture through the temperature and air humidity sensors is extremely accurate. The simple linear regression analysis demonstrates the high correlation as well as non-systematic deviation between the measurements methods (Fig. 7). Consequently, measurement of the wood moisture content through the calculated EMC is perfectly viable for the sensors. Nevertheless, individual programming of the moisture thresholds for each sensor depending on the individual conditions (outdoor or indoor, contact with soil, etc.) is necessary.

Technical development of advanced wireless sensors

Following the results obtained for the termite detection and the moisture content, the final sensor was designed and constructed including following electronic components: LED emitter, light detector, microcontroller, temperature and air humidity sensor and RF antenna. These components were integrated in a black wooden

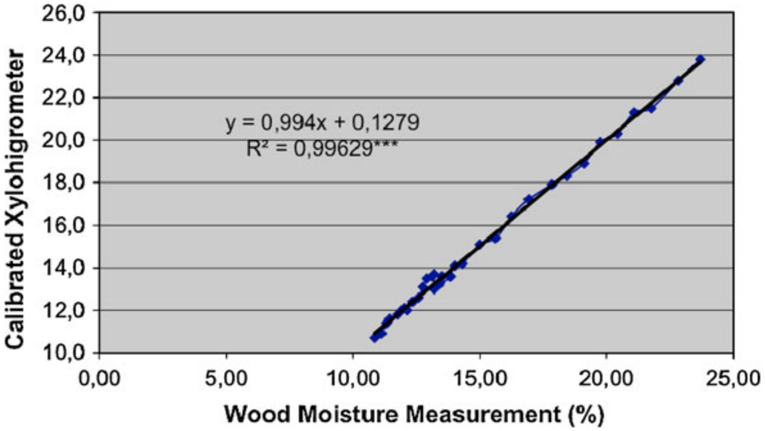

Fig. 7 Linear regression analysis between wood moisture measured by final sensor and wood moisture measured by a calibrated xylohygrometer

capsule with water-soluble paint to avoid possible termite repellence and to insert it in wood structural elements (Fig. 8).

Real tests in wooden constructions

After the laboratory tests, the sensors were tested in three real wood-based structures: the archive of the Cathedral of Valencia (Spain), as an example of cultural heritage with documented termite and rot damages during the last years, a 3-storeyed house with timber structural elements in the centre of Sueca (Spain) with current high termite activity and a single-family wooden house in Caudiel (Spain) with high risk of termite and fungi attack. These three examples were chosen in order to test and monitor the main wood-based building objects in the Mediterranean region. The sensors were installed in the main entrance points of both termite and fungi: base of pillars with ground contact, heads of beams on masonry walls, base of door and window frames, wood elements close to moisture sources or outdoor etc. The system has been working successfully since June 2009.

Wireless network

In order to manage the developed sensors, an integral wireless remote sensing system was developed. The alarm signals generated by the microcontroller are sent by radio frequency to a base station using a RF microantenna. This base station includes GSM module, GSM antenna, radio modem module connected to an ISM antenna as well as a microcontroller programmed to process alarm signals to be sent as SMS to a cellular telephone number. The radio modem and its antenna receive the RF alarm signals from the sensors and pass them to the microcontroller. Each base station can monitor up to 255 sensors. The maximum radius between the base station and the sensors are approx. 200 m without metal barriers. The source code

Fig. 8 Insertion of the sensor in the wood. The sensor is inside an open black-painted wooden housing to allow light reflection and entrance of termite workers

used by the microcontroller for managing the GSM module was developed through the subset of mandatory AT commands for the GSM 07.05 and GSM 07.07 standards. After processing an alarm signal, the base station sends a SMS over the GMS network with the following information: (a) the number of the sensor; (b) the number of the base station; (c) moisture content of wood; and (d) type of alarm (wood moisture content, insect detection, malfunctioning). The SMS are received by a cellular telephone connected to a remote PC, which acts as an alarm central: it processes the SMS and shows their data by means of a program with a graphical user interface.

Integral alarm system and remote sensing management

The information of the sensors is collected in a remote PC that acts as a remote sensing management unit as well as an alarm central. The management system allows the identification and positioning of each individual sensor in the building as well as the programming of individual moisture content and termite activity thresholds and alarm limits. It is also possible to control the battery level of each sensor and the overall functioning of each network. The alarm central processes the data from all sensors and shows them by means of a graphical user interface. Simple alarm e-mails indicating the sensor, alarm reason, possible causes and indicative possible solutions are sent automatically to both alarm manager and end-user.

Conclusions

The sensors developed are the result of a multidisciplinary research work developed during the last four years at AIDIMA and the Polytechnic University of Valencia integrating scientific and technical knowledge in very different fields like wood technology, wood durability, entomology and microbiology, architecture, electronics and telecommunication technologies.

The first conclusion is that the emission and recapture of light reflection is a very good quantitative parameter to detect termite activity in wood products. The results obtained of the different tests and the consequent adaptation of the sensor design and construction allow using this parameter to identify frequency and intensity of termite infestation.

Moreover, the capacitive measurement of temperature and relative humidity is also a very accurate technology to monitor moisture content changes in wood structures by calculating EMC and consequently fungal infestation risk.

The developed integral monitoring system based on the obtained research approach represents a radical innovation breakthrough beyond the state of the current technology. So, the sensor:

(a) has no moving parts, what increases its reliability,
(b) does not rely on the insects having to eat through the material,
(c) can be electronically monitored continuously by means of wireless data transfer,

(d) is able to detect risks for fungal decay by relating the wood conditions (moisture content and temperature) to the rotting conditions,
(e) is suitable for indoor or outdoor use,
(f) is small and compact and easy to install and maintain,
(g) can be installed in termite bait treatments in order to monitor them and to control the number of termites feeding without opening them from time to time,
(h) allows for additional integration of parameters that indicate wood degradation at an early stage (e.g. discolouration, mass loss, CO_2 emission, pH, ultra-sound etc.), opening up a highly innovative research area that will be intensively followed during the next years.

Finally, the combination of networks of wireless sensors, base stations and remote PC with alarm central software allows the development of an integral alarm system for wood degradation. This is also a radical innovation in the field of detection of wood decay and it provides the possibility to continuously monitor the conditions of the wood in buildings and homes. The results of the research approach demonstrate that the system is applicable to detect biodegradation of wood, primarily in the wood-based building sector both for structural elements (beams, trusses, rafters, ribs, pillars, stairs, etc.) as well as for non-structural elements (doors, wooden flooring, windows, furniture or ornamental wood pieces, etc.). Due to the possibility to detect biodegradation risk, this innovative technology can prevent future costs of repairing or replacing wooden elements, as well as the application of cost-intensive remedial chemical treatments with negative environment and health impacts contributing to improve the lack of image and confidence of technical prescription and consumption in wood as a competitive and sustainable construction material.

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