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ORIGINAL ARTICLE

Non-audible acoustic emission characterization of *Reticulitermes* termites in pine wood

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Abstract

This research evaluates and characterizes the acoustic emission activity generated by *Reticulitermes* termites as recorded by piezoelectric sensors with sensitivity in the ultrasound range (greater than 20 kHz). To this end, the acoustic emission activity was recorded under controlled conditions of temperature and moisture content in three pine wood samples in which termites were artificially inoculated: only soldiers, only workers, or a colony of workers and soldiers. Different traditional parameters of the acoustic emission signals were analyzed, in both the time and frequency domains. This study proved feasible to use acoustic emission to detect the activity of this kind of termites, although it was not possible to distinguish between workers and soldiers. It is also demonstrated that, by using several sensors, one can locate the activity of the insects, a finding of great practical interest for the accurate detection of colonies in real buildings.

1 Introduction

Wood is widely grown and used as building construction material. However, wood-based material reportedly has low durability because of wood-decaying insects, especially termites (Kozlov and Kisternaya 2014; Sugio et al. 2018; El-Hadad and Brodie 2019). The global economic impact of termites amounts to an estimated US$ 50 billion annually, and US$ 32 billion for control and damage repair (Kuswanto et al. 2015; Subekti et al. 2015; El-Hadad and Brodie 2019). The building construction is among the most affected sectors, as a termite colony tends to structurally compromise the integrity of a building, resulting in permanent damage and loss of value (Ghaly and Edwards 2011; Oi 2022).

Altogether, 79 termite species are considered as pests, responsible for about 80% of the total impact (Rust and Su 2012). Subterranean termites (*Reticulitermes* ssp.) are the most destructive insects for wooden buildings in warm regions, for example in Mediterranean Europe (Alcaide et al. 2010; Gaju-Ricart et al. 2015, 2018). Several national or international standards classify the subterranean termite problem as a municipality-wide issue, urging the establishment of protocols and mechanisms to provide a global solution to the pest.

Therefore, early detection of termites is an absolutely essential strategy to control their activity and substantially reduce the cost involved (Ahmed and French 2008; Ghaly and Edwards 2011; El-Hadad and Brodie 2019). Environmental laws are meanwhile becoming more restrictive regarding termiticides because of the health hazard they may represent.

Detecting xylophages largely relies on visual inspection to spot the tunnels they form, or check by hitting that no hollow sound is produced (Llana et al. 2020). These procedures, in addition to being subjective and imprecise, have the drawback of not distinguishing whether the galleries are from current or past activity (Oi 2022). Visual inspection is very time-consuming and can only be carried out on the accessible faces of the beam, not hidden by other materials. It must be emphasized that only about 25% of a building structure is accessible. Thus, new techniques have been developed to improve accessibility. Acoustic methods have

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emerged as one alternative (Gonzalez de la Rosa et al. 2005; Bertolin et al. 2020).

Some research has evaluated termite activity in the audible range, but it may also record environmental noise not coming from the activity of the xylophages (Fuchikawa et al. 2012; Llana et al. 2020). The acoustic emission (AE) method, analyzing signals recorded by piezoelectric sensors at frequencies higher than 20 kHz, in the non-audible range, has proven to be effective in relating an acoustic source generated by variations in the stress field of a material (Grosse and Ohtsu 2008; Martínez-Jequier et al. 2015; Mizutani 2016; Rescalvo et al. 2018a; Nasir et al. 2022).

Among other applications, AE has been found to be a useful technique for the inspection of wood structures and the determination of termite activity (Lemaster et al. 1997; Fujii et al. 1990; Gonzalez de la Rosa et al. 2005, 2006; Indrayani et al. 2007). The activity of xylophages—their feeding in the wood, their movements and their beating to communicate—generates very small variations in the stress field of the wood. These elastic wave sources of acoustic emission can reach the sensor placed on the surface, be converted into electrical signals, and finally be analyzed. Some research has explored variations in termite activity along with changes in humidity and temperature (Indrayani et al. 2003, 2007). Other studies had evaluated termite activity over a year under specific environmental conditions (Fuchikawa et al. 2012). Further authors reported on basic AE parameters such as the number of events and counts, without analyzing the signals individually in either the time or frequency domain (Indrayani et al. 2007; Lewis et al. 2011). Several studies had also distinguished the signals of worker termites caused by feeding-excavating and the beating of heads against wood produced by soldier termites, but at frequencies below 22 kHz, assigning the higher amplitude signals to soldier termites (Gonzalez de la Rosa et al. 2005, 2006, 2015).

This paper focuses on analyzing the acoustic emission activity generated by *Reticulitermes* spp. termites inoculated in pine wood samples. First, signals not coming from termite activity were characterized in order to adequately filter noisy signals. The signals from soldier and worker termites were recorded separately, and finally, a colony with both soldier and worker termites was analyzed.

2 Materials and methods

2.1 Material description

All tests were carried out on a solid wood sample of the species *Pinus nigra* with dimensions of 225 × 60 × 40 mm, in which subterranean termites *Reticulitermes grassei* Clèment, 1977—considered the most frequent termite genus in peninsular Spain (Gaju-Ricart et al. 2002, 2018)—were artificially inoculated.

Termites are insects with hemimetabolous development characterized by incomplete metamorphosis. They are considered eusocial insects, living in colonies with a close relationship among individuals (Laine and Wright 2003). Part of the evolutionary success of termites owes to the functioning of the termite mound as a super-organism where everyone collaborates in its survival. Basically, three castes are distinguished: primary reproductive (originated from nymphs with wing buds), workers, and soldiers, each having unique characteristics (Gaju-Ricart et al. 2015). In the present work, a distinction is made between soldiers and workers (Fig. 1). Soldier termites have a hypertrophied head, larger than that of workers, and highly developed jaws that they use to defend the colony. The soldiers, however, cannot feed themselves because of the size of their jaws. The worker termites represent a persistence of the juvenile state, having the appearance of nymphs that have not developed wing buds. The most significant characteristic of both soldiers and workers is that they lack eyes and body pigment. Only the soldier head is yellowish in color, because it is more chitinized. Eusociability entails the care by the workers of the rest of the individuals in the colony, to whom they transfer predigested food (trophallaxis). They also carry out the cleaning of the termite mound to avoid diseases, as well as body cleaning (grooming), among workers and the other members of the colony. The individuals of each colony can be identified through a mixture of cuticular hydrocarbons, which in addition to offering them protection by waterproofing their bodies to prevent water loss, serve to distinguish them from termites belonging to other colonies. Recognition is achieved when two termites touch each other's antennae.

Four different tests were carried out: in test 1, only wood without termites was analyzed; in test 2, only soldier termites were inoculated; in test 3, only worker termites were inoculated; and in test 4, both soldier and worker termites were inoculated, as detailed in "Description of the tests". In

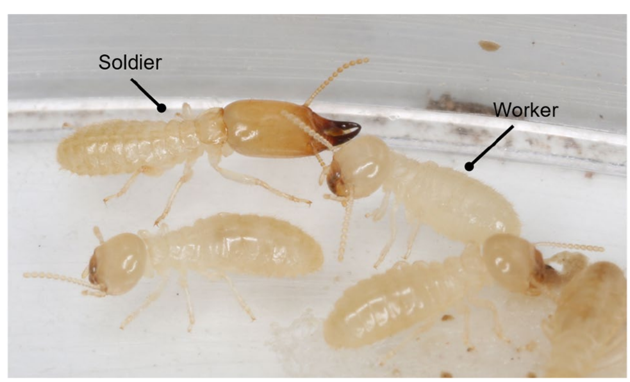

Fig. 1 Types of termites *Reticulitermes* spp.

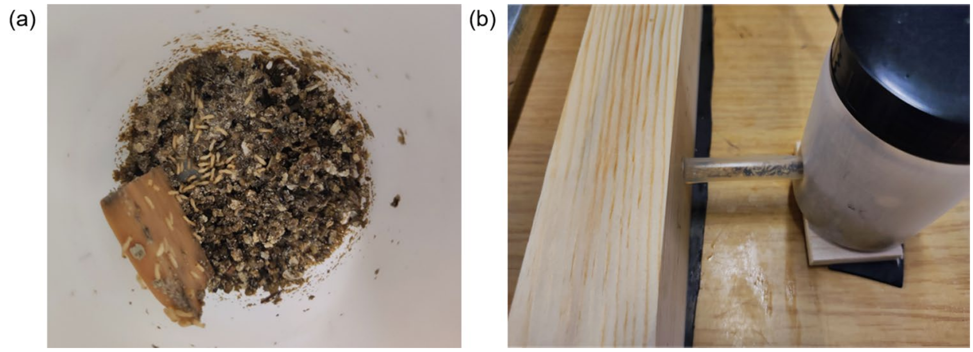

Fig. 2 **a** Colony of soldier and worker termites to be inoculated; **b** connection made between the termite colony and the wood sample for natural termite inoculation

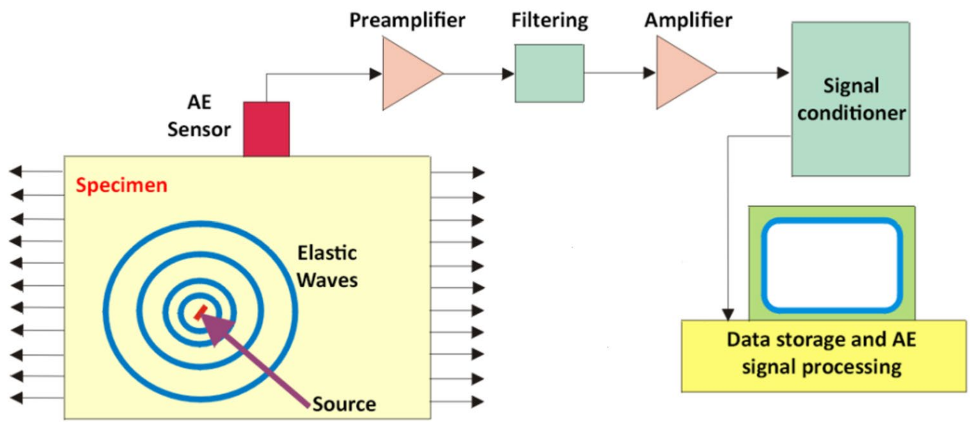

Fig. 3 Depiction of the acoustic emission method and instrumentation (Rescalvo et al. 2018b)

the tests where only one type of termite was studied, inoculation was done manually. The termite type was selected and introduced into a perforation previously made in the sample with the help of tweezers. In test 4, inoculation occurred naturally. Initially, the termites were placed in a plastic container with a quantity of moistened substrate and a small amount of wood from the same sample to ensure food for the termites (Fig. 2a). This container was connected to the wooden test sample by means of a tube. From the container, the termites freely reach the wood sample at the inoculation point (Fig. 2b).

During all the tests, an attempt was made to guarantee the survival of the termites, ensuring protection from light, ventilation, a temperature of 26 ± 2 °C, and a moisture content greater than 70 ± 5%.

2.2 AE monitoring

Acoustic emission (AE) testing is an effective and passive NDT (non-destructive testing) method for monitoring the behavior of materials or structures subjected to a change in the strain field. The generated elastic wave propagates through the material until it reaches the surface, where it can be captured by a piezoelectric sensor. The scheme of the method and the instrumentation used are shown in Fig. 3.

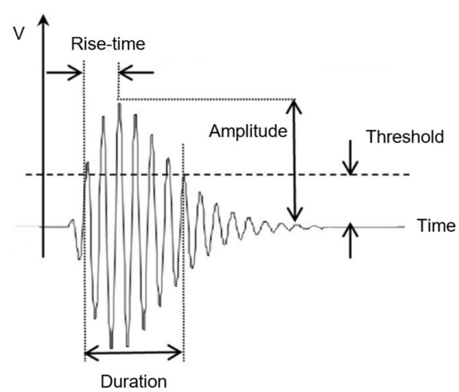

Fig. 4 Typical AE transient signal. Definition of amplitude, threshold, duration and rise-time. V: Voltage (Cruz et al. 2022)

Transient acoustic emission signals can be generically characterized as shown in Fig. 4. The traditional characteristics of these signals are the peak amplitude (A, dB), defined as the voltage of the transient; the duration (D, µs) defined by the time interval between the first and the last time the signal crosses the detection threshold; and the rise-time (RT, µs) defined as the interval of time between the first threshold crossing and the maximum amplitude. The threshold is established by the user and must be higher than

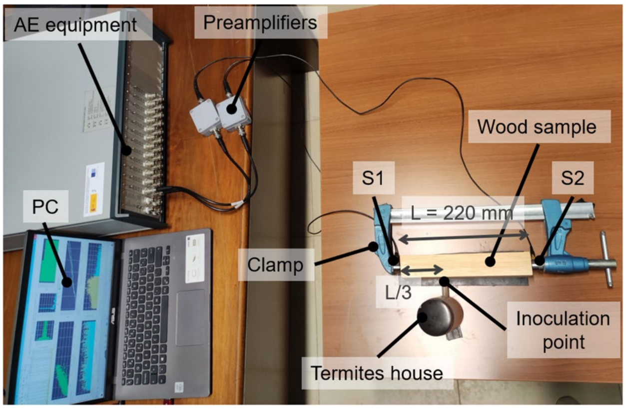

Fig. 5 Scheme of the test and acoustic emission sensors (S1 and S2)

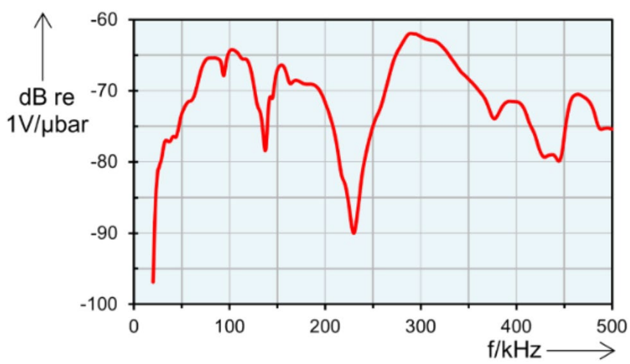

Fig. 6 Frequency response of *Vallen Systeme*® *VS45* sensors used in the tests

the background electromagnetic noise existing at the measurement place.

All tests were monitored by means of acoustic emission using Vallen Systeme® AMSY-6 equipment and two Vallen Systeme® VS45 piezoelectric multiresonant sensors placed on the extreme faces of the specimen, as shown in Fig. 5. The frequency response of the sensors used is shown in Fig. 6. The sensors were placed on a silicone grease base to ensure proper transmission of the acoustic waves between the wood and the sensor. In addition, a clamp was placed to ensure that the sensor-sample coupling remained stable throughout the duration of the test and to minimize the transmission of possible mechanical noise from the ground. A 30.1 dB threshold, 5 MHz sampling frequency, 34 dB preamplification and [95, 580] kHz digital input filters were used for the acquisition.

After mounting the sensors, installation of the AE instrumentation, the two sensors and the two acquisition channels were verified by mine breaks (PLBs, 0.5 mm 2H leads), i.e. standardized Hsu-Nielsen source. It was also verified that there was no background noise in the laboratory. After these verifications and before the inoculation of the termites, the AE activity was recorded in each of the samples, confirming that no AE activity was recorded or that it was insignificant and comparable to the results obtained in the specimen without termites.

2.3 Description of the tests

The four tests carried out and monitored with acoustic emission (Fig. 5) are detailed as follows.

Test 1: Wood without termites, used as a control, to characterize the acoustic emission associated with possible sources of background noise. This test lasted 18 h.

Test 2: Wood with soldier termites. Three soldier termites were inoculated into a 2.05 mm diameter and 15 mm deep borehole, at a distance of L/3 from the position of sensor S1. The small-diameter borehole was drilled to allow the head-banging activity of the soldiers in the gallery. The objective was to characterize the acoustic emission of this type of termite individually, as a control measure. The test was conducted for 5.5 h, because each type of termite not living in a colony has a limited life span.

Test 3: Wood with worker termites. Ten worker termites were inoculated in a 3 mm diameter and 15 mm deep borehole, at a distance of L/3 with respect to sensor S1. Likewise, the objective was to individually characterize the acoustic emission of this type of termite, as a control measure. The test was carried out for 10 h.

Test 4: Wood with soldier and worker termites. Two hundred workers and five soldiers were inoculated into a 5 mm diameter and 20 mm deep borehole, located at a distance of L/3 from S1. The aim was to monitor the acoustic emission associated with the simultaneous action of both types of termites. This test lasted 66 h.

3 Results

3.1 Propagation velocity

First, measurements were taken to determine the propagation velocity of the acoustic waves in the wood sample. For this purpose, 5 PLBs were performed on the wood sample without termites at the same point where the termite inoculation would occur. The wave propagation velocity can be determined by taking the difference between the arrival times at each sensor and the distance between the inoculation point and each sensor. The mean value obtained for the 5 PLBs was 470 ± 17 cm/ms. Figure 7 shows an example of the acoustic emission signal recorded during the test and the frequency response of the first 25 µs of signal, with a peak at 127 kHz, coinciding with the first resonance frequency of the sensor.

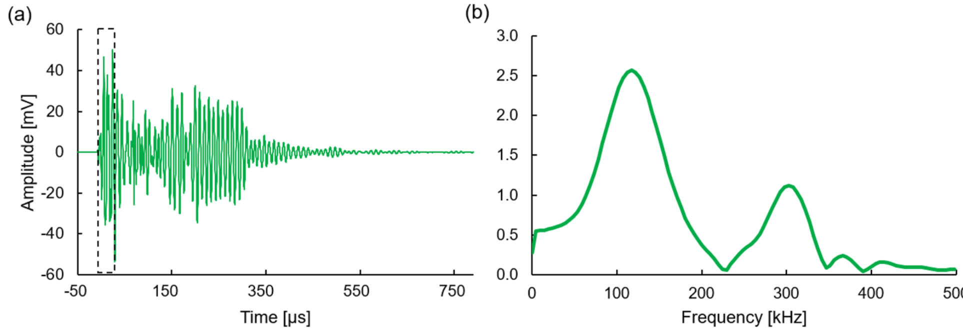

Fig. 7 Acoustic emission signal recorded in the test to determine propagation velocity. **a** Transient signal; **b** frequency spectrum

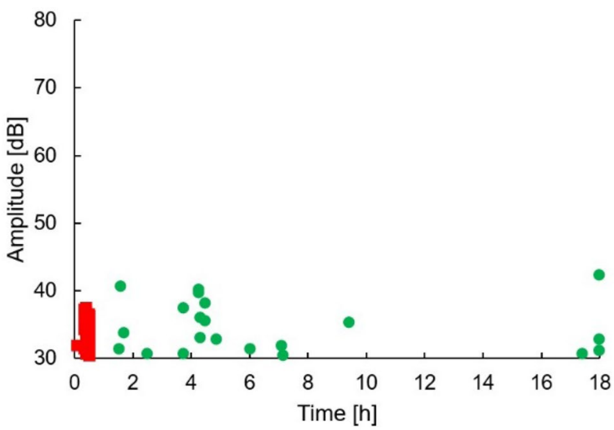

Fig. 8 Amplitude of the signals recorded during Test 1 as a function of time. Red square symbols: signals concentrated in time, of electromagnetic origin (Color figure online)

3.2 Test 1: Wood without termites

During Test 1 a cluster of several signals concentrated in time was observed, as shown in Fig. 8 and marked as red square symbols. Figure 9 shows an example of these signals and their frequency spectrum. As can be observed, these signals have a very small duration and rise-time, which suggests that they were related to electromagnetic noise generated in the room or by the acquisition equipment. Because of their well-defined characteristics, it was possible to apply filtering to remove them automatically. Figure 10 shows the plot of rise-time versus duration and peak amplitude versus duration for all recorded signals. A polygonal filter (Fig. 10a) defined by D < 9 µs and RT < 5 µs was used to remove the signals identified with a red square. Signals within this polygon were automatically removed for subsequent analysis.

The remaining signals that passed this filter have the shape seen in Fig. 11 (signal in time and its spectrum). These

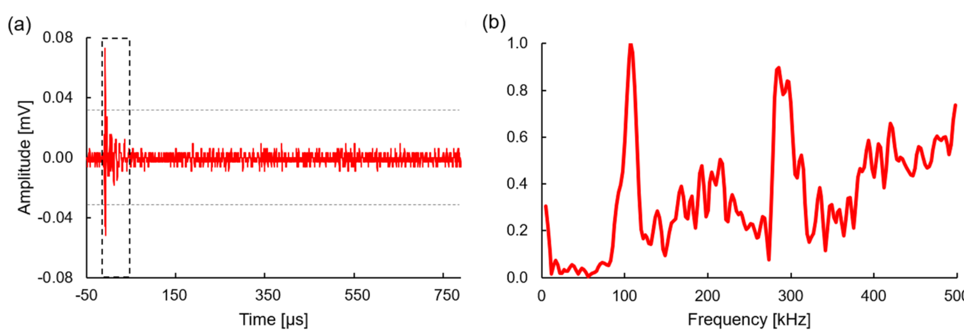

Fig. 9 Acoustic emission signal recorded in test 1, filtered and removed for further analysis. **a** Transient signal; **b** frequency spectrum

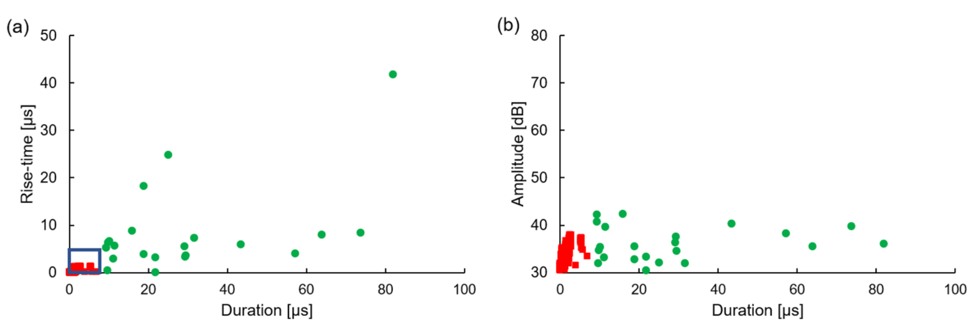

Fig. 10 Test 1: wood without termites. **a** Rise-time vs duration; **b** amplitude vs duration. Red square symbol: filtered signals (Color figure online)

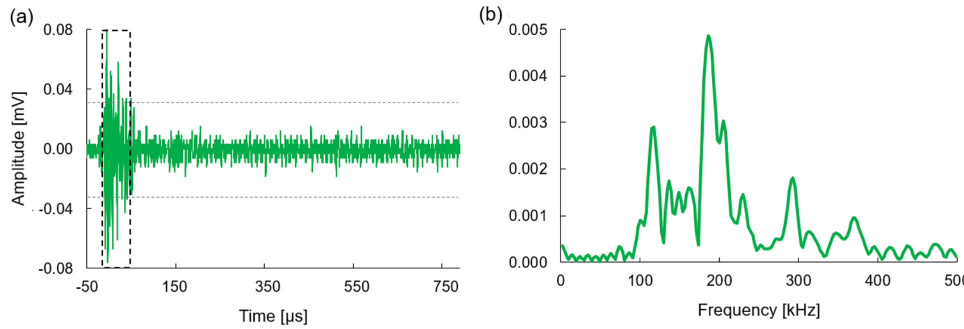

Fig. 11 Acoustic emission signal recorded in test 1, not filtered or considered in the analysis. **a** Transient signal; **b** frequency spectrum

signals exhibit wide variation in their main characteristics of duration and rise-time, but have similar amplitudes, as seen in Fig. 10. Owing to this, it was impossible to characterize them and establish a filter that automatically eliminated all of them. However, the activity of these signals was very low, 1.2 signals per hour. Therefore, their presence does not significantly affect the tests with termites. These signals were probably generated by spurious mechanical activity during acquisition, which was impossible to determine, due to its inaudible nature.

3.3 Samples with termites

Figure 12 offers the plots of amplitude and number of events versus time, peak amplitude versus duration, peak amplitude versus rise-time, and rise-time versus duration of the signals recorded in each of the three termite tests. That is, soldiers only (test 2), workers only (test 3) and soldiers and workers (test 4), respectively. In these three tests, the polygonal D-RT filter defined for the test without termites was applied automatically. It is clearly seen that the number of signals (AE activity) recorded in the test with soldiers and workers (third column) is considerably higher, due to the longer test duration and the higher number of inoculated termites. It should be noted that the activity recorded in the test with soldiers and workers is mainly associated with the workers, found in greater proportion: 200 workers as compared to 5 soldiers. In all three tests, the signals are grouped in a single cluster of the amplitude-duration graph.

Figure 13 shows the activity recorded in test 4 with soldier termites and workers over a 24-h period. As seen, the activity is not constant throughout the day; a cyclic activity was observed, with periods of higher and lower activity having a periodicity between 20 min and 1 h. In addition, the highest activity was detected at night.

Observing the activity of worker and soldier termites, no relevant differences were found in terms of amplitude, duration or rise-time characteristics that could differentiate between the signals generated by each. The acoustic activity generated by a soldier is due to the beating of its head against the wood, whereas that generated by a worker is due to the feeding-excavating process (Eggleton and Tayasu 2001; Evans et al. 2005; Lehrer 2013). Figures 14 and 15 respectively show transient signals and their frequency spectrum generated by a soldier during test 2 and by a worker during test 3. It can be observed that the signals are similar in both the time and frequency domains, which made it impossible to discriminate them.

In test 4, with soldiers and workers, two clusters of signals are seen in the amplitude-rise time graph (Fig. 12). Cluster 1 accumulates the largest number of signals, corresponding to a rise-time of below 100 μs and higher amplitudes. Cluster 2, with rise-time even higher than 400 μs and lower amplitudes than the first one, corresponds mostly to cascade signals, probably due to several termites generating noise simultaneously. Figure 16 shows an example of a transient signal corresponding to each cluster.

Using the previously measured propagation velocity, a linear localization of the signals recorded in the three tests with termites was performed. The results are shown in Fig. 17. The distance at which the termites were inoculated, 7.5 cm from sensor 1, is indicated by a dashed line. The distribution of located AE activity along the sample is shown with a solid line. As can be seen, in the test with soldiers, both the maximum activity and the maximum intensity (amplitude) were located right at the inoculation point. In the test with worker termites, the maximum intensity of acoustic emission was concentrated very close to the inoculation point, although the distribution of activity registered its maximum slightly shifted towards sensor S1. In the test with termites and workers, the maximum intensity of acoustic emission was also concentrated very close to the inoculation point, although the activity distribution recorded its maximum slightly shifted towards sensor S1, similarly to the test with worker termites. In addition, the located activity was 260 times higher than in the other tests, owing to the longer duration of the test and the larger number of termites. It is noteworthy that there are signals with very high amplitudes of almost 80 dB.

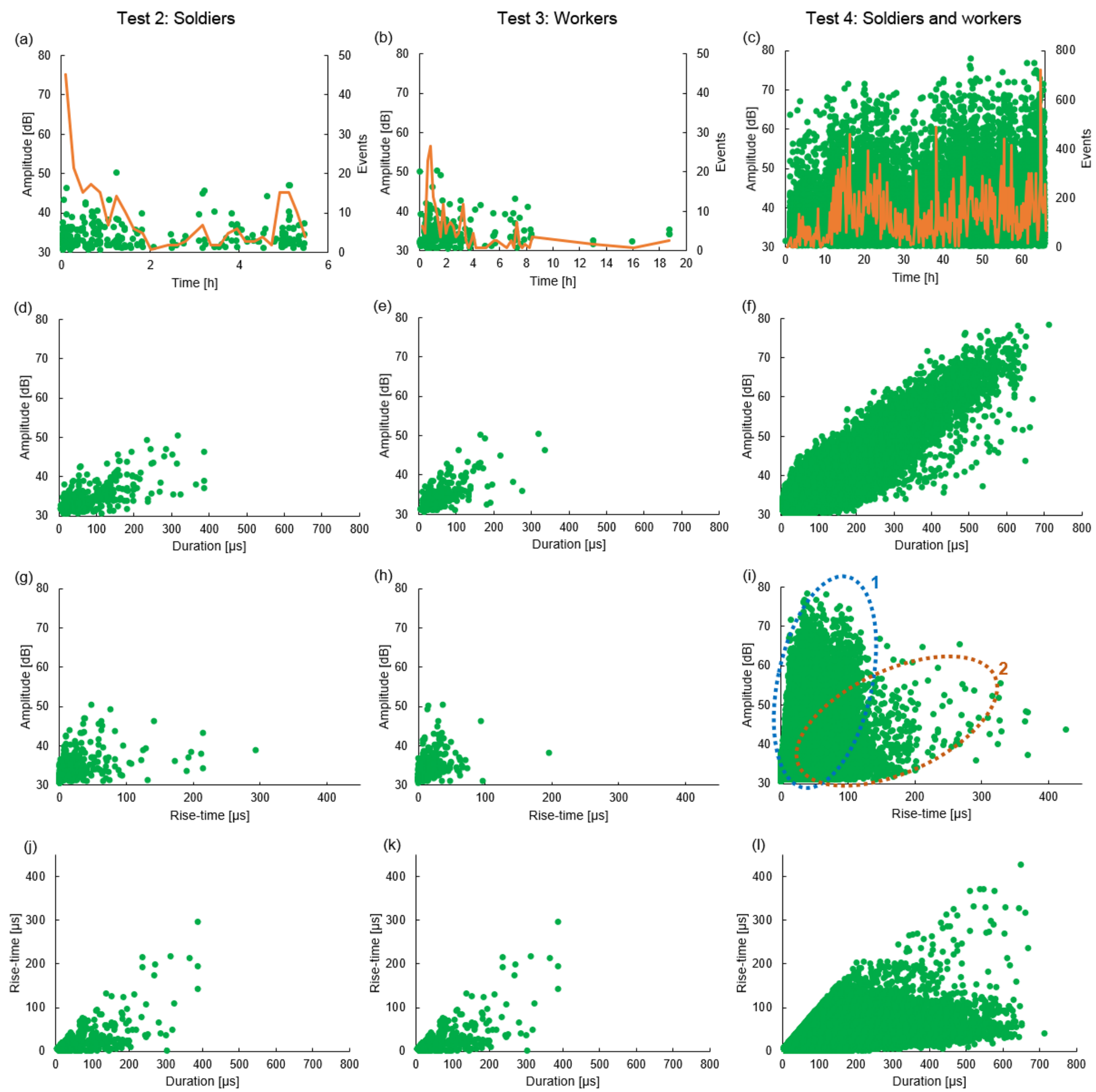

Fig. 12 1st row: amplitude and events vs time; 2nd row: amplitude vs duration; 3rd row: amplitude vs rise-time; 4th row: rise-time vs duration. 1st column: test 2: workers. 2nd column: test 3: soldiers. 3rd column: test 4: soldiers and workers

4 Discussion

According to the results shown, it is possible to identify acoustic emission signals in the range of ultrasonic frequencies generated by the activity of *Reticulitermes* termites, both workers and soldiers. A main advantage of AE testing with respect to other NDT methods is its ability to detect AE signals in real time, which makes it a highly effective alternative for termite detection, even at very early stages of infestation.

The termites activity, as expected, is not constant over time, even when temperature and moisture content are stable. A previous study reports changes in the daytime activity of *Incisitermes minor* (Hagen), Westerm drywood termite, but it is concluded that they are related to temperature changes (Lewis et al. 2011). Because the present study was carried out under controlled conditions (moisture, temperature), variations in activity are not associated with environmental changes.

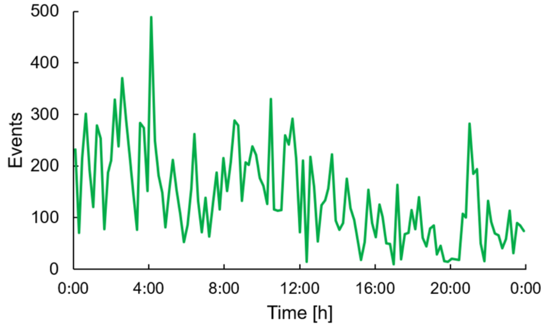

Fig. 13 AE activity distribution recorded in test 4 with soldier and worker termites during 24 h

The characteristics of the recorded wave are affected by the distance between sensor and source, and by the direction of wave propagation according to the orientation of the wood grain. It is well known that the wave suffers more attenuation in the tangential and radial directions, therefore, the highest amplitudes are obtained in the longitudinal direction (Kawamoto 2002). In addition, the greater the distance between the AE source and the sensor, the greater the attenuation and distortion of the recorded wave compared to the initial wave. The position of the sensors in the test setup had been chosen to record the longitudinal propagation of the wave, in which the attenuation is lower. Moreover, the dimensions of the test specimens were restricted to minimize the influence

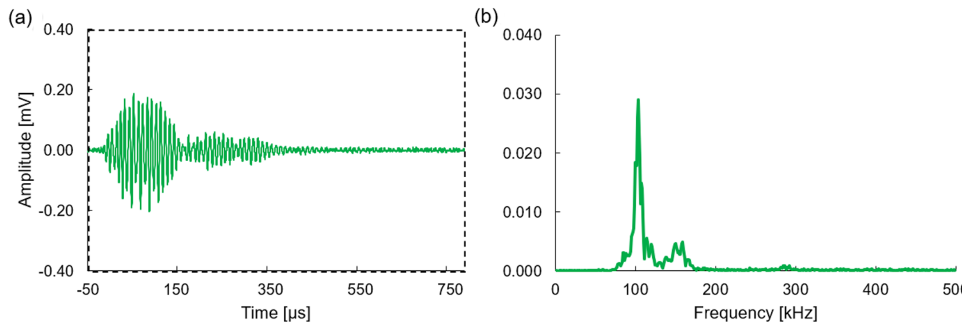

Fig. 14 Example of transient signal recorded in test 2 (soldier termites only) and its frequency spectrum

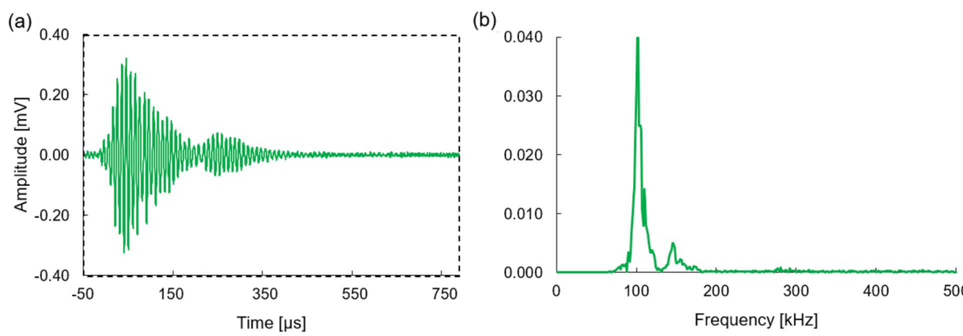

Fig. 15 Example of transient signal recorded in test 3 (worker termites only) and its frequency spectrum

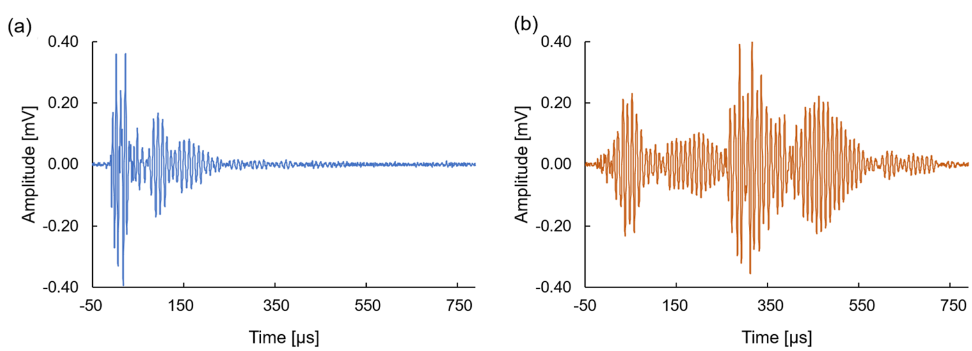

Fig. 16 Example of transient signal recorded in test 4 (with soldier and worker termites). **a** Signal from Cluster 1; **b** signal from Cluster 2. Cluster 1 and 2 are indicated in Fig. 12

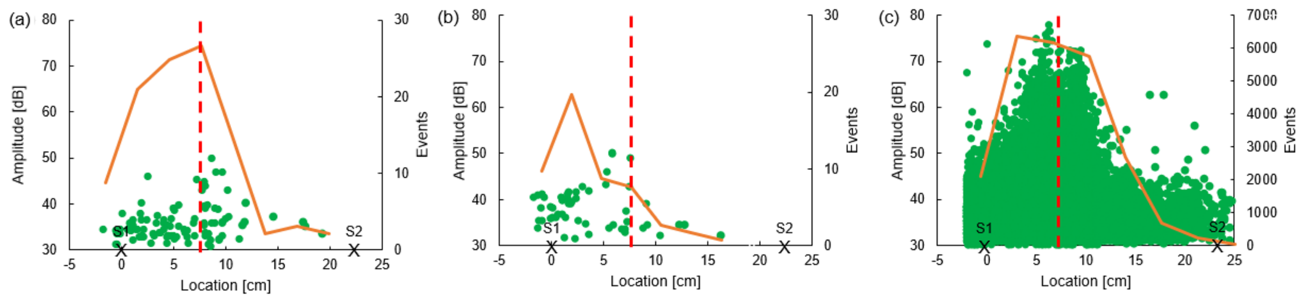

Fig. 17 Located events along the sample. **a** Test 2: only soldier termites; **b** test 3: only worker termites; **c** test 4: soldier and worker termites. Dashed line: point of termite inoculation

of distance. Furthermore, the presence of wood defects, such as knots, resin pockets, cracks or discontinuous interfaces within the wood could induce wave scattering (Wang et al. 2021). In order to minimize the impact of wave scattering induced by defects, specimens without defects were selected.

It is shown that as the number of inoculated termites increases, and especially when in a eusocial realm, the acoustic emission activity increases, as do the duration and amplitude of the recorded signals.

Previous works have evaluated the AE produced by termites in various types of wood, but no research has been found on pine wood samples with *Reticulitermes* termites and in a range of ultrasound frequencies. One study was carried out on pine samples of similar dimensions, but with *Coptotermes Curvignathus* termites and in an audible frequency range (Nanda et al. 2018b).

According to our findings, there are no relevant differences between signals coming from workers and those from soldiers—neither in the time nor in the frequency domain—that would allow them to be distinguished. Previous authors report that the acoustic signals generated by soldier termites and workers can be discerned by the amplitude of the recorded signal, yet considering frequencies < 2 kHz (Evans et al. 2005; Oliver-Villanueva and Abian-Perez 2013) and < 20 kHz (Lehrer 2013; Gonzalez de la Rosa et al. 2005, 2006, 2015; Nanda et al. 2018a, b). The analysis of frequencies in the audible range may be affected by ambient noise.

Machine learning models have been applied to various AE applications to distinguish different types of damage by finding patterns in the signals. For example, accuracy values higher than 95% have been achieved for AE from natural gas pipeline by applying clustering technique (Zhu et al. 2018) and 96% for AE activity from reinforced polymer by implementing Artificial Neural Network (ANN) technique (Kalafat and Sause 2015). However, they have been more limitedly applied to AE monitoring in wood and timber (Nasir et al. 2022). They have been mainly applied to monitoring AE in wood machining processes (Ciaburro and Iannace 2022) as well as in the classification of the level of heat treatment using an ANN-based model that analyzes AE signals characteristics in the time, frequency, and wavelet domains (Nasir et al. 2019). In the field of termite research, it had been used to distinguish termite signals from environmental noise (Nanda et al. 2018a) and to predict termite population in wood specimens by combining temperature and AE parameters (Nanda et al. 2019), both in the audible frequency range. Therefore, machine learning could potentially be applied to distinguish signals coming from workers and soldiers.

By using piezoelectric sensors in the ultrasonic range, it is therefore possible to localize termite activity, as successfully demonstrated here. Localization errors are most likely due to the heterogeneity and orthotropic nature of wood, as well as wave reflections at the ends of the sample, and natural defects in the wood, implying possible changes in the propagation mode (Kang and Booker 2002; Li et al. 2021).

5 Conclusion

This study demonstrated the feasibility of detecting acoustic emission signals in the non-audible range (frequencies in the ultrasonic range) generated by the activity of *Reticulitermes* termites, both workers and soldiers. At this stage, qualitative results have been obtained, which are not sufficient to establish quantitative statements due to the low number of specimens analyzed. No significant differences were found between the signals generated by workers or soldiers, neither in the time nor in the frequency domain. It has also been demonstrated that it is possible to locate termite activity.

Author contributions Conceptualization, AG and MG; methodology, ES and YF; software and validation, ES and YF; formal analysis, AG and ES; investigation, AG, ES and YF; resources, AG and MG; data curation, YF; writing—original draft preparation, ES; writing—review and editing, all authors; visualization, ES and YF; supervision, AG and MG; project administration and funding acquisition, AG and ES. All authors have read and agreed to the published version of the manuscript.

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Data Availability The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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