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Investigation of heat transfer in timber boards and a simulated wall section to eliminate colonies of the west Indian drywood termite, *Cryptotermes brevis* (Blattodea: Kalotermitidae)

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Abstract

Cryptotermes brevis (Walker) (Blattodea: Kalotermitidae) is one of the most destructive drywood termites that attack moisture-protected timber in service. Heat treatment has been studied to control these termites, but the low thermal conductivity of wood can result in prolonged treatment times and the need for high temperatures to eliminate termite colonies. The current study investigated heat transfer through a heat transfer model and experiments within solid timber boards and a representative wall section. The aim was to optimise targeted spot heat treatment as a cost-effective method for eradicating this pest within structural elements. Through experimental work and the development of a deterministic heat transfer model, valuable insights were gained into temperature distribution within wooden structural elements. The findings revealed that proximity to the heated surface played a crucial role, with closer distances reaching equilibrium temperatures faster. The heat transfer model, validated against experimental data, accurately predicted temperature distributions within the timber. Termite survival was significantly influenced by heating time and distance from the heated surface when a wall section was heated at 60°C. The mean survival of *C. brevis* pseudergates kept inside wall studs varied from 30% to 96.7% depending on the distance from the heated surface after 1.5 h of heating, where the temperature ranged from 43°C to 45°C. However, after extending the heating duration to 3 h, the temperature in wall studs was elevated to 51°C, 49°C and 47°C at 22, 40 and 60 mm from the heated stud face, respectively. All *C. brevis* pseudergates across all distances were killed at a 3-h duration. This research underscores the importance of understanding temperature distribution in structural wood elements and exposure times when employing heat as a spot treatment for drywood termite control.

KEYWORDS
heat, modelling, pest management, spot treatment, termites, wood

INTRODUCTION

Cryptotermes brevis (Walker) (Blattodea: Kalotermitidae), commonly known as the West Indian drywood termite (WIDT) is the world's most destructive drywood termite and is found mostly in tropical and temperate regions of the world, including Australia (Scheffrahn et al. 2009). It is known to colonise moisture-protected wood in service, including framing, cladding, flooring and furniture (Haigh et al. 2022). Structural fumigation using a toxic gas such as sulfuryl fluoride is the most common method for eliminating drywood termites (Lewis 2003;

Lewis & Forschler 2014). However, fumigation is expensive, disruptive, labour intensive and requires the specialised knowledge of a licensed, professional pest control firm (Gouge et al. 2009a). Drywood termite infestations may also be eliminated by treating a specific area of timber with termiticides ('spot treatment') where termites are present in a structure (Hassan et al. 2023). Spot treatments are much less expensive and less disruptive to the homeowner than fumigation. However, the success rate of spot or localised treatment with a termiticide is variable. One possible impediment to full eradication is the amount of termite frass packed within a gallery hindering the delivery of the chemical to the target site. Gravity works against an even distribution of insecticides, and liquid formulations may be difficult to deliver to the colony's core. They may not fully penetrate the termite galleries, especially during vertical application (Hassan et al. 2023; Hassan & Fitzgerald 2023).

Heat treatment is an attractive alternative to eliminate structural pests without fumigation (Hansen et al. 2011). Heat treatment has been used to eliminate drywood termites in structures (Lewis & Haverty 1996). However, heat treatment has never been used to eliminate *C. brevis* in Australia. Until January 2021, this pest was managed by whole-of-structure fumigation at the government's expense under the WIDT Prevention and Control Program in Queensland, where this pest has established itself since the 1960s (Hassan et al. 2023). Heat treatment to whole structures is complicated in a real-world application. The size and the variability of timber in a structure make it challenging to ensure a sufficient core temperature is attained in the wooden elements to kill the termites without excessive heating of smaller units. While there are examples of whole-of-house heating (Lewis 2003; Perry & Choe 2020; Tay & James 2021; Woodrow & Grace 1997), the heating times are long, and a large amount of energy is required to achieve the desired time/temperature target to kill the termites. This is due to the excellent thermal insulation properties of wood and its density (Tay & James 2021). Therefore, spot treatments to precisely located drywood infestations may be used as an alternative to heating the entire structure (Gouge et al. 2009b; Vernard et al. 2014). As with other spot treatments, a reasonably accurate detection method for locating colonies inside a structure is required for heat treatment to be effective (Haigh et al. 2022). Heating at a minimum of 56°C for 30 min was recommended by many studies and by ISPM 15 (International standard for solid wood packaging material) to eliminate pests (McDonald et al. 2022). *C. brevis* can be killed by exposure to high temperatures, with lethal wood core temperatures of 54.4°C (Woodrow & Grace 1997). McDonald et al. (2022) investigated the potential of heating at lower temperatures to determine the effect on termite survival and gut fauna. They found that a 1-h exposure at 45°C was lethal and exposure for as little as 3 min at 50°C or 2 min at 55°C was also lethal. These results suggest that short-term exposures to 50°C or 55°C could be used to eliminate infestations, creating an opportunity for localised spot heating as a remediation treatment.

The field of heat transfer theory and modelling is well-established (Cengel 2002; Incropera et al. 1996). Using a validated heat transfer model for timber can optimise heating time, resulting in improved outcomes through reduced time and energy consumption. The validated model can also provide a platform for conducting parametric analyses, facilitating a comprehensive exploration of factors such as timber density and thermal conductivity. Comprehensive heat and mass transfer models for drying have been developed where force convection around the surface occurs with flowing air (Kumar et al. 2012; Kumar et al. 2015; Perré & Turner 2002; Redman et al. 2017; Turner 1996). However, little has been reported in the literature on a validated heat transfer model for eliminating *C. brevis* when heating timber under natural convection boundary conditions.

This study examined heat transfer within solid timber boards and a representative wall section and used a deterministic heat transfer model to estimate temperature distribution within timber boards, which was validated against experimental data. The validated model was applied to investigate the temperature distribution over time within timber boards and wall section. Survival of *C. brevis* pseudergates, housed in the wall section studs at varying distances from the heated surface was observed. These results can be used to determine heating duration for the effective treatment of *C. brevis* in timber structures.

MATERIALS AND METHODS

Several experiments were carried out to determine heat transfer in solid wood boards and wall sections mimicking the elimination of drywood termites when present in solid wood products such as floorboards, vertical joint wall panels, roof decking and wall studs. In most cases, only one side of boards or wall sections with a drywood termite infestation will be accessible to heat, leaving the other side exposed to ambient temperatures.

Heat transfer in southern pine boards

Commercially available, hybrid southern pine (*Pinus elliottii var. elliottii.* × *Pinus caribaea* var. *hondurensis*) boards measuring 35 × 95 × 600 mm were selected to determine heat transfer in wooden boards. Three thermocouples (T-type) were inserted at various depths (6, 14 and 21 mm) from one end of each board to measure the temperature inside the boards, as shown in Figure 1a,b. One face of each of the three boards was heated at a constant temperature of 64°C using a heated metal plate for 5 h. This temperature was selected based on preliminary experiments so that at least 45°C was achieved on any surface of the boards. Our previous study suggests that prolonged exposure to lower temperatures (i.e., 45°C) may be an

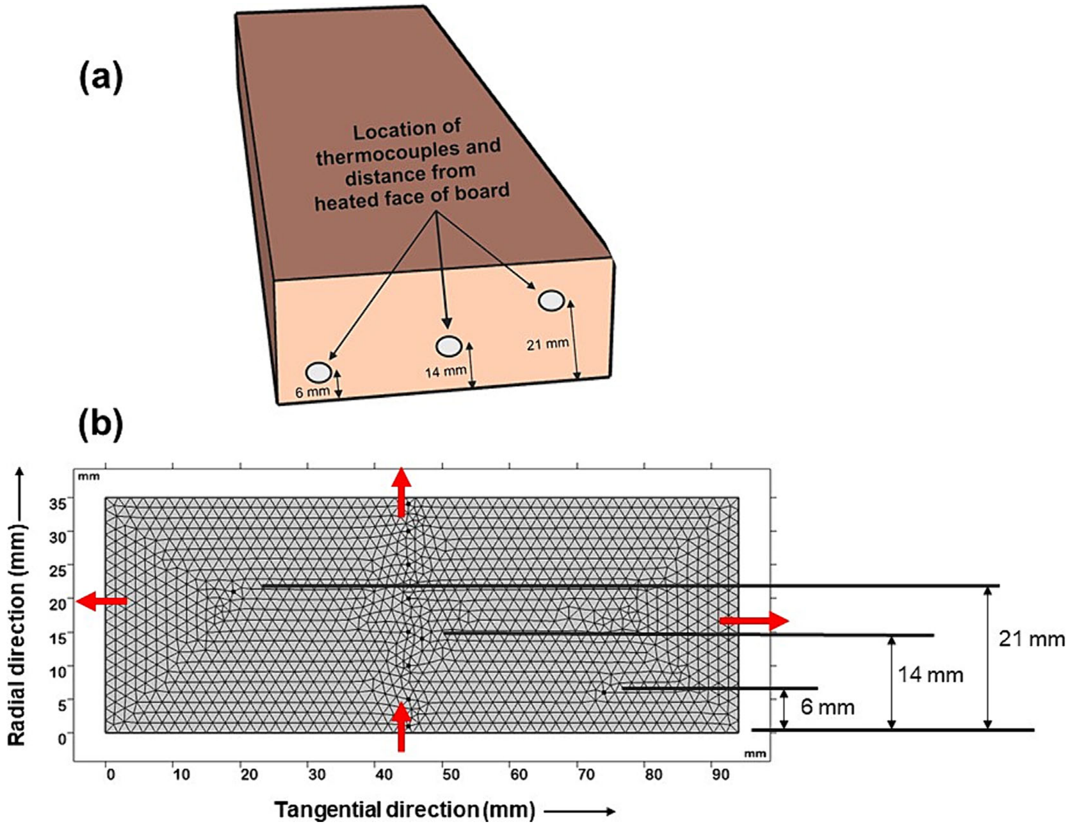

FIGURE 1 Thermocouple locations and distances from the heated surface of a wooden board (35 × 95 × 600 mm) heated using a metal plate (a); geometry, mesh and boundary conditions for the heat transfer experiment and board simulation (b). Red arrows indicate the direction of heat flow.

acceptable substitute for shorter, more intensive exposures and that a 30-minute exposure is required to kill *C. brevis* at 45°C (McDonald et al. 2022). Three boards with an average density of 570 kg/m^3 were placed on the metal plate after it reached the set point temperature of 64°C. Other non-heated faces of boards were exposed to ambient temperature. The longitudinal end of the boards was insulated with foam to minimise the heat loss near the thermocouple insertion hole and thermocouple shielding. Thermocouples were also placed on the surface of the boards and heated plates using adhesive tape. The experiment was repeated three times on new boards, for a total of nine boards. Other materials, such as wood, may surround drywood termite-infested wood in structures. Consequently, when infested material is heated to kill drywood termites, the rate of heat loss will depend on the thermal conductivity of the material around it and ambient temperature. Therefore, in the current experiment, data from only the middle board were recorded. The remaining two boards were regarded as surrounding material.

Residential wall section construction and heat transfer

A representative residential wall section was built using traditional building materials following AS 1684.2. (2021) for non-loadbearing interior studs (Figure 2a,b). The demonstration wall was comprised of four sections: the wall stud frame, a gyprock sheet (plasterboard), outside framing and a back insulation panel with wall insulation. The materials used are listed in Table 1. The frame consists of a top and bottom plate with four studs spaced 180 mm on centre points. The insulation sheet was then stapled to the back as per industry practice. The outer timber frame was fabricated from 90-mm timber studs to provide an air gap behind the sheet and increase the insulation of the external edges of the wall section. The back insulation panel was then screwed into the outer timber frame such that limited heat transfer could occur from behind the wall section. The painted plasterboard was then attached to the front of the frame with screws. The painted front side, which simulates the wall section of a room, was heated at 60°C using an experimental kiln drying facility at the Queensland Department of Agriculture and Fisheries (QDAF), Salisbury Research Facility. The external side of the wall section was exposed to ambient conditions to simulate a room heating scenario for termite treatment. Thermocouples were installed throughout the wall section to gain a comprehensive understanding of the heat transfer and temperature distribution inside the studs of the wall section during heat treatment (Figure 2c).

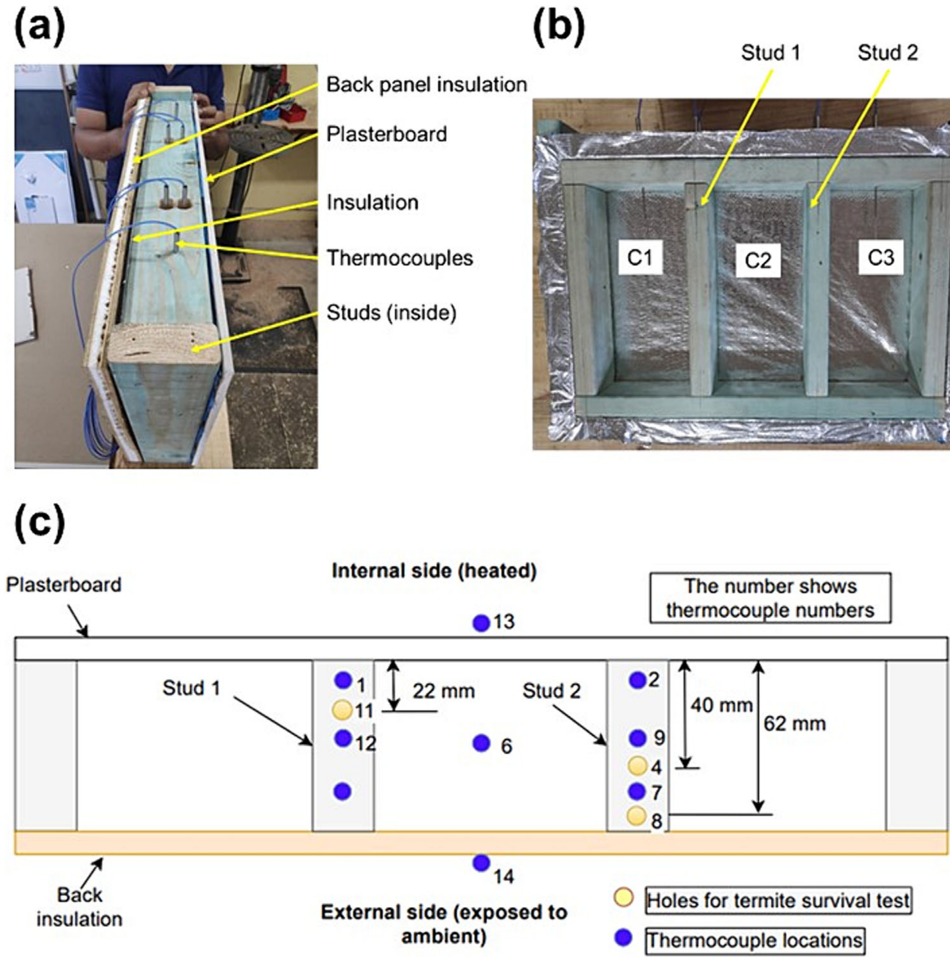

FIGURE 2 A representative wall section constructed according to AS 1684.2-2010 for a non-loadbearing interior stud wall: top view (a), front view with plasterboard removed (b). Schematic of the top view of the representative wall section with thermocouples inserted at various locations inside the studs. Blue circles represent the positions of thermocouples, and yellow circles indicate the holes where live termites were housed for the survival test (c).

TABLE 1 Materials used for the wall section construction.

Materials	Size (mm)	Density (kg/m^3)
MGP12 pine timber framing (wall studs)	70 × 35 90 × 45	496
Gyprock CSR Plasterboard RE	470 × 665 × 10	537
Ametalin Reflective Wall Insulation LD	470 × 665	—
Wood screws	50	—

Artificial infestation of wall studs and termite survival

Pseudergates of *C. brevis* were retrieved from floorboards and a door collected from a building in Maryborough, Queensland, as described previously by Hassan et al. (2023). The faecal pellet morphology examined with a microscope confirmed the species of termite. After extraction from the wood, healthy termites were maintained on hoop pine (*Araucaria cunninghamii* Mudie) wood veneers (1.5–3 mm thick) that were kept on two layers of black filter paper in Petri plates (9 cm diam.) (McDonald et al. 2022). Only third or fourth instar pseudergates, belonging to multiple colonies with no evidence of wing buds, were used in the experiments.

To facilitate the artificial infestation of wall studs, three separate holes (yellow-filled circles in Figure 2c), located at three distances, were drilled in two wall studs. These holes were used to house the pseudergates during heat treatment. The holes were situated at a depth of 22 mm within stud 1 (point 11) and at depths of 40 and 60 mm within stud 2 (points 4 and 8) from the heated interior side of the wall. Ten *C. brevis* pseudergates were gently introduced into each stud hole, and holes were closed using wood dowels to avoid termite escape. The wall section was heated for 1.5 and 3 h at 60°C. Termites were then gently removed from each hole by disassembling the studs from other wall elements and inverting them into the Petri plates containing the two layers of filter paper. Termite survival was recorded immediately following heat treatment and again at 24- and 48-h post-treatment. Termites were housed in stud holes for 3 h without heat treatment for the control treatment and all experiments were repeated three times.

Numerical simulation

COMSOL Multiphysics 5.6, which uses partial derivative equations for modelling and simulating any physical process, was used to develop all the heat transfer simulations in this study. A schematic diagram of the two-dimensional (2D) geometry, mesh and the dimensions are shown in Figure 1b. A 2D (radial-tangential plane) cross-section of 90 × 35 mm was considered for the simulation. The board was heated from the bottom surface using a hot plate maintained at a constant temperature of 64°C, and the other three surfaces were open to natural convection.

Governing equation

The transient heat transfer in solid material (timber boards in this case) can be expressed by Equation (1).

$$\rho c_p \frac{\partial T}{\partial t} - \nabla.(k\nabla T) = Q \tag{1}$$

where T is the temperature, ρ is the material density (kgm^{-3}), c_p is the specific heat ($Jkg^{-1}K^{-1}$) and k is the thermal conductivity (Wm^{-1}K^{-1}). Q is the heat generated (Wm^{-3}) inside the body, which is zero for this study.

Input properties

Commercially available hybrid pine boards with a density of 570 kg/m^3 were used. The thermal conductivity was considered to be 0.14 W/m/K (Glass & Zelinka 2021). The heat capacity of dry wood can be approximated as a function of temperature by (Ross 2010) (Equation 2).

$$C_p = 1000(0.1031 + 0.00386T) \tag{2}$$

Initial and boundary condition

The initial temperature of the timber was set to room temperature (i.e., $T_{(t=0)} = 13^{\circ}$C).

The temperature of the heated boundary was set to 65°C and the other boundaries are set to a convection heat transfer defined by Equation (3),

$$Q_c = h_c(T - T_a) \tag{3}$$

where T_a is the ambient temperature, T is the temperature at a particular x and y location on the plate surface and h_c is convection coefficient. T_a was considered 25°C for the sides and 22°C for the top as the sides were not entirely exposed to ambient due to other boards.

Natural convective heat loss occurring from the non-heating surfaces depends on the surface geometry, orientation, temperature and thermophysical properties of the fluid (i.e., air in this case). The best-known and widely used Nusselt and Rayleigh numbers were used to calculate the natural convection coefficient. The Rayleigh number (Ra) is the product of the Grashof number (Gr) and Prandtl number (Pr), defined as the Grashof number as expressed in Equation (4)

$$\mathrm{Ra} = Gr.Pr = \frac{\rho_a^2 g\beta(T_s - T_a)L_c^3}{\mu_a^2}.Pr \tag{4}$$

where T is the temperature, ρ_a is the density of air (kg m^{-3}), g is the gravitational acceleration (ms^{-2}, β is the coefficient of volume explanation for air $\left(K^{-1}\right)$, T_s is the temperature of the wood surface (K), T_a is the air temperature (K), L_c is the characteristic length of timber (m), μ_a is the dynamic viscosity of air (specific heat, $Jkg^{-1}K^{-1}$) and k is the thermal conductivity (Wm^{-1}K^{-1}). Pr is the Prandtl number.

The convection heat transfer coefficient was calculated using Equation (5),

$$h_c = Nu.k_a/L_c \tag{5}$$

where Nu is the Nusselt number and k_a is the thermal conductivity of air.

The Nusselt number for side surfaces of the boards (vertical surfaces) and the top surface (horizontal surface facing up) was calculated using Equations (6) and (7) (Cengel & Ghajar 2014), respectively.

$$Nu = \left\{0.825 + \frac{0.387Ra^{\frac{1}{6}}}{\left[1 + (0.492/Pr)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right\}^2 \tag{6}$$

$$Nu = 0.59Ra^{1/4} \tag{7}$$

Statistical analysis

Jamovi 16.9 (Jamovi, Sydney, Australia) under AGPL3 licence was used to analyse the data obtained from the termite survival test. Data were subjected to multivariate repeated measure analysis to investigate the effects of heat treatment, with distance from the heated surface and heat duration as factors. Analysis of variance was followed by Tukey's honest significant difference test for significant differences between means. The level of significance was set at $\alpha = 0.05$.

RESULTS

Heat transfer in southern pine boards and model validation

Results showed that temperature distribution inside 35-mm thick pine boards varied based on the distance from the heated surface. The closer it was to the heated surface, the quicker the wood surface reached equilibrium temperature (Figure 3a). The first 6 mm of board thickness, closest to the heated surface, attained an equilibrium temperature in 0.5 h, followed by 14 mm in an hour and 21 mm in approximately 2 h. The equilibrium temperatures were around 59°C, 50°C and 45°C at 6, 14 and 21 mm, respectively. Moreover, the model successfully predicted temperature profiles within pine boards, which correlated well with the experimentally measured temperature (Figure 3a). The two-dimensional temperature distribution from the simulation, after equilibrium was reached, is shown in Figure 3b. As anticipated, the temperature is highest near the heated surface and decreases further away. The formation of a dome shape results from convective heat loss occurring from both the top and side surfaces. Further results showed that the termite gallery can impact the heat transfer rate and may result in lower temperatures behind the gallery (Figure 3c). However, the final steady state temperature away from the gallery (i.e., 14 and 21 mm) was not affected significantly.

Heat transfer in a wall section

Temperature measurements obtained at various distances from the heated surface within the wall studs, the internal heated surface of the wall and the external surface exposed to ambient conditions are shown in Figure 4a. Temperature data within the studs are discussed further, focusing only on locations where live termites were held for subsequent survival experiments.

As expected, the temperature at the heated surface was identical to the hot air temperature of the kiln (i.e., 60°C). Furthermore, as with the temperature distribution in a pine board, the temperature within stud 1, closer to the heated surface (22 mm) was higher than the temperature from stud surfaces at greater distances (i.e., 40 and 62 mm) from the heating surface. The temperatures measured after 1.5 h of heating were approximately 45, 44 and 43 at distances of 22, 40 and 60 mm, respectively. After 3 h, these temperatures increased to

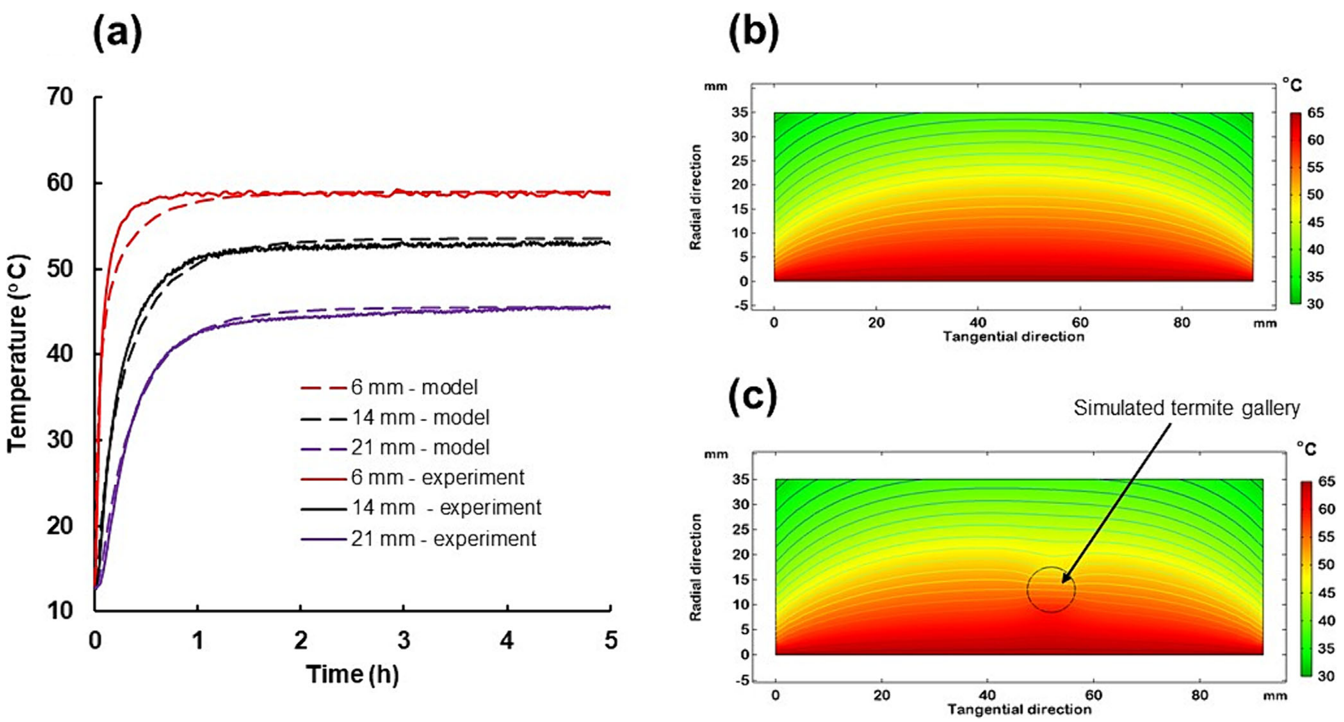

FIGURE 3 Temperature distribution within 35-mm thick southern pine boards: solid lines represent experimental data, and broken lines represent the model (a). Temperature distribution inside the board after 5 h of heating from the bottom surface without a termite gallery (b) and with an ellipsoid hole mimicking a termite gallery (c).

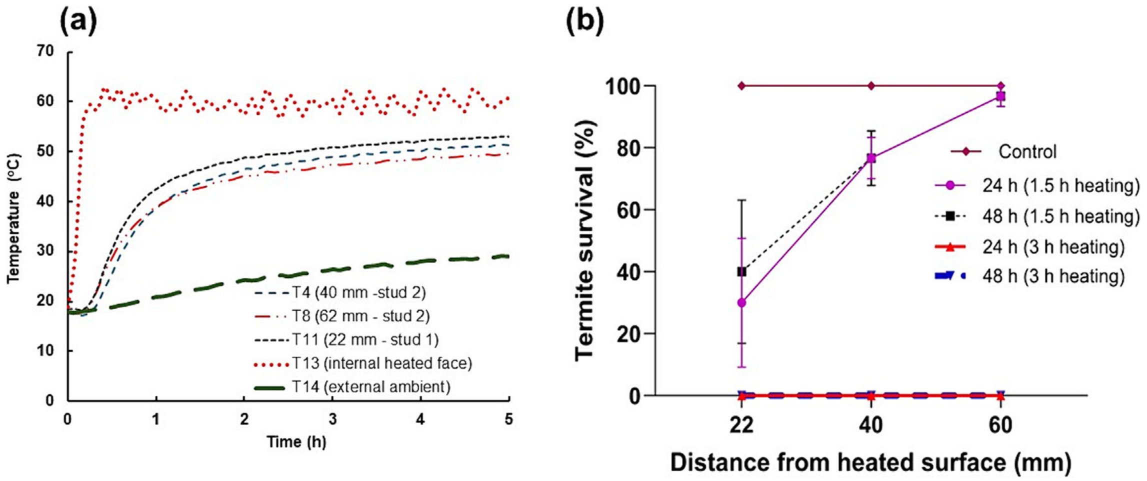

FIGURE 4 Temperature change in the wall section at 22, 40 and 62 mm from the stud face (a). Drywood termite survival within a wall stud section at varying depths after 1.5 and 3 h of heating that was assessed 24- and 48-h post-treatment (b).

51°C, 49°C and 47°C, respectively. Following 5 h of heating, temperatures reached a state close to the equilibrium temperature, with readings of approximately 53°C, 51°C and 49.6°C recorded at distances of 22, 40 and 62 mm, respectively from the heated surface (Figure 4a).

Termite survival

Survival of termites housed in wall studs at different distances from the heated surface following 1.5 and 3 h of heating is shown in Figure 4b. In survival tests, the effect of distance from the heated surface ($F_{2,18} = 5.60$; $p = 0.013$), heating time ($F_{2,18} = 133.64$; $p < 0.01$), and their interaction (heating time × distance from heated surface) ($F_{4,18} = 5.60$; $p \leq 0.004$) were highly significant. All termites survived in the control treatment (Figure 4b). Most of the termites kept at three different locations in studs were moribund immediately after exposure following a 1.5-h heat treatment. However, within 24 h, many termites recovered, and survival rates were 76 and 96% of those housed 35 and 65 mm away from the heating surface. Therefore, estimating mortality immediately following heat exposure at higher temperatures was a poor indicator of actual mortality and was excluded from data analysis.

Furthermore, no significant difference in termite survival was observed after 24 and 48 h. However, with termites housed closer to the heated surface of the stud (i.e., 22 mm), mean survival rates dropped to 30% at 24 h and 40% at 48 h post-assessment. For the 3-h heating treatment, all termites were dead at all distances from the heated surface after 24 and 48 h. These results indicate that extended heating times considerably improve termite mortality, even at greater distances from the heated surface (Figure 4b).

DISCUSSION

Using heat to treat drywood termite infestations requires raising the temperature of the immediate surroundings to a specific lethal level. This depends on several factors, such as the type and size of wood or structural material, the configuration of the treatment area, and the ambient outside temperature. It can take several hours to reach the lethal temperature for drywood termites, depending on ambient conditions (natural convection) and wood species (Tay & James 2021). Consequently, it is crucial to comprehend the temperature distribution within the wood or structural materials during heat treatment to eliminate drywood termite colonies successfully. The current study showed that the equilibrium temperature in wood can change depending on the boards' ambient conditions and surface or boundary conditions. For example, if the boards are insulated or the ambient temperature is higher, the equilibrium temperature will be higher due to slower heat loss through the unheated surfaces (Kadem et al. 2011; Zhang et al. 2017). Moreover, differences in wood core and surface temperature were observed. The results are consistent with a previous study where differences in wood core temperature and surface temperature in 8.3 cm Douglas-fir cubes were observed (Rust & Reierson 2019). The model we used successfully predicted temperature profiles within pine boards. The advantage of the deterministic and physics-based models is that they can be used for parametric analysis once they are validated.

Drywood termites construct small to extensive galleries inside the wood, depending on the infestation age and the colony size (Haigh et al. 2022). The results of our study showed that the termite gallery system may impact how heat is distributed in infested materials. This is because air molecules in the termite galleries are not in continuous contact with one another, unlike in solid materials such as wood, resulting in a lower temperature compared with material without termite galleries. The findings from termite survival tests indicate that drywood termites residing at greater distances from the heated surface may require prolonged heat treatment periods for successful eradication. Most termites exhibited a moribund state immediately after 1.5-h heat treatment and recovered after some time. These results agree with a previous study which showed that *C. brevis* pseudergates exposed to lower lethal temperatures can recover, including their gut protozoa, which are essential for the digestion of wood in termite guts (McDonald et al. 2022).

Our study findings demonstrate that even with the current experimental design, 1.5 h of heating did not result in 100% termite mortality, which is consistent with earlier studies by McDonald et al. (2022), which found that termites must be exposed to 45°C for at least an hour to be killed. Extending the heating duration to 3 h killed all *C. brevis* pseudergates across all distances from the heated surface. Unlike 1.5-h heating, 3 h of heating killed all termites, and no termite recovered 48 h post-treatment.

In the current study, the temperature where termites were housed reached 51°C, 49°C and 47°C at various distances from the heated surface of the stud. Previous studies show that temperatures between 47°C and 51°C are lethal to drywood termites (McDonald et al. 2022; Tay & James 2021). Woodrow and Grace (1998b) reported 45°C as the minimum temperature capable of killing the drywood termite, *Incisitermes immigrants*. Forbes (1987) reported 49°C as the lethal temperature for drywood termite management. A recent laboratory study found that a temperature of approximately 49.6°C for 2 h is required to achieve 100% drywood termite mortality under a heat sink effect (Perry & Choe 2020). However, in this study, a slightly lower lethal temperature was observed compared with some previous studies which reported a wood-core temperature of 54.4°C as sufficient to kill *C. brevis* in timbers (Scheffrahn et al. 1997; Woodrow & Grace 1998a).

Although the temperature on any wall stud surface did not reach the 56°C threshold required by the ISPM 15 (International Standard for Solid Wood Packaging Material), it proved lethal to all termites evaluated in the current study. This can be attributed to the extended exposure time above 45°C, which is known to be effective in termite mortality, as established in the study by McDonald et al. (2022).

Our findings demonstrate that drywood termites in structural elements can be effectively eradicated without reaching the 56°C threshold stipulated by ISPM 15, provided they are exposed to lethal temperatures for a sufficient duration. This underscores the importance of understanding temperature distribution and exposure times when employing heat treatment to ensure the complete eradication of drywood termites. The thermal conductivity of wood depends on several factors, including wood species, wood density, widths of growth rings, volumetric fraction of wood rays, latewood content and moisture content (Olek et al. 2003). However, the current model can be used to predict the time required to acquire lethal temperature for eradication of a *C. brevis* infestation.

This research highlights the potential of targeted spot heating as an innovative and cost-effective method for eradicating termites in structural elements and the importance of understanding the complexity of heat distribution and the required duration of heating to effectively eliminate termites.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest regarding this article.

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