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Section 1 **Biology**

Impact of termite-induced damage on the mechanical performance of timber

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ABSTRACT

Assessment of termite damage has traditionally relied on visual ratings and mass loss measurements, which indicate biological degradation but do not directly quantify changes in the mechanical performance of timber. Timber may appear externally sound despite internal gallery formation, and reductions in stiffness and strength are highly non-uniform, depending on the extent, location, and geometry of termite excavations. Consequently, localised damage in highly stressed regions of timber can cause disproportionate losses in mechanical capacity of timber even when overall mass loss is low. Improved relationships between measurable damage indicators and mechanical properties are therefore required for the reliable evaluation of in-service timber. This study examined the effect of termite-induced damage on the mechanical performance of timber using field exposure trials. Hybrid pine beams were exposed under conditions designed to concentrate termite attack within a predefined central region of beams. Changes in mass, density, and both dynamic and static elastic moduli were measured before and after termite exposure. Termite attack was successfully localised in most beams using this exposure method, with more than 80% of specimens exhibiting controlled damage suitable for testing. Pre-exposure static elastic modulus measurements were strongly correlated with dynamic elastic modulus measurements ($R^2 = 0.74$). After exposure, pre-exposure stiffness remained a predictor of residual stiffness ($R^2 = 0.59$), although overall stiffness declined. Stiffness loss increased linearly with mass loss ($R^2 = 0.78$), while cumulative mass loss showed no relationship with initial density and post-exposure density was only moderately related to stiffness reduction ($R^2 = 0.32$). Bending strength also decreased with increasing damage but showed considerable variability, reflecting the influence of gallery location and geometry rather than total material removal alone. The results highlight the value of mechanical evaluation for termite-damaged timber. The findings support improved durability assessment, service-life evaluation, and performance-based management of timber structures exposed to termite hazard conditions.

Keywords: Termite damage, mechanical performance, residual capacity, durability, timber assessment.

1. INTRODUCTION

Termites are among the most important biological agents responsible for the deterioration of timber in service, particularly in tropical and subtropical regions (Hassan and Morrell 2021). Termite attack can cause extensive internal damage to large structural members while leaving minimal external evidence, complicating early detection and reliable assessment of residual performance. This concealed deterioration is especially critical where timber elements are required to maintain structural integrity or serviceability following exposure (Hassan and Nanda 2024).

Assessment of termite damage has traditionally relied on visual rating systems and mass loss measurements (Hassan and Morrell 2021). While these approaches provide useful indicators of biological degradation, they do not directly quantify changes in mechanical performance. Reductions in stiffness and strength caused by termite attack are often highly variable and depend strongly on the extent, location, and geometry of internal galleries (De Groot *et al.* 1998, Shirmohammadi *et al.* 2023). Localised damage within highly stressed regions can therefore result in disproportionate losses in mechanical capacity even when overall mass loss is relatively low, because internal degradation of load-carrying elements near the tension or compression regions can reduce stiffness and strength far more rapidly than total mass loss would suggest in timber subjected to biological deterioration (Curling *et al.* 2002, Ibach and Lebow 2014). Moreover, timber can appear intact externally despite extensive internal gallery formation that compromises structural integrity (Hassan and Nanda 2024).

Assessing residual structural properties of insect-degraded timber depends on whether the element is fully excluded via an "effective cross-section" approach or whether it retains a reduced mechanical contribution that can be accounted for analytically (Löwe *et al.* 2022, Mori *et al.* 2010, Nunes *et al.* 2019, Verbist *et al.* 2020). Developing a clearer understanding of how termite attack influences mechanical behaviour is essential for improved evaluation of in-service timber. In particular, there is a need to establish robust relationships between measurable indicators of termite damage and changes in mechanical properties that govern load-bearing performance (Mori *et al.* 2010). Such relationships would assist in interpreting the significance of termite damage beyond qualitative ratings alone.

In this context, non-destructive evaluation techniques, including vibration-based acoustic methods, offer a potential means of detecting internal damage and monitoring changes in timber stiffness (De Groot *et al.* 1998). Anecdotal evidence shows that assessing residual structural properties of insect-degraded timber depends on whether the element is fully excluded via an "effective cross-section" approach or whether it retains a reduced mechanical contribution that can be accounted for analytically. However, limited experimental data are available describing how termite-induced damage affects both dynamic and static mechanical properties. A further challenge in termite durability research is the inherent variability associated with natural termite attack (Shirmohammadi *et al.* 2023). Standard field exposure tests often produce inconsistent damage patterns, complicating post-exposure mechanical testing and comparisons between specimens. Experimental approaches that encourage termite attack in predefined regions of test specimens can improve reproducibility and allow more meaningful before-and-after assessments of mechanical performance.

The present study addresses these challenges by combining field exposure with pre- and post-exposure mechanical testing. Timber beams were exposed using a standardised field configuration designed to concentrate termite attack within the central region of each specimen. Changes in mechanical behaviour (bending stiffness, MOE, and bending strength, MOR) were quantified using both dynamic acoustic measurements and static four-point bending tests, and the results were related to density, mass loss, and internal material loss.

The objective of this work was to develop and apply a method for accurately evaluating changes in timber stiffness and strength following termite attack. By directly linking termite-induced material loss with reductions in mechanical performance, this study aims to improve the interpretation of termite exposure tests and support more informed durability and service-performance assessments of timber products.

2. MATERIALS AND METHODS

2.1 Wood Material, Beam Preparation and Selection

Hybrid pine (*Pinus elliottii* var. *elliottii* × *Pinus caribaea* var. *hondurensis*) boards (100 × 38 × 900 mm) were re-machined into 32 × 32 × 600 mm beam specimens (radial × tangential × longitudinal), producing 500 beams. All beams were sourced from boards containing at least five growth rings per 25 mm. Sapwood was confirmed using a chemical spot test, and beams containing heartwood or defects were excluded. Specimens were conditioned to constant mass at 20 ± 2 °C, 65 ± 5% RH to achieve approximately 12% equilibrium moisture content (EMC).

After conditioning, beam mass and dimensions were measured to determine density, which ranged from 370 to 750 kg m^{-3}. Beams were assigned to four density groups spanning the full range, from which 20 beams per group (n = 80) were selected for pre-exposure static four-point bending tests. Selection was stratified to ensure representative density coverage, while the remaining specimens were allocated to termite exposure and post-exposure evaluation.

2.2 Mechanical Testing (Dynamic and Static)

Mechanical properties were evaluated using a combination of non-destructive dynamic testing and static bending tests before and after termite exposure. Before exposure and testing, the dynamic MOE of all 500 beams was measured using Beam Identification by Non-destructive Grading (BING®), a resonance-based acoustic method based on fundamental longitudinal vibration frequency, specimen mass, and geometry (Baillères *et al.* 2009).

Figure 1: Four-point bending test of a timber specimen using a Shimadzu universal testing machine.

Pre-exposure static properties of the overall population were determined by destructively testing a subset of beams (n = 80; Section 2.1) in four-point bending to determine static MOE and modulus of rupture (MOR). These results were used to define group-specific 30% maximum load levels for subsequent non-destructive static bending tests of the remaining beams.

The remaining 420 beams were then subjected to non-destructive static bending before exposure, with loading limited to 30% of the group-specific maximum load. The approximate mean densities of the four groups and corresponding 30% load levels were 460 kg m⁻³ (≈1045 N), 520 kg m⁻³ (≈1394 N), 580 kg m⁻³ (≈1499 N), and 650 kg m⁻³ (≈1831 N), ensuring elastic behaviour and avoiding pre-damage.

All static bending tests were conducted using a Shimadzu Universal Testing Machine with a 100 kN load cell fitted (Fig. 1), a 540 mm span and a displacement rate of 6.5 mm min⁻¹, in accordance with AS/NZS 4063.1. Following pre-exposure testing, the central ~150 mm of each of the remaining 420 beams was wrapped with corrugated cardboard secured with plastic cable ties (Fig. 3). This treatment was applied to promote termite foraging and attack within the central region of each beam.

2.3 Termite Exposure

Termite exposure trials were conducted at a field site in Esk, Southeast Queensland, Australia (27.23330° S, 152.41670° E), selected for its consistently high activity of the subterranean termite *Coptotermes acinaciformis*. Two previously established trenches (~5 m long, ~0.3 m deep) were used for the trials. Briefly, the trenches had been excavated several weeks before exposure, filled with untreated pine feeder material, and fitted with hollow concrete blocks containing multiple cavities. Untreated pine stakes (400–500 mm long) were inserted vertically through the cavities and backfilled with soil to provide termite access to the feeder timber. Additional feeder material (corrugated cardboard and untreated pine boards) was placed above the blocks, lightly watered, and covered with shade cloth and polyethylene sheeting to maintain a dark, humid microenvironment conducive to termite activity (Fig. 2).

Figure 2: Steps used to prepare a trench for termite testing: Trench being filled with feeder wood (a), concrete blocks with stakes to encourage upward termite movement (b), blocks covered with soil (c) and then corrugated carboard (d), final assembly with pine feeder material on top being wetted (e) and then the covering tarp to protect the termites (f).

Termite activity was confirmed in both trenches. Then the original multi-cavity concrete blocks were replaced with smaller blocks (~200 mm high) containing a single cavity. New untreated pine stakes (400–500 mm long) were inserted vertically through each cavity, which was then backfilled with soil and covered with cardboard. Test beams were placed on the concrete blocks such that only the central portion of each beam was positioned above the hollow cavity, while the beam ends remained elevated and isolated from soil contact. The central exposure zone was further wrapped with cardboard and overlaid with untreated pine boards (Fig. 3 – top row). This configuration, established through preliminary trials, reliably concentrated termite attack within the central portion of the beam, ensuring consistency for subsequent mechanical testing (Fig. 3 – bottom row).

Figure 3: Field exposure setup showing timber beams positioned on hollow concrete blocks to encourage termite attack in the central portion of the beams (top row). Preliminary trial demonstrating that, in most beams, termite attack was successfully restricted to the designated central exposure zone (bottom row).

Following beam placement, the shade cloth and polyethylene covering were replaced to encourage termite activity. The beams were inspected regularly for signs of termite attack, and the central portions of exposed beams were gently probed to assess the progression of damage. Once a sufficient amount of termite attack was observed, beams were removed, feeder material was replenished, and new beams were introduced. The timing of beam placement and removal was guided by termite activity to produce specimens exhibiting a range of damage severities. In total, the exposure of 420 beams spanned approximately two years, involving sequential placement and retrieval of specimens to achieve varying degrees of termite-induced degradation. This staged exposure approach ensured that the final dataset encompassed a broad spectrum of damage levels suitable for subsequent mechanical and material performance assessments.

2.4 Post-Exposure Assessment

Following removal from the field, exposed beams were air-dried for a few days to facilitate removal of adhering soil and debris, then cleaned using compressed air, fine needles, and soft brushes. Care was taken to remove soil and termite excreta from termite galleries without removing intact wood material. Cleaned specimens were reconditioned to 12% EMC and reweighed to determine termite-induced mass loss.

Dynamic modulus of elasticity (BING MOE) was re-measured on all beams using the same procedure applied before exposure, followed by static four-point bending tests to determine post-exposure static MOE and MOR using the methods described in Section 2.3. Only beams with termite damage visually confined to the designated central exposure zone were tested; specimens with extensive damage on either end of the centre zone were excluded.

After mechanical testing, a subset of beams was sectioned through the central exposure zone to quantify cross-sectional material loss. Transverse sections were scanned and analysed using ImageJ to determine the proportion of remaining solid wood relative to the original cross-sectional area. An equivalent volume loss was also estimated from mass loss using pre-exposure apparent density as a bulk proxy for material removal.

2.5 Data Analysis

Pre- and post-exposure responses were evaluated using relative change metrics, with percentage change calculated against pre-exposure values. The magnitude of termite-induced effects on mechanical performance was quantified using effect size statistics. Associations between density, mass loss, and changes in mechanical properties were examined using correlation and regression analyses to assess the strength and direction of relationships. Statistical significance was evaluated at $\alpha = 0.05$ using standard statistical software unless otherwise stated.

3. RESULTS AND DISCUSSION

Termite attack in most beams was successfully concentrated within the designated central exposure zone, demonstrating the effectiveness of the exposure method in directing termite foraging to a predefined region of the beam. Damage in some specimens extended beyond the central zone up to approximately 200 mm in total, reflecting variation in exposure duration and foraging intensity (Fig. 3). Dissection of a subset of beams confirmed that internal gallery development generally corresponded with externally observed damage, with some variation (typically within 5-10%), except in few specimens exhibiting extensive attack where internal damage extended beyond the visibly affected regions.

Termites transported soil in a small number of specimens and sealed portions of the beam surfaces outside the intended central exposure zone, effectively creating secondary access points. This behaviour allowed the termite attack to extend along the beam length, resulting in more widespread off-zone damage (Fig. 4 & 5). These specimens were excluded from post-exposure mechanical testing. Overall, more than 80% of beams from each harvest exhibited damage patterns suitable for post-exposure testing. This exposure method therefore provided controlled localisation of attack while still allowing natural variability in damage severity, producing a realistic range of termite-induced degradation appropriate for evaluating residual mechanical performance.

Figure 4: Examples of pine beams after subterranean termite exposure, showing predominantly localised damage within the designated central exposure zone. In most specimens, termite galleries were confined to the beam centre. Beams marked with an "X" experienced damage extending beyond this region and were excluded from post-exposure testing.

Figure 5: Example of termite behaviour where soil transport and surface sealing outside the central exposure zone enabled attack to extend along the beam length, resulting in extensive damage outside the flexure zone.

Pre-exposure static MOE was strongly related to BING® MOE across all specimens (static MOE = 0.896 × BING MOE + 2517; $R^2 = 0.73$, $p < 0.001$) (Fig. 6). Static MOE values were generally within approximately 5–10% of dynamic estimates, consistent with expected differences between static bending and resonance-based stiffness measurements, supporting the use of BING MOE as a proxy for static stiffness (Baillères *et al.* 2009).

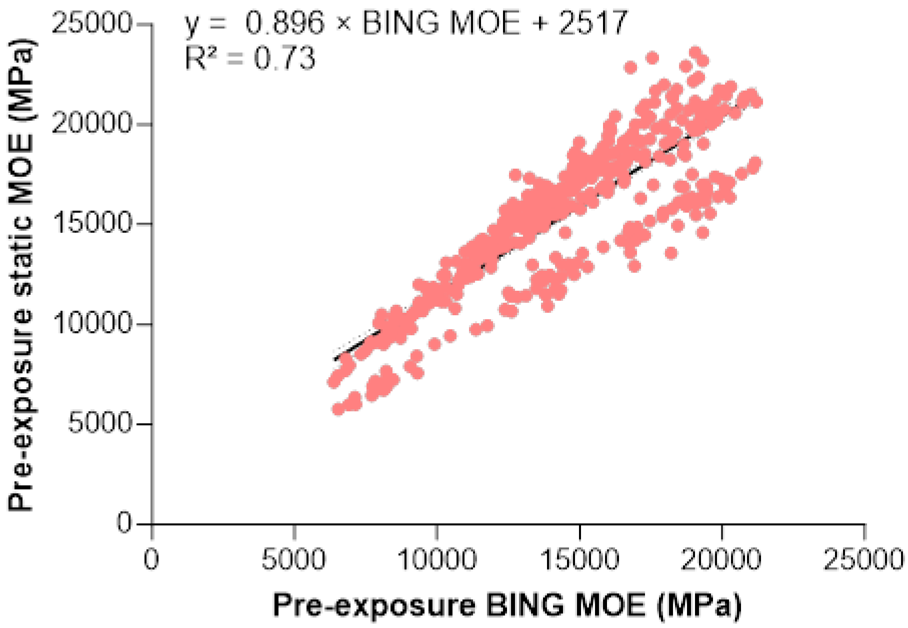

Figure 6: Relationship between pre-exposure static MOE and dynamic BING® MOE for pine hybrid beams prior to termite exposure.

Pre- and post-exposure BING MOE showed a significant positive relationship, indicating that pre-exposure stiffness remained a strong predictor of residual stiffness following termite exposure (Fig. 7). Linear regression demonstrated a clear association between pre- and post-exposure BING MOE ($y = 0.845x - 1404$; $R^2 = 0.59$, $p < 0.001$). Post-exposure BING MOE values were lower than pre-exposure values, indicating reduced dynamic stiffness after termite attack.

Stiffness loss was strongly related to termite damage severity. BING MOE reduction increased linearly with increasing mass loss ($y = 0.81x + 11.1$; $R^2 = 0.78$, $p < 0.001$) (Fig. 8), demonstrating that progressive material removal by termites resulted in proportional reductions in stiffness. Notably, measurable stiffness loss was observed even at low levels of mass loss, highlighting the sensitivity of bending stiffness to early and localised damage.

In contrast, mass loss of beams due to termite feeding was poorly correlated with pre-exposure wood density, indicating that density alone did not govern the extent of material removal during the long-term field exposure. Although negative relationships between wood density and termite feeding rate have been reported under controlled laboratory conditions (Hadi *et al.* 2014, Waller *et al.* 1990), our findings are consistent with studies reporting no clear relationship between termite feeding and wood density under field conditions (Peralta *et al.* 2004). Responses may also vary among termite species; for example, *C. acinaciformis* has been shown to consider multiple factors in foraging decisions and may even utilise denser wood (Oberst *et al.* 2018) . The absence of a density–mass loss relationship in the present study likely reflects the heterogeneous and opportunistic nature of field termite attack, where exposure duration, colony pressure, access pathways, and localisation of galleries exert a stronger influence on cumulative material removal than density alone.

Post-exposure density was significantly negatively correlated with BING MOE loss ($y = -0.151x + 106.7$; $R^2 = 0.32$, $p < 0.001$), indicating that beams experiencing greater termite-induced material removal generally exhibited larger stiffness reductions. However, the moderate coefficient of determination highlights the limitation of bulk density as a predictor of stiffness loss. While post-exposure density reflects overall material removal, stiffness loss is strongly influenced by the location and geometry of termite galleries relative to the bending stress distribution (Löwe *et al.* 2022, Verbist *et al.* 2020). These factors are not captured by density measurements alone.

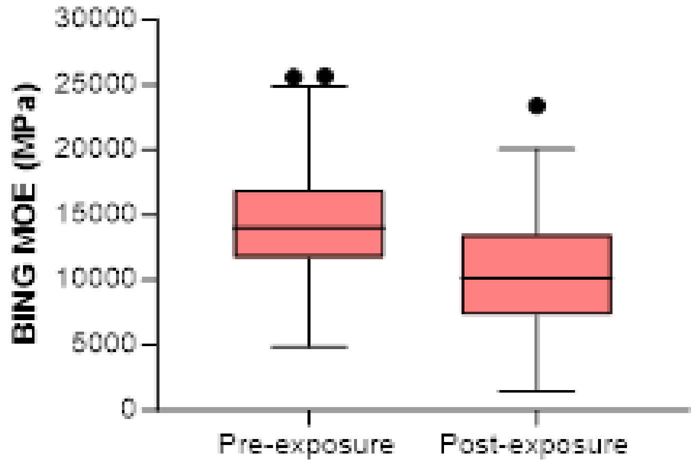

Figure 7: Box plot comparing pre- and post-exposure BING MOE, showing a general reduction in dynamic stiffness after termite attack.

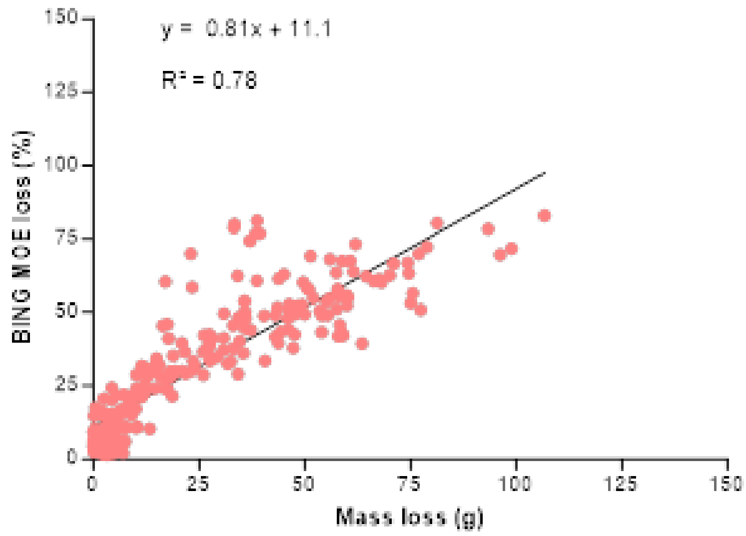

Figure 8: Relationship between BING MOE loss (values before and after termite exposure) and mass loss of hybrid pine beams following subterranean termite exposure

Figure 9: Example of transverse cross-sections of pine beams after subterranean termite exposure, showing varying degrees of internal damage and loss of effective cross-sectional area

Static bending strength (MOR) decreased with increasing termite damage (Fig. 10). Beams with low mass loss generally retained much of their original strength, whereas specimens exhibiting higher mass loss showed substantial reductions in MOR. The relationship indicates that termite-induced material removal directly compromised load-bearing capacity, although considerable scatter was present, reflecting variability in the location and geometry of internal galleries (Shirmohammadi *et al. 2023)*. Some beams with relatively small mass losses still experienced pronounced strength reductions, suggesting that localised damage within highly stressed regions had a disproportionate effect on failure behaviour. The larger effect of termite attack on denser beams is important because current grading practices in Australia use predicted MOE to assign timber grades, and this property is dependent on density. As a result, denser materials receive a higher grade and can be used in more structurally challenging applications. This place added importance on building inspectors to accurately determine the degree of termite damage in these materials.

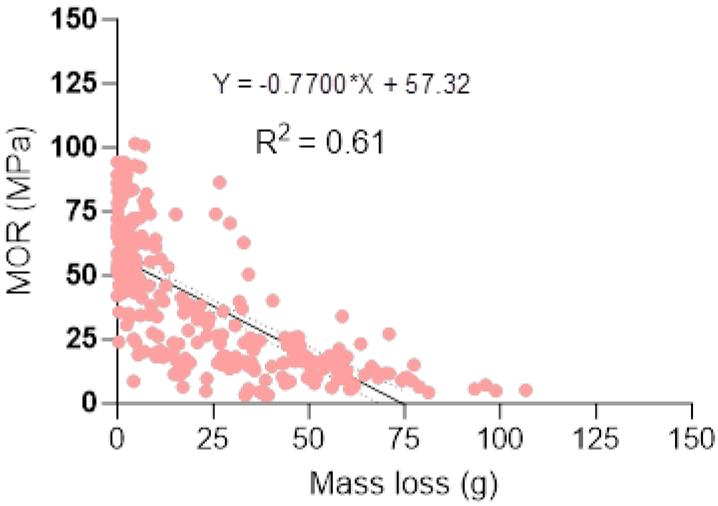

Figure 10: Relationship between Static MOR and mass loss of hybrid pine beams following subterranean termite exposure

4. CONCLUSIONS

A field exposure method successfully concentrated termite attack within a defined central region of the beams, with more than 80% of specimens showing suitable and controlled damage for mechanical testing. Dynamic BING® MOE was strongly correlated with static MOE before exposure, confirming the usefulness of acoustic measurements for estimating stiffness. Overall stiffness declined after termite exposure, although pre-exposure stiffness remained a predictor of residual stiffness. Stiffness loss increased with mass loss and was detectable even at low damage levels.

Beam mass loss was poorly correlated with initial density, while post-exposure density was only a moderate predictor of stiffness reduction. Static bending strength also decreased with termite damage but showed substantial variability, indicating that mechanical performance depended more on the location and geometry of internal galleries than on total material removal.

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