Minimally Destructive Bamboo Property Estimation of *Phyllostachys makinoi* Using Drilling Resistance Method

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Drilling resistance amplitude was used to estimate properties such as density, modulus of elasticity (MOE), and modulus of rupture (MOR) in *Phyllostachys makinoi* bamboo. The purpose of this study was to replace subjective visual estimation with a scientific method, using drilling resistance to estimate bamboo maturity, thereby providing a basis for selecting high-quality bamboo materials. The results indicated significant linear correlations between both average and maximum drilling amplitudes and bamboo density, MOE, and MOR. The coefficients of determination (R^2) for average and maximum drilling amplitude with bamboo density ranged between 0.55 and 0.56, and a significant linear correlation was also observed between average and maximum drilling amplitudes (R^2 = 0.75). Additionally, the profile curve of drilling resistance amplitude varied significantly across the thickness of the bamboo culm. From the culm surface inward (bamboo skin, flesh layer, and cavity layer), the amplitude rose rapidly, reaching a peak at approximately 28% of culm thickness, then gradually decreased, with a secondary reduction observed around 67% of the thickness, eventually reaching the hollow core. Based on these findings, maximum drilling amplitude could serve as an indicator of bamboo density and may be applied as a minimally destructive technique for evaluating bamboo quality.

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Keywords: Bamboo; Drilling; Resistance amplitude; Minimally destructive method; Wood density

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INTRODUCTION

Makino bamboo (*Phyllostachys makinoi* Hayata) plays a crucial role among economically valuable bamboo species in Taiwan, featuring high bending strength and durable material properties, as well as broad application potential. Traditionally, Makino bamboo has been widely used in crafts, papermaking, windbreak supports, and everyday bamboo-woven items. It is particularly valued in bamboo handicrafts, often serving as the primary material for Japanese-style bamboo chairs. In construction, Makino bamboo culms are frequently employed as roofing materials or structural bamboo components, adding natural beauty to buildings while also providing reliable strength.

As forest plantation resources dwindle, bamboo is increasingly viewed as an alternative to wood due to its rapid growth and stable supply. Generally, bamboo reaches mechanical strength, performance, and anatomical stability suitable for product manufacturing after a growth period of 3 to 5 years. However, to make effective use of high-quality Makino bamboo, understanding its properties is crucial. Traditionally, experienced bamboo farmers assess bamboo maturity by visually inspecting the color of the culm surface. However, this method is prone to human error, making it difficult to ensure consistent bamboo quality. Even Makino bamboo older than three years may display unstable material properties or insufficient strength due to environmental factors or other conditions. Consequently, there is a pressing need for a rapid, accurate, and minimally destructive method to assess bamboo quality, enabling the scientific selection of high-quality Makino bamboo and enhancing the precision of material selection. This approach would supplement or replace traditional visual inspections and promote the efficient utilization of Makino bamboo resources.

Wood density is a critical quality indicator, directly influencing material strength, hardness, and durability (Tomczak *et al*. 2022). Higher-density wood generally exhibits superior mechanical performance, making density an important parameter in fields such as construction materials, furniture manufacturing, and the pulp industry. Moreover, wood density holds significance in ecology and genetics. In forest ecology, wood density helps estimate forest biomass and carbon storage, providing insights into forests' roles in climate change (Gao *et al*. 2017). Geneticists also regard wood density as an essential trait in tree breeding, aiming to enhance commercial value by selecting high-density species. Wood density is a key functional trait influencing tree species' performance and growth strategies. It is also a fundamental factor in determining the physical and mechanical properties of wood, such as strength and stiffness, closely tied to forest ecosystem carbon storage and industrial wood applications (Vieilledent *et al*. 2018).

Over the past two decades, wood scientists and the forest products industry have invested in developing nondestructive testing (NDT) technologies to measure wood density, strength, and other physical properties. These NDT tools have been applied across various materials, including standing trees, for non- or minimally destructive density measurements. Among them, the drilling resistance technique measures resistance changes as an electronically controlled drill penetrates the material. This resistance reflects the material's density; denser areas cause increased resistance, while less dense areas reduce it. This method provides a profile of wood density with high sensitivity and minimal damage, leaving only a small 3 mm hole, making it suitable for high-value trees or repeated measurements (Llana *et al*. 2018). Drilling resistance values have been used to gauge wood density and diagnose wood health (Tomczak *et al*. 2022). However, few studies have applied drilling resistance values to estimate bamboo properties. Key issues addressed in recent research include the reliability of drilling resistance in detecting basic density patterns in trees and minimizing tool errors in estimating basic wood density (Singh *et al*. 2022). While drilling resistance technology has shown significant success in wood research, studies on drilling resistance in bamboo, particularly Makino bamboo, remain limited. Existing literature primarily focuses on Moso bamboo (*Phyllostachys edulis*) (Lin *et al*. 2006). Given the demand for bamboo applications, an in-depth investigation into the drilling resistance properties of Makino bamboo could support its diverse applications and meet industrial development needs.

This study aimed to fill the research gap regarding drilling resistance in Makino bamboo. Through density testing and static bending tests, the mechanical properties, including modulus of elasticity and bending strength, of Makino bamboo specimens were determined. The drilling resistance technique was then applied to measure drilling amplitude. The study further analyzed the correlations between drilling amplitude and bamboo density, modulus of elasticity, and bending strength. This analysis was aimed at establishing a rapid selection criterion based on drilling amplitude to estimate the quality of Makino bamboo, offering an alternative to traditional visual estimation methods and enhancing the efficiency and value of its diverse applications.

EXPERIMENTAL

Materials

The experimental materials in this study were Makino bamboo (*Phyllostachys makinoi*), sourced from Fuxing Township, Taoyuan City, Taiwan. Bamboo samples of varying ages and diameters were randomly selected and harvested in February 2024. Sampling was conducted from the lower culms, taken within 50 cm above ground level. The bamboo culms were split into slats and further processed into rectangular specimens, yielding a total of 42 bamboo slats. Each slat measured 200 mm (longitudinal) × 20 mm (tangential) × 6.5 to 10 mm (radial). Specimens were conditioned in a controlled environment at 20 °C and 65% relative humidity for one month prior to testing.

The experiments began with the measurement of wood density for all 42 specimens. Subsequently, drilling resistance tests were conducted at a position located a quarter distance from the ends of the materials. Finally, bending strength failure tests were performed. The wood density test, static bending test, and drilling resistance test were conducted in a temperature and humidity-controlled environment (at 20 °C and 65% relative humidity).

Wood Density Test

The wood density test followed the standards of CNS 451 (2018). The specimens were conditioned to a moisture content of approximately 12% and then cut to the specified dimensions. Length, width, and thickness were measured to calculate volume, and dry mass was recorded. Density was calculated by dividing the specimen’s weight at equilibrium moisture content (12%) by its volume, expressed in grams per cubic centimeter (g/cm^3). The bamboo specimens were weighed after achieving a constant weight in a temperature- and humidity-controlled environment to determine density, facilitating the subsequent analysis of the relationship between bamboo density and mechanical properties.

Static Bending Test

The static bending test adhered to CNS 454 (2018). This test utilized a centrally concentrated load applied by a Shimadzu UH-10A universal testing machine, with a loading rate of 100 kgf/cm^2/min. Each specimen was positioned horizontally on a support span of 18 cm, with the bamboo surface facing upward and the inner surface downward. The measurement range for calculating the slope of the stress-strain curve for MOE is from the starting point of the stress-strain curve to the maximum load at the point of material failure. Load-deflection curves were recorded during testing to determine the proportional limit, maximum load, and deflection, enabling calculation of the modulus of elasticity (MOE) and modulus of rupture (MOR), as follows,

$$MOR = \frac{3PL}{2ah^2} \ (\text{kgf/cm}^2) \quad (1)$$

$$\text{MOE} = \frac{\Delta PL^3}{4\Delta y a h^3} \ (\text{kgf/cm}^2) \quad (2)$$

where P is the maximum load, L is the span length, a is the width of the specimen, h is the thickness of the specimen, ΔP is the difference between the upper and lower load limits within the proportional range, and Δy is the corresponding deflection at the center of the span due to ΔP.

Minimally Destructive Drilling Resistance Test

Radial minimally destructive drilling resistance tests were conducted on 42 bamboo slats. The IML RESI PowerDrill 200 (PD200) was used for the drilling tests, which involved drilling radially from the bamboo surface (bamboo skin) through to the interior (bamboo flesh to bamboo cavity layer), following the radial thickness direction of the culm (Fig. 1). The specimens, free of nodes and defects and without any preservation treatments, were tested according to the IML Resistograph operating manual, with a feed speed of 2000 cm/min and a drilling rotation speed of 2500 RPM.

During the experiment, the state of the drill bit was carefully monitored. When dulling or wear was observed, the drill bit was immediately replaced to ensure that it remained sharp throughout the testing process. This measure was taken to minimize any potential impact of drill bit condition on the experimental results.

The primary variable in this study was drilling resistance amplitude (%), which quantifies the resistance force the bamboo material exerted on a drill bit moving at a constant speed. Amplitude was measured from 0 to 100% at 0.1 mm increments. Drilling resistance amplitude data were extracted using PD-Tools PRO software, with each 0.1 mm increment yielding a drilling resistance amplitude value (%). The data were exported to text files for statistical analysis using Microsoft Excel.

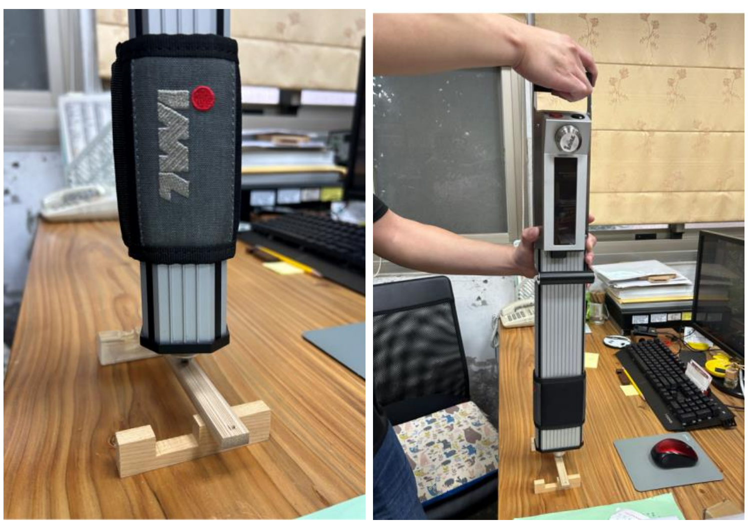

Fig. 1. Equipment for drilling amplitude of Makino Bamboo specimen detected by minimally destructive drilling resistance method

RESULTS AND DISCUSSION

The mean values and standard deviations for the density, modulus of elasticity (MOE), modulus of rupture (MOR), and drilling resistance amplitude of the 42 Makino bamboo specimens are presented in Table 1. The average density of Makino bamboo was 0.70 g/cm³, with an average MOE of 139,000 kgf/cm², an average MOR of 1,500 kgf/cm², and an average drilling resistance amplitude of 29.8%. The highest drilling resistance amplitude reached 54.9%. The average density and bending strength characteristics of the bamboo samples observed in this study aligned with trends reported in the literature, which indicates that the specific gravity of Makino bamboo generally ranges from 0.56 to 0.80, bending strength ranges from 1,300 to 2,050 kgf/cm², and MOE ranges from 95,000 to

170,000 kgf/cm² (Tang 1990).

Typically, the fiber content and air-dried density of bamboo (Moso bamboo (*Phyllostachys edulis*), Makino bamboo (*Phyllostachys makinoi*), Long-branch bamboo (*Bambusa dolichoclada*), Ma bamboo (*Dendrocalamus latiflorus*), Thorny bamboo (*Bambusa stenostachya*), and Green bamboo (*Bambusa oldhamii*)) are lowest at the base of the culm and increase with height, with the upper part of the culm displaying greater strength, which decreases towards the base (Tung 1990). Radially, the fiber content decreases from the outer to the inner portions of the culm, with air-dried density and strength following a similar trend (Cheng *et al*. 2023). Longitudinal strength is significantly higher than transverse strength, which makes bamboo prone to longitudinal splitting upon failure. In living bamboo, green moisture content is generally highest at the base and decreases with height. Basic density, longitudinal compressive strength, tensile strength, and bending strength stabilize between the fourth and fifth years of growth (Lee 2012; Wu *et al*. 2014). These findings indicate that variations in the physical properties of bamboo are influenced by both the age and height of the culm.

For *Bambusa rigida*, the green moisture content and shrinkage rate decrease as the basic density gradually increases between the ages of 0.5 and 4.5 years. By approximately 3.5 years, compressive and shear strengths stabilize. From the base to the top of the culm, there is a decreasing trend in green moisture content and shrinkage rate, while basic density, bending, compressive, and shear strength increase accordingly (Li *et al*. 2017).

In various bamboo species, such as Dama bamboo (*Bambusa wenchouensis*), Moso bamboo (*Phyllostachys edulis*), *Bambusa textilis*, Water bamboo (*Phyllostachys heteroclada*), and Green bamboo (*Bambusa oldhamii*), basic density increases with height (Su *et al*. 2007). Similarly, the basic density, bending, and compressive strength of Lei bamboo (*Phyllostachys praeox*) increase with age and height along the culm, while moisture content decreases (Yu *et al*. 2004).

In Taiwan, the specific gravity and strength of bamboo species, including Moso bamboo (*Phyllostachys edulis*), Makino bamboo (*Phyllostachys makinoi*), Long-branch bamboo (*Bambusa dolichoclada*), Ma bamboo (*Dendrocalamus latiflorus*), Thorny bamboo (*Bambusa stenostachya*), and Green bamboo (*Bambusa oldhamii*), generally reach peak levels between 3 and 5 years of growth. Additionally, the strength of bamboo culms typically increases gradually from the base towards the top (Lee 2012). Selecting mature bamboo for various applications relies heavily on skilled bamboo farmers, who assess maturity primarily by visually inspecting culm color. However, even when experienced bamboo farmers select mature culms, variations in bamboo properties necessitate further confirmation of the mechanical properties across different batches of bamboo.

In general, the density and strength of wood and certain bamboo species tend to decrease with height, as the base of the trunk or culm must bear higher loads. Therefore, it is logical that the density and strength are greater at the base. However, various factors such as species, genetics, height, age, and environmental conditions can lead to differences in these characteristics. In a bamboo forest, the swaying effect caused by wind and rain primarily occurs in the upper part of the culm. Thus, it is hypothesized here that the density and strength of the bamboo at the tip will be higher than those at the base.

Table 1. Drilling Amplitude and Flexural Strength Properties of *Phyllostachys makinoi* Bamboo Slices (n=42)

Property	Average	SD
ADA (%)	29.83	3.63
MDA (%)	54.87	6.89
BD (g/cm^3)	0.70	0.08
MOE (kgf/cm^2)	138854.4	21072.0
MOR (kgf/cm^2)	1502.5	325.0

SD, standard deviation; ADA, Average drilling amplitude (%); MDA, Maximum drilling amplitude; BD, Bamboo density; MOE, Modulus of elasticity; MOR, Modulus of rupture

The statistical linear relationships between the average density of Makino bamboo strips and their modulus of elasticity (MOE), between MOE and bending strength, and between average density and bending strength yielded coefficients of determination (R^2) of 0.61, 0.66, and 0.85, respectively, indicating highly significant correlations, as shown in Figs. 2 through 4.

In addition, the statistical linear relationships between the average drilling resistance amplitude and the average density of bamboo, between the average drilling resistance amplitude and MOE, and between the average drilling resistance amplitude and bending strength yielded R^2 values of 0.55, 0.12, and 0.41, respectively, also demonstrating highly significant correlations, as shown in Figs. 5 to 7. The results indicate that the accuracy of estimating bamboo density using average drilling resistance amplitude was relatively high, while the accuracy for estimating MOE was lower, as evidenced by the low R^2 value of 0.12.

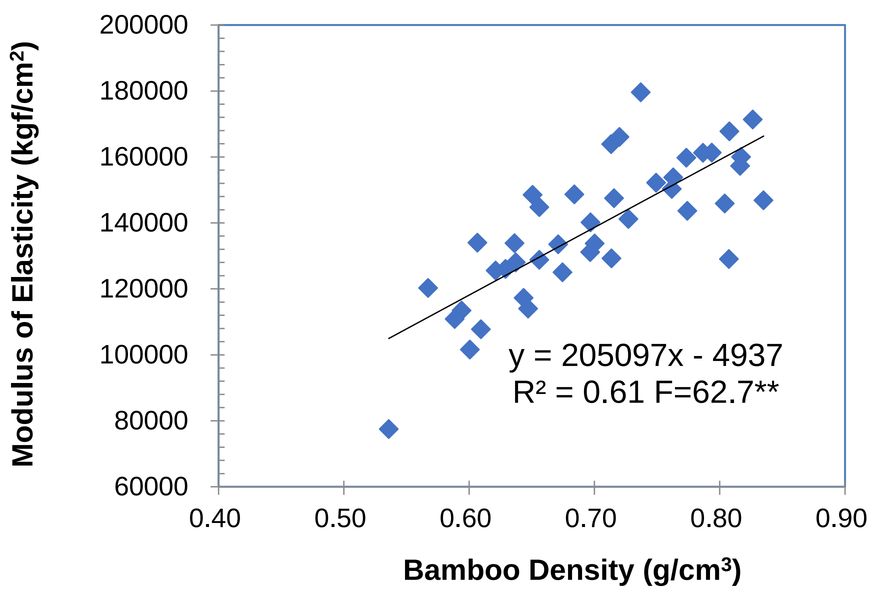

Fig. 2. Relationship between bamboo density and modulus of elasticity

Note: F value: Indicates the overall significance of the model, reflecting the impact of explanatory variables on the response variable. **: Indicates statistical significance at the 0.01 level ($p < 0.01$), denoting "highly significant" in Figs. 2 through 11.

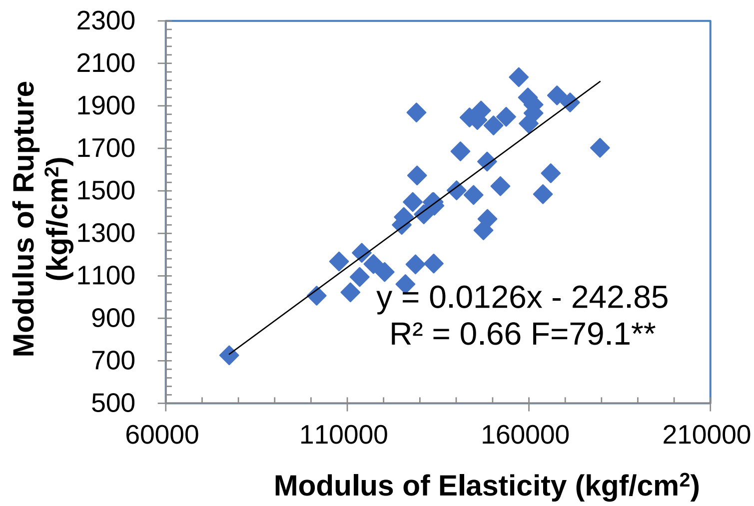

Fig. 3. Relationship between modulus of elasticity and modulus of rupture

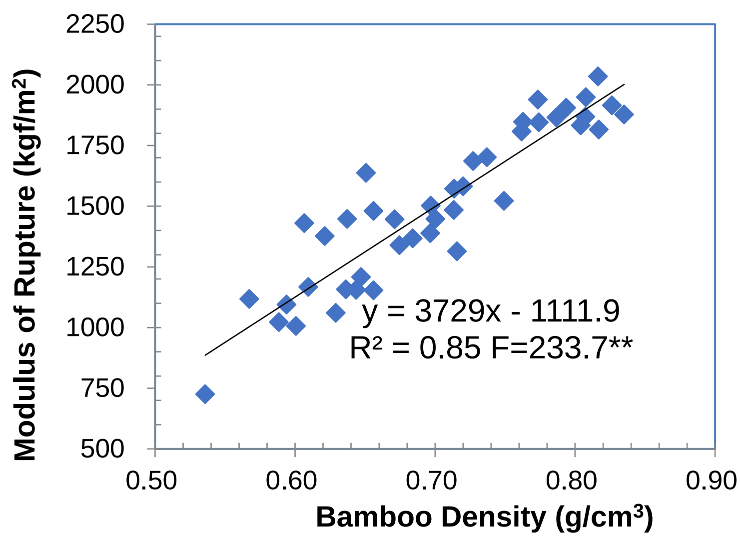

Fig. 4. Relationship between bamboo density and modulus of rupture

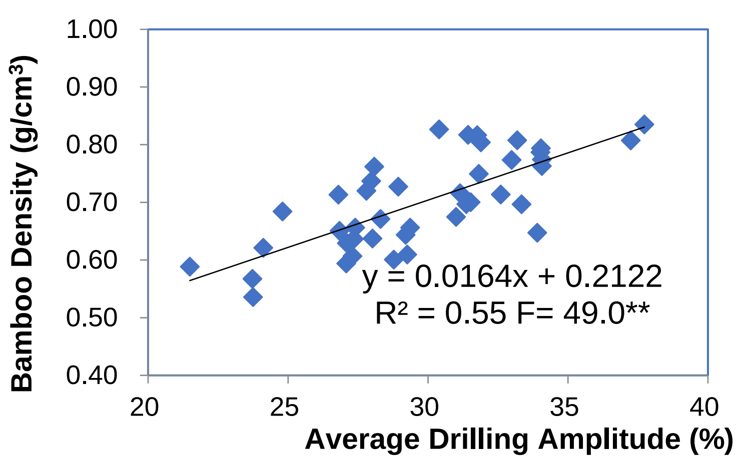

Fig. 5. Relationship between average drilling amplitude and bamboo density

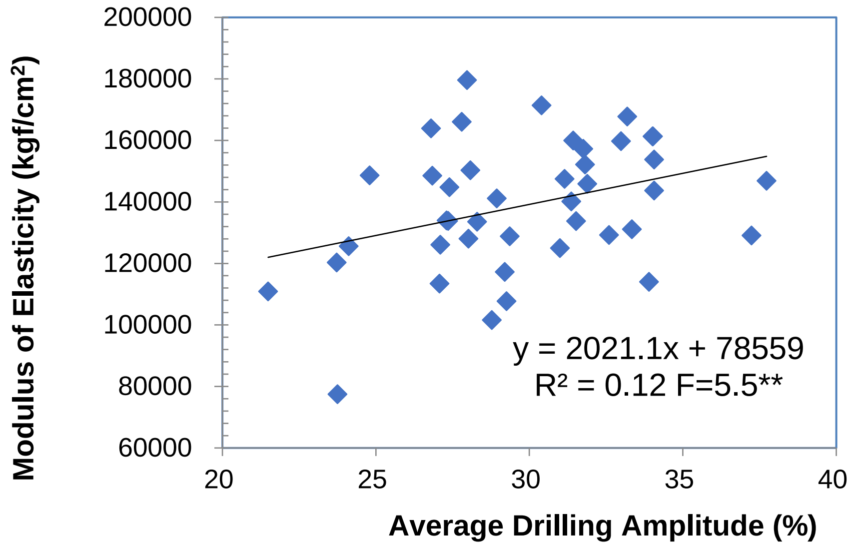

Fig. 6. Relationship between average drilling amplitude and modulus of elasticity

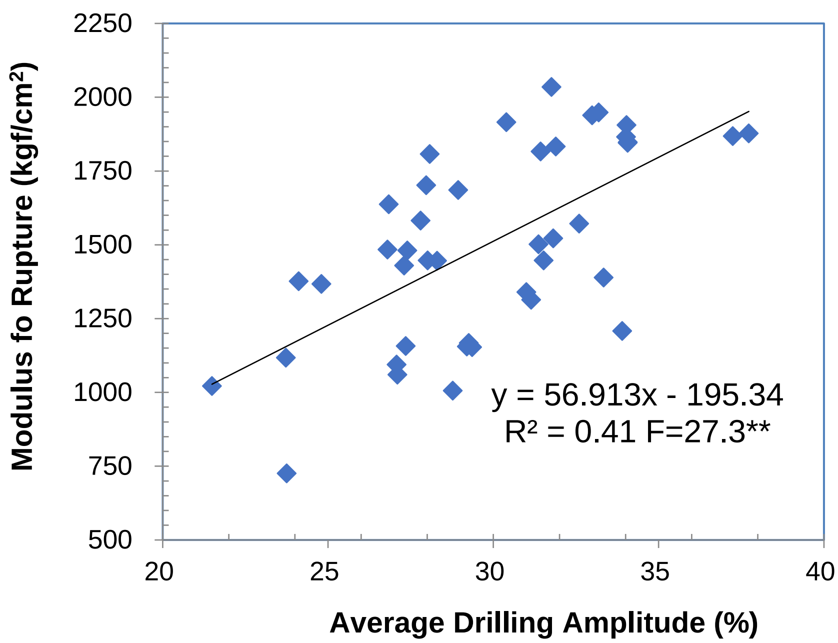

Fig. 7. Relationship between average drilling amplitude and modulus of rupture

Similarly, the statistical linear relationships between the maximum drilling resistance amplitude and the average density of bamboo, between the maximum drilling resistance amplitude and MOE, and between the maximum drilling resistance amplitude and bending strength yielded R^2 values of 0.56, 0.17, and 0.49, respectively, which also showed highly significant correlations, as depicted in Figs. 8 to 10. These results indicate that the accuracy of estimating bamboo density using maximum drilling resistance amplitude was relatively high, while the accuracy for estimating MOE was lower, as indicated by the R^2 value of 0.17. Furthermore, the maximum drilling resistance amplitude provided slightly higher predictive accuracy than the average drilling resistance amplitude.

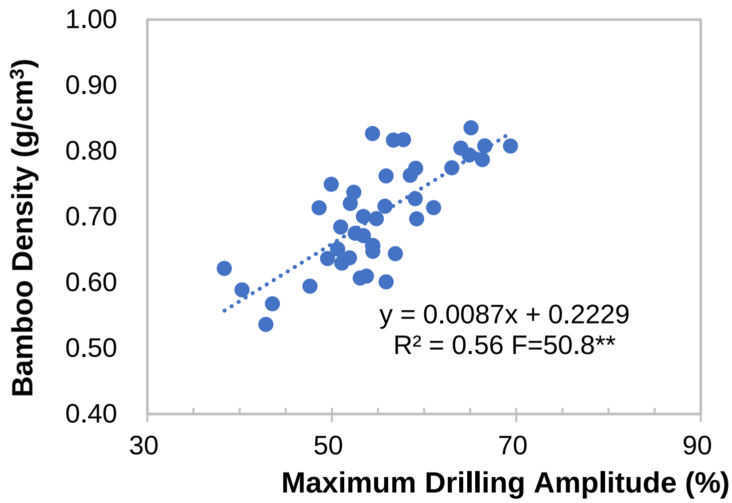

Fig. 8. Relationship between maximum drilling amplitude and bamboo density

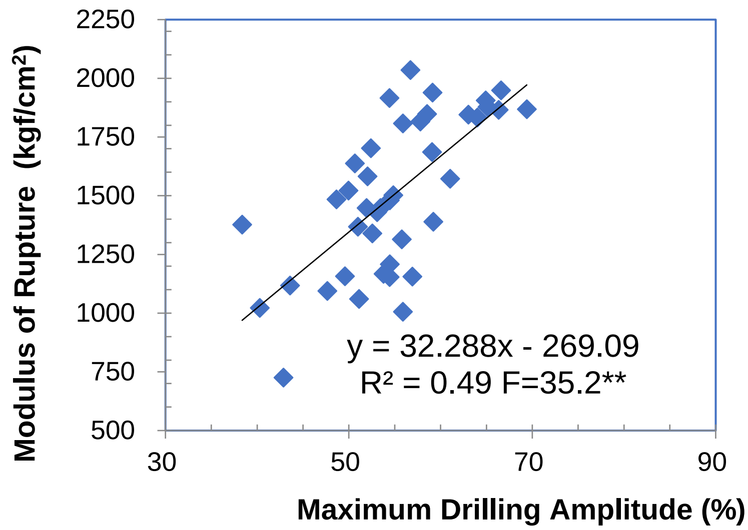

Fig. 9. Relationship between maximum drilling amplitude and modulus of rupture

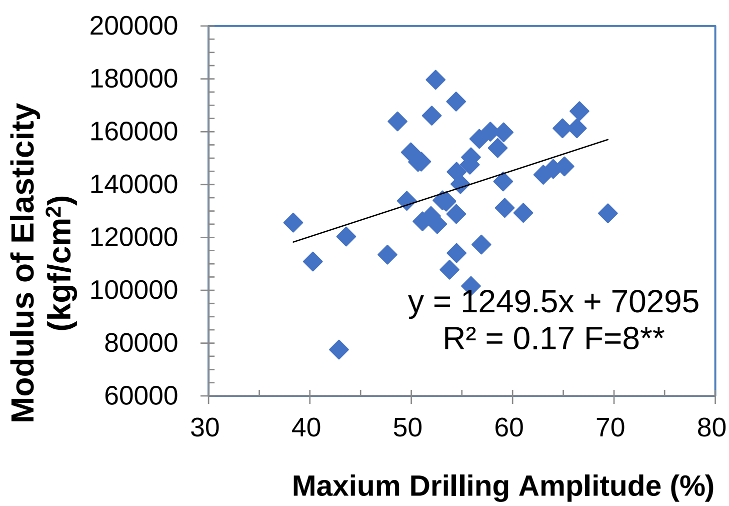

Fig. 10. Relationship between maximum drilling amplitude and modulus of elasticity

Finally, the statistical linear relationship between maximum and average drilling resistance amplitudes yielded an R^2 value of 0.79, indicating a highly significant correlation, as shown in Fig. 11.

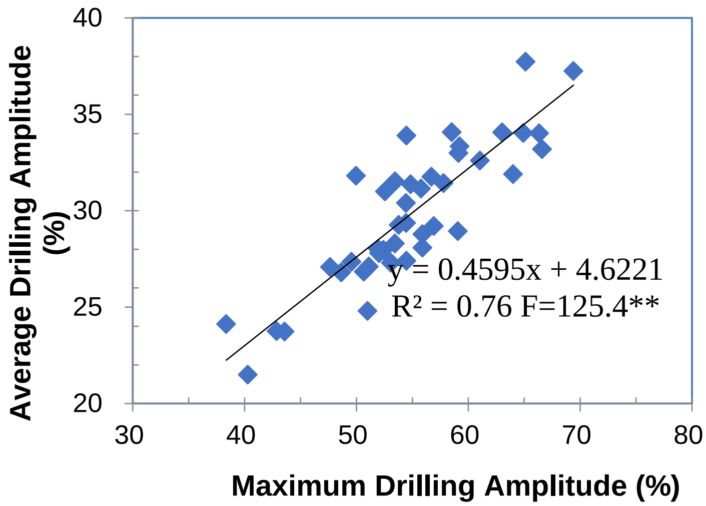

Fig. 11. Relationship between maximum drilling amplitude and average drilling amplitude

Comprehensive research on different tree species has shown a positive linear regression relationship between drilling resistance values and wood density (Icel and Guler 2016; Downes *et al*. 2018; Singh *et al*. 2022; Brunetti *et al*. 2023). Additionally, studies on *Eucalyptus grandis*, *Eucalyptus urophylla*, and their hybrid *Eucalyptus urograndis* have demonstrated that the regression model exhibits a good correlation (R^2 = 0.51 to 0.79), with statistical significance at a 95% confidence level (Singh *et al*. 2022).

In experiments with *Quercus robur*, linear regression analysis was used to examine the relationship between basic wood density and drilling resistance amplitude (%). The coefficient of determination (R^2) showed a significant linear relationship between the two variables (Tomczak *et al*. 2022). However, due to the variability in wood density, the linear model between wood density and drilling resistance amplitude performed poorly, with cases of overestimation or underestimation of basic density. The natural logarithmic model, however, provided the best fit (Gendvilas *et al*. 2024). Since there is an exponential relationship between wood strength and wood density, the relationship between drilling resistance and wood density does not follow a linear pattern. Except for Japanese cedar (*Cryptomeria japonica*), logarithmic models generally outperform linear models in fitting accuracy (Yao *et al*. 2024).

In this study, drilling resistance was used to measure the drilling resistance amplitude curve along the thickness direction of Makino bamboo strips. The results showed that the drilling resistance amplitude varied significantly in the bamboo culm thickness direction, rising sharply around 28% of the thickness from the surface (bamboo skin) inward, then gradually decreasing, with a further decline around 67% of the thickness (bamboo flesh layer), eventually reaching the bamboo cavity layer. For example, the drilling resistance amplitude curves of six selected samples, with different variations, are shown in Fig. 12. The bamboo surface near the bamboo skin area exhibited higher drilling resistance amplitude values, and as the measurement moved toward the inner bamboo flesh layer, the resistance amplitude gradually decreased. The resistance amplitude dropped more sharply as it approached the bamboo cavity layer.

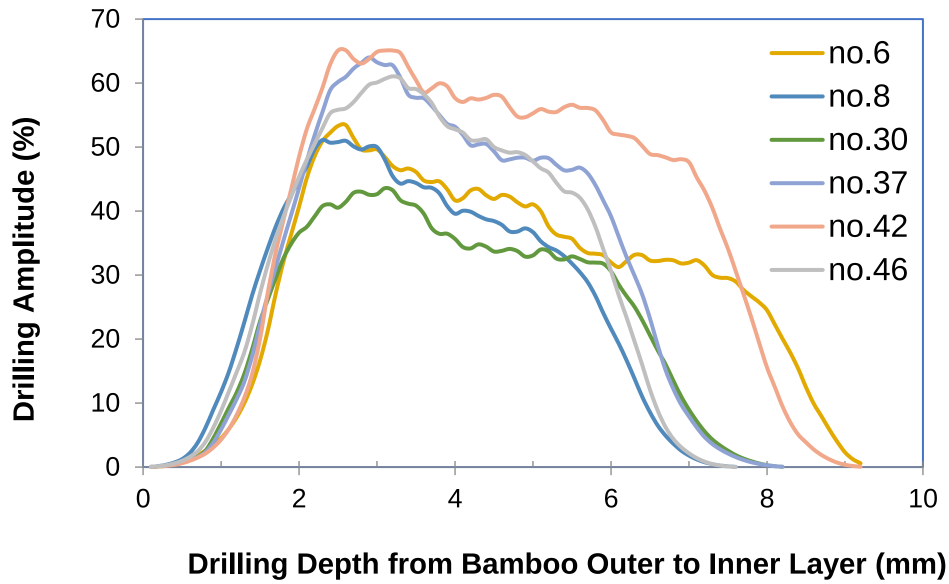

Fig. 12. Drilling resistance profiles of different bamboo slices from outer to inner layer (Drilling resistance record measured and selected from six bamboo samples)
(Note: These six samples were selected based on their drilling resistance amplitude, which shows significant high-low variations in the thickness direction of the bamboo, clearly indicating the density differences among different samples.)

When the average or maximum drilling resistance amplitude is higher, there is a trend showing that the bamboo density and bending strength are also higher. Therefore, the drilling resistance method can serve as a minimally destructive technique for selecting bamboo, replacing visual judgment of the bamboo culm's appearance or maturity, and confirming the bamboo's properties for relevant processing applications.

In this study, the drilling resistance method demonstrated potential for assessing the density and mechanical properties of Makino bamboo, providing a scientific and minimally destructive measurement method for bamboo selection, which holds significant implications for the bamboo industry. First, the moderate correlation (R^2 = 0.55 to 0.56) between drilling resistance amplitude and bamboo density shows that this method can accurately reflect the changes in the internal structure of bamboo and objectively assess its quality. However, it is important to note that the unique properties of bamboo, such as its natural variability and anisotropic nature, may influence the correlation observed. Additionally, factors such as growth conditions and maturity can further affect the drilling resistance values. Therefore, while this method offers a reliable approach for assessing bamboo quality, further research is needed to explore these influencing factors and validate the results across different bamboo species. This is particularly valuable in applications requiring high-strength bamboo, such as furniture structures or building support materials, offering a selection method superior to traditional visual inspections.

The application potential of the drilling resistance method in this study is not limited to felled bamboo but can also be used for live bamboo inspection, accurately assessing bamboo density and bending characteristics. Traditional bamboo inspection largely relies on visual or experiential judgment, which makes it difficult to deeply understand the internal structure of bamboo, especially in the preliminary screening of live bamboo. As a minimally destructive technology, the drilling resistance method allows rapid estimation of bamboo maturity, density, and internal structure, while avoiding material waste and ecological disturbances caused by cutting, offering an environmentally friendly and cost-effective solution for bamboo selection.

For felled bamboo, the drilling resistance method can also effectively estimate the uniformity of the internal structure and mechanical properties of the bamboo, which is crucial for subsequent processing applications. Through data analysis, the drilling resistance method can precisely select bamboo suitable for load-bearing structures or high-strength requirements, improving product reliability and stability, and expanding bamboo applications in different fields.

Furthermore, the changes in the drilling resistance amplitude profile curve along the thickness direction of bamboo provide in-depth insights into the internal structural differences of bamboo. The variation trends in drilling resistance from the surface to the interior of the bamboo, especially at 28% and 67% of the thickness, may reflect the distribution of fiber density and lignification levels within the bamboo. These characteristics aid in selecting bamboo with specific strength and elasticity requirements. This finding not only contributes to the precision of bamboo processing but also provides a more scientific basis for bamboo selection. Literature reports have discussed methods based on materials such as European beech (*Fagus sylvatica*) and Norway spruce (*Picea abies*), demonstrating the relationship between tree ring width, wood anatomical structure, and drilling resistance density (Arnic *et al*. 2022).

However, this study also found that the accuracy of predicting bending modulus and bending failure strength using the drilling resistance method was lower (with smaller R^2 values), indicating that while the method is effective for estimating density and strength, it has limitations in evaluating the modulus of elasticity (MOE). This may be related to the heterogeneity of bamboo's internal structure, as the arrangement of fibers and the distribution of nodes affect bending performance in a more complex manner. Therefore, when using the drilling resistance method to estimate the mechanical properties of bamboo, it is necessary to consider the heterogeneity of the bamboo and combine other testing methods or models for comprehensive analysis to improve predictive accuracy.

As a minimally destructive measurement technology, the drilling resistance method holds broad application potential. It can provide scientific foundations and efficient material selection methods for raw material grading, live bamboo inspection, and quality estimation of felled bamboo. However, it is acknowledged that the properties of bamboo can vary significantly due to factors such as moisture content, position in the stem, and age of the plant. Therefore, while the drilling resistance method offers valuable insights, the results may be specific to the samples tested in this study and should not be considered universally applicable. Although improvements are needed in predicting bending performance, the drilling resistance method is undoubtedly an important tool for bamboo selection and quality control, opening new directions for bamboo applications.

CONCLUSIONS

1. This study used the drilling resistance method to measure the drilling resistance amplitude of Makino bamboo strips and analyzed the relationship between drilling resistance amplitude and the density, modulus of elasticity, and modulus of rupture of bamboo to estimate the feasibility of using this method for assessing the maturity and quality of Makino bamboo.

2. The results showed that both the average and maximum drilling resistance amplitudes had moderately good correlations with density and modulus of rupture (MOR) but poor correlations with modulus of elasticity (MOE). The coefficients of determination for the average and maximum drilling resistance amplitudes in relation to bamboo density were $R^2 = 0.55$ and $R^2 = 0.56$, respectively, and a significant linear correlation was observed between the two amplitudes ($R^2 = 0.75$).
3. The drilling resistance amplitude profile along the thickness of the culm exhibited notable changes, with a peak amplitude at approximately 28% of the thickness and a gradual decline reaching the inner cavity at 67%.
4. These findings suggest that maximum drilling resistance amplitude can serve as an effective indicator of Makino bamboo density, demonstrating that the drilling resistance method holds potential as a minimally destructive technique for selecting high-quality bamboo. This provides a scientific basis for material selection in bamboo applications.

ACKNOWLEDGMENTS

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Availability of Data and Materials

The bamboo detection dataset used in this study is confidential but can be made available by the corresponding author upon reasonable request after the article is published online.

Competing Interests

The authors declare that there are no competing interests.

Author Contributions

Po-Heng Lin contributed to the preparation of experimental materials, conducted the experiments, and analyzed the data. **Cheng-Jung Lin** proposed the research idea and the experimental framework and wrote the manuscript. All authors read and approved the final manuscript.

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