

SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation
of Civil Structures

Pre-grading of structural timber boards by means of non-destructive dynamic testing

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Abstract

Timber constructions are rapidly gaining popularity due to their strong performance and environmental sustainability. However, certain stages of the structural timber production process, such as drying, are energy-intensive and have a significant environmental impact. Additionally, many wood species suffer from low yield. For this reason, assessing the quality of the green (freshly sawn) material before it undergoes the most costly and impactful production steps is crucial. This study investigates the variation in the dynamic modulus of elasticity (MOE_dyn), a key parameter used in mechanical grading of structural timber, as a function of moisture content during the drying process of Sardinian maritime pine boards intended for laminated timber production. The MOE_dyn was derived from the measurement of the natural frequency corresponding to the first vibration mode of the timber boards, constrained in a cantilever configuration. The measurements were carried out through a dynamic test involving the mechanical excitation of the boards and the use of accelerometers to detect the parameters of interest. The findings demonstrate that the dry MOE_dyn can be reliably estimated from the dynamic test performed on green boards. This provides a foundation for implementing a pre-grading system for Sardinian maritime pine, which could lead to reduced manufacturing costs, lower environmental impact, and improved yield of structurally graded timber.

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Peer-review under responsibility of SMAR 2026 Organizers

Keywords: Structural Timber; Green Timber Grading; Non-destructive Dynamic Testing; Dynamic Modulus of Elasticity

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1. Introduction

Timber construction is rapidly expanding across Europe due to the combined benefits of sustainability, mechanical efficiency and reduced environmental impact compared to conventional building materials. Timber products require lower manufacturing energy, act as long-term carbon sinks and align well with current research directions emphasizing innovative monitoring and assessment strategies.

Despite its advantages, the timber production chain presents critical phases, most notably kiln drying, which is often responsible for a substantial share of the total energy consumption and environmental footprint of structural timber. This issue is particularly relevant for local Mediterranean softwoods such as Sardinian maritime pine (*pinus pinaster*), whose mechanical properties exhibit significant variability and may lead to suboptimal grading yields. These challenges motivate the development of non-destructive testing (NDT) capable of predicting the final mechanical performance at the green state, thus enabling early segregation, reduction of unnecessary processing and improved overall efficiency of the supply chain.

Among the parameters used in machine grading, the dynamic modulus of elasticity (MOE_dyn) is one of the most reliable indicators of mechanical quality. It is typically derived from vibration-based measurements that exploit the fundamental natural frequency of a timber element. These techniques fit naturally within the European regulatory framework: EN 14081 explicitly recognizes stiffness-related indicating properties (IP) such as density and dynamic stiffness for machine-controlled grading, while EN 408 provides reference procedures for determining dimensions, density and static mechanical properties. Accurate knowledge of the moisture content (MC) is essential for interpreting and adjusting mechanical properties, and the EN 13183-2 electrical resistance method represents one of the reference standard adopted for MC determination.

The influence of MC on stiffness has long been recognized. Below the fiber saturation point (FSP $\approx$ 30%), timber stiffness increases as MC decreases, with a nonlinear response near the FSP. Foundational studies, such as those summarized by Gerhards (1982), document the sensitivity of elastic behavior to MC and explain its implications for structural use. More recent investigations confirm the strong correlation between MOE_dyn and MC and demonstrate the predictive capability of vibration-based methods. Villasante and Fernández-Serrano (2022), for instance, reported strong relationships between MOE_dyn obtained from the first and higher bending modes and the static modulus of elasticity (MOE_stat) in Scots pine, highlighting the potential of dynamic testing to capture both global stiffness and material inhomogeneity. Further evidence comes from studies on engineered wood, where vibration-based MOE has been successfully applied to cross-laminated timber, confirming the robustness and versatility of resonance-based non-destructive testing across different product geometries (Giaccu et al. (2019)). The sensitivity of dynamic stiffness to moisture content has also been investigated through resonance techniques by Unterwieser and Schickhofer (2011), who demonstrated that increasing MC leads to systematic reductions in MOE_dyn, and that appropriate correction models enable reliable adjustment of dynamic stiffness to reference moisture conditions. This evidence further supports the use of MC-aware dynamic grading models under varying environmental states.

Bringing these observations together, the well-documented MC-MOE relationships, the availability of fast and reliable vibration-based non-destructive techniques, the industrial need for pre-grading before energy-intensive drying, and the strategic interest in enhancing the value of Sardinian maritime pine, it becomes clear that predicting the dry dynamic modulus from measurements collected in the green state would provide substantial technical and environmental advantages.

In this context, the present study investigates the evolution of MOE_dyn along the drying process by means of accelerometer-based cantilever vibration tests and evaluates whether MOE_dyn in dry condition can be accurately predicted from green-state measurements, employing moisture-dependent correction models. The ultimate objective is to assess the feasibility of a pre-grading strategy for Sardinian maritime pine that is fully compatible with European standards and capable of reducing energy consumption, environmental impact and production costs while increasing grading yield.

2. Materials and Methods

The experimental program was designed to evaluate whether the dynamic modulus of elasticity in dry conditions can be reliably predicted from green-state vibration tests on Sardinian maritime pine boards. The methodology

includes: (i) characterization of geometric and physical properties, (ii) vibration testing in a cantilever configuration, and (iii) moisture-dependent MOE_dyn adjustment modelling.

2.1. Timber material and dataset

The experimental campaign considered 36 structural boards of Sardinian maritime pine (*pinus pinaster*), tested in two moisture states, wet (green) and dry, with paired vibration measurements at both stages.

Board geometry was recorded prior to testing. Dimensional measurements (length, width, thickness) were taken according to the requirements of EN 408, ensuring traceability and compatibility with structural-timber classification procedures. For each board, width and thickness were measured at three or four equally spaced locations and averaged. MC was measured at both wet and dry stages using a resistance-type hygrometer, following the procedure of EN 13183-2, ensuring consistent calibration and reproducibility. MC values obtained from hygrometer readings were averaged over three measurement points per board. Board mass was recorded at the dry stage, allowing estimation of bulk density using the geometrical measurements. The dynamic response was evaluated in a cantilever configuration (see §2.2). Characteristics of the tested boards are summarised in Table 1.

Table 1. Characteristics of the tested boards.

Parameter	Mean	Std. Dev.	Min	Max	Units
Sample size (boards)	36	–	–	–	–
Length L	2799.0	1.44	2794	2800	mm
Width b	105.92	3.24	100.58	111.79	mm
Thickness h	42.66	1.09	40.25	45.12	mm
Area $A = b \cdot h$	4520	196	4121	4976	mm ²
Second moment $I = b \cdot h^3 / 12$	687061	60469	574175	842234	mm ⁴
Mass (dry)	6.41	0.49	5.40	7.40	kg
Moisture (wet) MC	24.05	2.37	17.23	30.80	%
Moisture (dry) MC	11.98	0.56	10.90	12.90	%

2.2. Dynamic testing

Dynamic testing was carried out in a cantilever configuration, where the board was rigidly clamped at one end, leaving the remaining length free (Fig. 1). This configuration is widely used in vibration-based NDT of timber members because of its simplicity and suitability for long prismatic specimens, consistently with the literature on cantilever-beam dynamic modulus evaluation (Turk et al. (2008)).

The board was excited manually using a light impulse applied near the free end. A single accelerometer placed close to the free end recorded the time-history response, allowing identification of the first bending natural frequency, which was processed via FFT. Two acquisition bands were used in the dataset (700 Hz and 1000 Hz), with the 1000 Hz band providing the cleanest and most repeatable peaks; therefore, $f = 1000$ Hz is used for MOE_dyn computation in this study.



Fig. 1. Cantilever vibration setup.

The MOE_{dyn} was computed from the measured fundamental frequency using the Euler-Bernoulli beam formulation for a uniform cantilever:

$$MOE_{dyn} = [(2\pi f_1)^2 \mu L^4] / (\beta_1^4 I) \quad \beta_1 = 1.875$$

where:

- f_1 is the first bending natural frequency,
- μ is the linear mass,
- L is the effective free length,
- I is the section second moment of area.

The expression is the standard reference for MOE_{dyn} estimation in slender timber members tested as cantilevers and is consistent with validated approaches in the technical literature (Barrett and Hong (2010)). Shear and rotary-inertia effects (Timoshenko corrections) were considered unnecessary because the tested boards have high slenderness ($L/h \approx 65$), and only the first vibration mode was used, a regime where Euler–Bernoulli assumptions remain valid (Villasante and Fernández-Serrano (2022)). Paired wet/dry dynamic results of the tested boards are summarised in Table 2.

Table 2. Paired wet/dry dynamic results.

Metric	Wet (mean ± SD)	Dry (mean ± SD)	Δ (abs)	Δ (%)	Units
Fundamental frequency f_1	20.34 ± 2.96	23.53 ± 2.79	3.19 ± 1.21	16.35 ± 7.79	Hz / %
MOE_dyn	5.998 ± 1.497	6.010 ± 1.419	0.012 ± 0.490	0.96 ± 8.52	GPa / %
Moisture content (MC)	24.05 ± 2.37	11.98 ± 0.56	12.07 ± 2.30	–	%

2.3. Moisture-dependent adjustment models

The relationship between MC and the mechanical properties of wood is well documented to be non-linear below the FSP, owing to the progressive loss of bound water and the associated stiffening of the cell wall. Several recent studies report pronounced non-linear variations of stiffness for MC below approximately 25–30%, affecting both static and dynamic moduli (Carreira et al. (2022); Hassan Vand & Tippner (2024); Yassine et al. (2025)).

This behaviour suggests that moisture-adjustment models accounting for curvature (e.g. power-law or sigmoidal forms) may offer improved predictive accuracy, especially when wet and dry states span a wide MC range.

However, in the present dataset the wet-dry MC interval is relatively narrow (wet $\approx$ 24%, dry $\approx$ 12%, both clearly below FSP), and the MOE_dyn values maintain a nearly proportional relationship between the two states. For this reason, and to provide a transparent first approximation, the dry-state MOE_dyn is initially predicted using a simple linear correction model of the form:

$$\text{MOE}_{\text{dry}} = \text{MOE}_{\text{wet}} (1 + \alpha \Delta \text{MC}),$$

where ΔMC is the difference in moisture content between wet and dry states, and α is a species-dependent empirical coefficient. This approach is consistent with linear corrections used for other hardwood and softwood species documented in MC-MOE relationships (EN 13183-1).

This linear model is intentionally adopted as a first step, before considering more elaborate non-linear formulations, in order to evaluate how much predictive power can be achieved with the simplest possible model, assess whether the experimental wet-dry relationship exhibits residual curvature significant enough to justify more complex moisture-adjustment schemes, and maintain continuity with existing grading approaches that commonly rely on linear MC adjustments.

3. Results

The experimental dataset includes the paired wet/dry vibration measurements carried out on the 36 boards, together with the geometrical and physical values (Table 1). The fundamental bending frequency was clearly identifiable for all specimens in both moisture states. As expected, frequencies increased after drying: values rose from an average of 20.34 Hz in the wet state to 23.53 Hz in the dry state, corresponding to a mean increment of 3.19 Hz ($\approx$ +16%). These variations are consistent with the reduction of mass and the increase in stiffness associated with moisture loss in the sub-FSP regime, where wood properties are known to vary non-linearly with moisture content.

The corresponding MOE_dyn, derived from the first bending mode at the 1 kHz acquisition band, displayed less pronounced average variation, with population means of 5.998 GPa (wet) and 6.010 GPa (dry). Although the mean difference is small (+0.012 GPa), individual boards show noticeable scatter (SD $\approx$ 0.49 GPa), which reflects material heterogeneity as well as the sensitivity of dynamic modulus estimation to small geometric and mass variations. These values, together with the paired moisture contents (wet $\approx$ 24%, dry $\approx$ 12%), are summarised in Table 2.

Despite the relatively modest mean change in dynamic stiffness, wet-state measurements proved to be strongly correlated with the corresponding dry-state values. A linear regression model produced:

$$\text{MOE}_{\text{dry}} = 0.638 + 0.896\text{MOE}_{\text{wet}} \quad R^2=0.893$$

indicating that wet-condition vibration tests are effective predictors of the dry dynamic modulus for the examined boards. The scatter plot with regression line, 1:1 reference and 95% prediction band is shown in Figure 2. The prediction interval width is compatible with the intrinsic variability of maritime pine and with the non-linear sensitivity of MOE to moisture below the FSP.

Overall, the results highlight that frequency measurements, more sensitive to moisture-driven changes in mass and stiffness, exhibit a clearer wet-dry separation compared to the modulus values, while still providing a robust basis for predicting dry MOE_dyn from green-state tests.

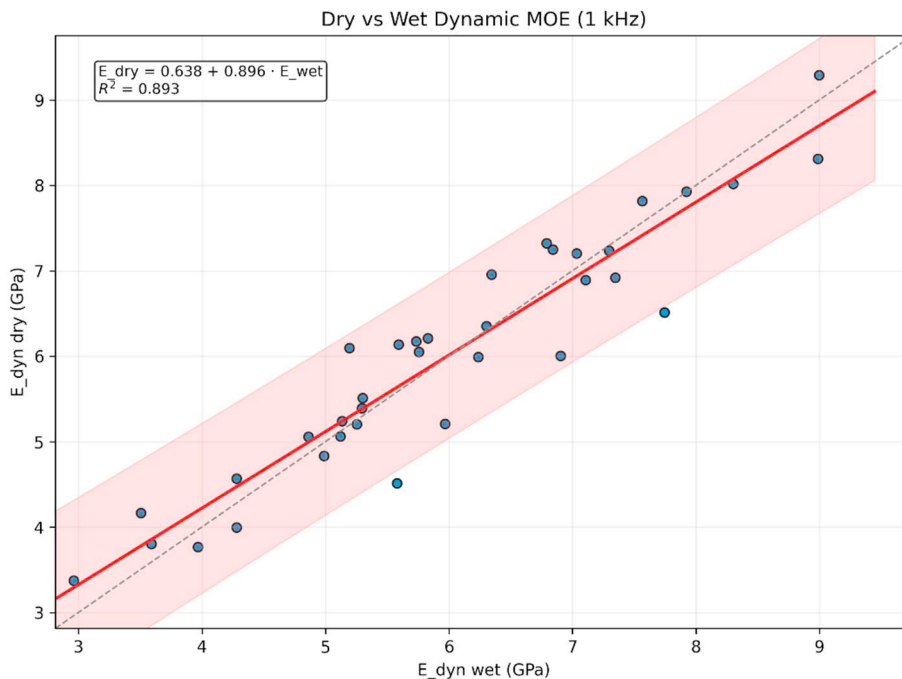


Fig. 2. MOE_dyn vs MOE_wet at 1 kHz. The red line represents the linear regression model, while the shaded area indicates the 95% confidence band. The dashed line denotes the 1:1 correspondence between wet and dry measurements.

4. Discussion

The results indicate that vibration testing in the wet state provides a reliable basis for estimating the dry MOE_dyn, even when using only a first-order linear correction model. The strong linear correlation observed between wet- and dry-state dynamic moduli ($R^2 \approx 0.89$) shows that most of the board-to-board stiffness variability is already present and detectable in the green condition, making the wet test an efficient pre-grading tool.

Although the literature consistently emphasises that the relationship between moisture content and mechanical properties is intrinsically non-linear below the FSP, with recent studies showing marked curvature or steep stiffness changes for MC below 25–30% (Carreira et al. (2022); Hassan Vand & Tippner (2024); Yassine et al. (2025)), the behaviour observed in the present dataset is remarkably close to linear. This is likely due to two factors:

- The wet–dry MC interval is moderate ($\approx 12\%$ difference), and entirely within the sub-FSP range where non-linearities are present but less dramatic than in broader MC transitions (e.g. from $> 40\%$ to $< 10\%$).
- The experimental scatter of the MOE_dyn is relatively large, masking small degrees of curvature. In this context, introducing a non-linear model may improve nominal accuracy but offers limited practical benefit unless additional parameters are tightly constrained.

Consequently, the linear model used as first approximation proves unexpectedly effective: it captures the predominant trend, yields small mean prediction error, and maintains the simplicity typically preferred in industrial pre-grading contexts. The regression slope close to unity (≈ 0.90) further indicates that dry MOE_dyn increases almost proportionally to wet MOE_dyn, with no strong evidence of curvature within the tested range.

This does not contradict the non-linear nature of wood-moisture interactions reported in the literature; rather, it suggests that within the specific MC band of this experiment, the portion of the non-linear curve being sampled is nearly straight. Thus, applying a non-linear model at this stage would risk over-fitting without producing a tangible improvement in predictive power.

In summary, the linear moisture-adjustment model provides a robust, practical and sufficiently accurate first-order predictor for converting wet-state vibration results into dry-state stiffness for the tested material. The adoption of a non-linear model remains justified scientifically, especially for larger MC spans or species exhibiting stronger moisture sensitivity, but its implementation is not required for a reliable first approximation in the present conditions. The results support the use of green-state dynamic testing for pre-grading, provided that an appropriate linear MC adjustment is applied.

5. Conclusions

This study shows that wet-state vibration testing provides a reliable basis for estimating the dry MOE_dyn of Sardinian maritime pine boards. Despite the well-documented non-linear influence of moisture below the FSP, the wet-dry relationship observed here is locally near-linear, owing to the moderate MC interval investigated ($\approx 24\%$ to 12%). As a result, a simple linear moisture-adjustment model proved to be an effective first-order predictor, with strong correlation between wet and dry MOE_dyn values ($R^2 \approx 0.89$).

These findings support the practical feasibility of green-state pre-grading, while leaving room for future refinement using non-linear models in cases involving wider moisture ranges or stronger MC sensitivity.

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