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Analysis of the Strain-Dependent Damping of Paulownia Wood to Reduce Vibrations in Maritime Transport

Jürgen Göken[1], Nicolas Saba[2]

[1]University of Applied Sciences Emden/Leer Faculty of Maritime Sciences, Leer, Germany
[2]University of Balamand Faculty of Engineering, Department of Mechanical Engineering, Tripoli, Lebanon

Abstract

The shipping industry is striving to optimise efficiency and safety regarding sound and vibration protection through innovations. A key aspect of these innovations is the development of new insulation materials that help minimise vibrations and noise. In addition to protecting the ship's structures, the protection of the crew members is also of great importance. Noise pollution and persistent vibrations can adversely affect the health and well-being of the crew. This, in turn, can reduce performance and responsiveness in critical situations. Paulownia wood is an innovative natural product and a fast-growing and lightweight wood that can be cultivated worldwide. In light of the increasing interest in sustainable building materials and the growing demand for lightweight construction solutions, especially in shipbuilding, it is crucial to better analyse and hence understand the damping potential of Paulownia wood which significantly affects its acoustic behaviour. Damping was investigated by measuring the logarithmic decrement of freely decaying bending oscillations as a function of the maximum strain amplitude. The measurements were carried out on a common Paulownia species (obtained from plantations in Georgia, Italy, and Spain) and a new species of Paulownia obtained from a plantation in Germany. It was found that all damping curves exhibited a strain-independent and a strain-dependent range. Moreover, it was shown that the influence of the fibre orientation on the damping behaviour was less than expected.

Keywords: Wood, Bio-based materials, Damping, Dynamic mechanical analysis

1. Introduction

Sustainable thinking and action are gaining increasing importance in society. This is evident, for example, in shipping, where the recycling of ship parts plays a significant role [1]. Therefore, it is advisable to consider resource-saving and easily recyclable materials during the construction phase of the ships. Ecological action is accompanied by an increased demand for sustainable and renewable raw materials. Wood is one of these raw materials.

Something that is often forgotten: Wood has a long and significant tradition in shipbuilding and played a crucial role for centuries. The oldest known boats are dugouts, which were used before Christ. Boats from ancient Egypt, built from Cedar wood imported from Lebanon, are also of historical importance. They were used for transport, hunting, and exploration [2]. Even in modern times, wood holds a significant position in shipbuilding and is employed in various areas. Wood is often deployed in the interior design of ships due to its aesthetics and structural properties. Its high-quality appearance gives wood a warm look and creates a luxurious atmosphere [3].

The shipping industry is working towards becoming eco-friendlier without compromising on safety standards for ships and their crews. Reducing vibrations and noise is essential to safeguard the ship's structure and the health and well-being of crew members. These challenges are managed according to recognised international regulations [4-6]. To comply with these standards, it is vital to conduct studies on renewable materials and their properties.

A fast-growing raw material is the wood of the Paulownia tree. This tree is also known as the Empress tree, Royal Paulownia, or Kiri. In one year, this tree grows an average of 4 metres in height and about 2 centimetres in width. After approximately

Address for Correspondence: Jürgen Göken, University of Applied Sciences Emden/Leer Faculty of Maritime Sciences, Leer, Germany
E-mail: juergen.goeken@hs-emden-leer.de
ORCID iD: orcid.org/0000-0002-4847-2870

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a period of 10 years, 0.5 m^3 to 1.5 m^3 of wood can be harvested [7]. With a specific density of about 250 kg/m^3 (see Table 1), this wood is also considered very light. Paulownia wood is gaining significant attention in technical fields because of its impressive strength-to-density ratio. In addition to this, the large size of its leaves gives the Paulowina tree a key position in terms of photosynthetic efficiency. One Paulownia tree can absorb daily up to 22 kg of CO_2 and produce approximately 6 kg of O_2. In comparison, a mature tree absorbs approximately 22 kg of CO_2 from the atmosphere annually [8].

As the Paulownia tree is better known worldwide as the Kiri tree, this name will be retained in the following. In Table 1 some essential properties about Kiri wood are listed.

Kiri wood is utilised in various applications. Some fields of its use including concrete examples are shown in Table 2.

For the maritime industry, the damping properties and density of wood are of particular interest. However, these properties are still largely undetermined. Establishing these properties will enable a definitive conclusion on the suitability of Kiri wood for noise and vibration insulation. Potential areas of application include cabins on cruise ships and yachts. The potential use of this renewable raw material in shipbuilding concerns, for example, the cladding of cabins or its utilization as a structured wall element.

The fire hazard on board ships is generally a significant concern. Thus, the International Maritime Organization developed fire safety regulations, including the "International Code for Application of Fire Test Procedures" (FTP Code) [11]. Since wood is already being used (e.g., in the interiors of yachts), there are no new regulatory barriers to the use of Kiri wood to overcome in this regard.

Its low density makes it ideal for a variety of lightweight construction projects. Furthermore, that the lower weight results in reduced fuel consumption, enabling a more environmentally friendly journey [12]. In addition to its low density, Kiri wood is highly recyclable, setting it apart from other materials [13].

In this work, the assessment of the suitability of Kiri wood for damping vibrations is performed based on strain-dependent damping measurements. These measurements were executed at room temperature and constant moisture content.

2. Experimental Details

2.1. Material

It was important to obtain Kiri wood from different growing regions, as the growth conditions (e.g., nutrient content of the soil) and climatic circumstances influence the structural development of the wood [14]. The Kiri wood to be analysed was provided by a supplier specialising in Kiri wood from controlled European sources. This company has access to various plantations across Europe.

Tested samples were taken from Kiri trees originating from plantations in a) Italy, b) Spain, c) Georgia, and d) Germany. Note: The Kiri trees from German plantation are considered non-invasive species (called NordMax21®) and are a hybrid of Paulownia tomentosa and Paulownia fortunei. The genetic

Table 1. *Properties of Kiri wood [9]*

Property	Description of Kiri wood
Specific density	About 250 kg/m^3; comparison: oak: ~ 770 kg/m^3; beech: ~ 720 kg/m^3; pine ~ 480 kg/m^3; spruce: ~ 450 kg/m^3 → Low weight saves transport and energy costs.
Strength	Honeycomb-like cell structure → Kiri wood is very strong and stable in relation to its weight.
Dimensional stability	Extremely low swelling and shrinking behaviour → This makes Kiri wood the first choice in environments with changing humidity levels.
Thermal conductivity	Only 0.09 W/mk → Kiri wood stores a lot of air in its vacuoles and therefore insulates more than twice as well as oak or beech.
Weather-proof	No splitting, no cupping, no warping
Knot occurence	Completely knot-free assortment is possible → The delicate grain and pleasantly smooth feel make it attractive for different areas of application.
Processing	Does not splinter, can be easily processed manually and mechanically, can easily absorb glazes and varnishes, and is very good for gluing

Table 2. *Application areas of Kiri wood [10]*

Mobility	Construction	Lifestyle
Ship and boat construction, surfboards, model and glider airplanes, caravan manufacturing	Ceilings, stairs, windows, modular buildings, tiny houses, wooden facades, structures for trade shows, events, and stages	Furniture, home accessories such as vases and bowls, garden furniture, packaging and storage containers

influence of Paulownia tomentosa provides this hybrid breed with particularly wide site tolerance and high frost resistance. The cross-breeding partner, Paulownia fortunei, dominates the straight, robust, and homogeneous stem growth of this variety [15]. Samples of this special variety (location of the German plantation: Ladenburg, growing time: 11 to 12 years) were harvested for the first time and made available for this study.

All samples used in this work were sourced from wood harvested about a year ago. The Kiri wood was delivered as boards which were cut in the direction of the tree trunk's growth. The cutting direction was not necessarily the growth direction of the tree. This resulted in an inconsistent fibre orientation of the samples which were used as bending beams. The designation of the fibre orientations is shown in Figure 1.

2.2. Measuring Procedure

Damping measurements were carried out at room temperature and constant moisture content [equilibrium moisture content ~ 10% (accompanied by randomised corresponding measurements)] using wooden samples with rectangular shape and the following dimensions: thickness *a* about 3 mm, width *b* of 10 mm and total length *l* of 120 mm. The specially configured experimental damping setup is shown in Figure 2. A metallic cylinder is rotated using a hand crank. On this cylinder, a bevelled cuboid touches the free end of the bending sample and sets it into vibration. Depending on the degree of overlap between the bevelled cuboid and the free end of the bending beam, a variation in the initial amplitude can be achieved. When contact with the sample is lost, the deflected bending beam undergoes free damped harmonic oscillation. The oscillation amplitude is measured using a laser triangulation sensor (model: ILD1320-100,

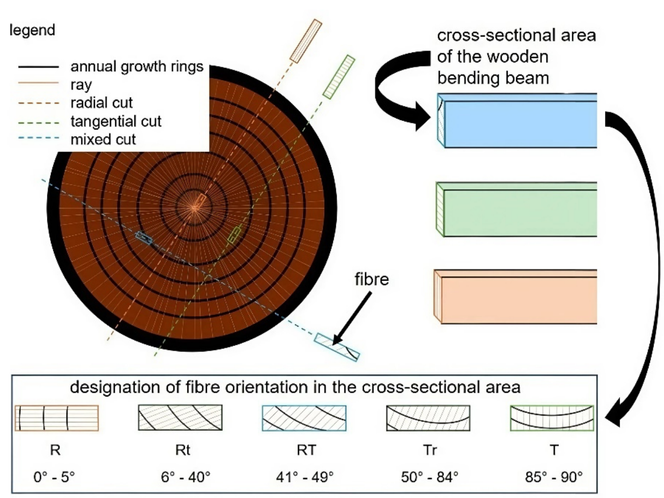

Figure 1. *Fibre orientations of the bending beams and designation of the fibre orientation. Adopted from [16] (modified)*

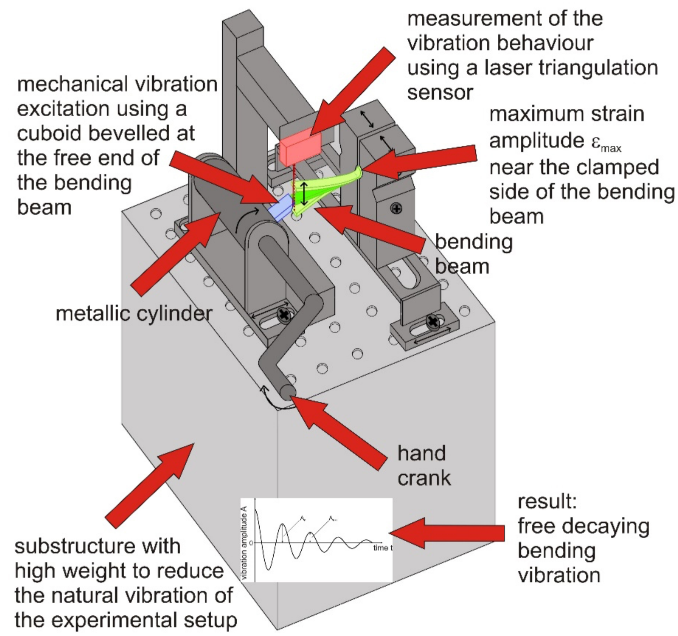

Figure 2. *Experimental damping setup. Adopted from [16] (modified)*

Micro-Epsilon, Ortenburg, Germany) with a set sampling rate of 2000 measurement points per second. It is attached above the free end of the sample and records the vibration data as a function of time by measuring distance data. The laser software transfers the data to a PC and visualises it.

According to Figure 2, the maximum strain ε_{max} is generated near the clamped side of the bending beam, which is used as a reference value for amplitude-dependent damping measurements.

Material damping was measured in terms of the logarithmic decrement δ which is defined by [17]:

$$\delta = \frac{1}{k} \ln \left(\frac{A_n}{A_{n+k}} \right) \quad (1)$$

and represents the measure of the rate of decay in vibration amplitude of a harmonically decaying oscillation. In Equation (1), the vibration amplitude A_n at time nT (T: periodic time) and A_{n+k}, the vibration amplitude after k oscillation periods at time $(n + k)T$, are shown, where n and k are whole numbers. To obtain the current damping behaviour of a damped system, two consecutive oscillation amplitudes are therefore considered [18].

Damping is subject to the superposition principle, meaning that various external damping mechanisms (such as apparatus damping and air damping) can overlap and thus distort material damping. It is not trivial to detect this additional damping, and in individual cases it may be difficult to determine. This makes it challenging to compare absolute damping values.

Relative changes between damping data naturally remain even if the apparatus damping is retained.

As the bending sample exhibits approximately harmonic decaying behaviour immediately after vibration excitation, the vibration frequency f can be calculated according to $f = 1/T$ (T: periodic time). Knowing f and the specific density ρ, the bending modulus E_{bend} (here in the unit N/mm^2 (or MPa)), can be determined as [19]

$$E_{bend} = 10^{-12} 4\pi^2 f^2 \frac{l^4}{c^4} \frac{\rho ab}{I_y}, \quad (2)$$

where c is a constant (eigenvalue) taken from the modal analysis of a cantilever beam. Using $c = 1.875$ the first vibration mode of such a beam is described. I_y is the area moment of inertia of a rectangle (→ end face of the bending beam) with respect to the resistance to bending around the Y-axis, with $I_y = (a^3 b)/12$ (a: thickness, b: width).

More detailed information about the experimental setup and the extensive data analysis (using self-written software) can be found in another own work [20]. A key component of the software is the consideration of possible offsets and noise when recording the vibration amplitudes. Ignoring offsets and noise can lead to excessively high values of the logarithmic decrement due to the logarithmization [see Equation (1)].

3. Results

In Figure 3, the strain-dependent damping of Kiri wood from Georgia can be seen. The bending modulus E_{bend} was calculated according to Equation (2) and added as well.

The damping curves can be divided into a strain-independent range (δ_0 → parallel to the X-axis) and a strain-dependent range ($\delta_h(\varepsilon_{max})$ → increase with increasing maximum strain amplitude) where δ_h is the hysteretic damping (structural damping). Such behaviour is well known for strain-dependent damping measurements of metals [21]. A noticeable increase in material damping is observed at a maximum strain amplitude of approximately 0.1 (in terms of ε_{max} x 1000). The tangential fibre orientation T appears to result in a higher material damping at the same strain amplitude.

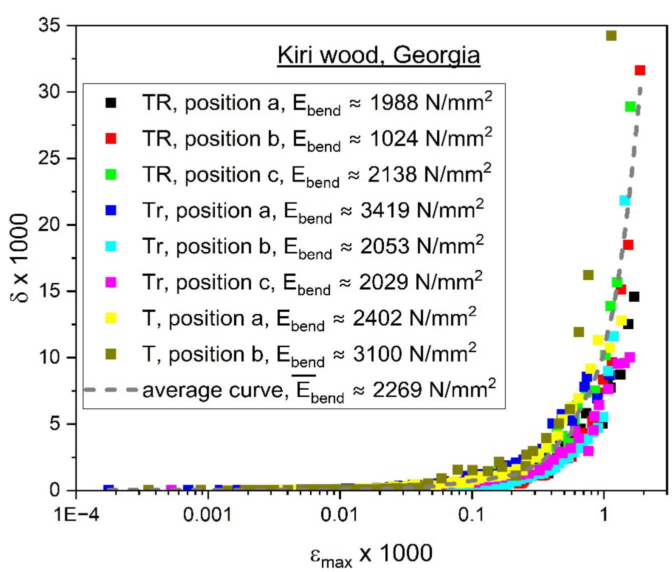

Figure 3. Strain-dependent damping of Kiri wood from Georgia in consideration of the fibre orientation. The calculated bending modulus E_{bend} is added

Kiri wood from Germany (Figure 4) shows the same curve progression as Kiri wood from Georgia. Here, TR and Tr are the directions that lead to increased damping. The curve profile, represented by the averaged curve, is similar to the profile of the averaged curve of Georgian wood. The bending modulus of the Kiri wood sample from Germany is higher than that of the Georgian wood, resulting in slightly higher strength.

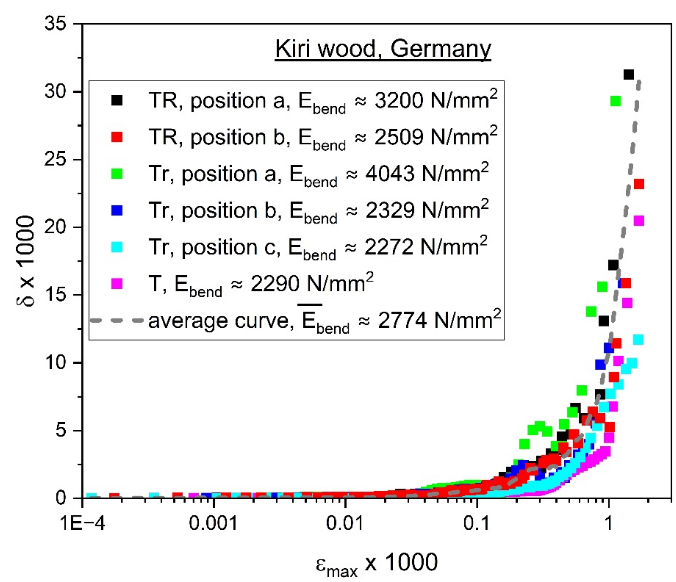

Figure 4. Strain-dependent damping of Kiri wood from Germany in consideration of the fibre orientation. The calculated bending modulus E_{bend} is added

A significant difference in both the strain-dependent damping and the bending modulus can be observed in the Italian Kiri wood samples, Figure 5. The bending modulus is significantly lower than that of the Georgian or German samples. For example, when considering the logarithmic decrement at maximum strain amplitude with a value of 1 (in terms of ε_{max} x 1000), an approximately 30% lower value of material damping is recorded. The maximum damping is only reached at higher maximum strain amplitudes. Moreover, the wood tested is less rigid than the samples from Georgia and Germany.

Figures 6-8 show the results of strain-dependent damping measurements of Kiri wood samples from Spain. There was mainly a radial fibre orientation present. In all cases, the bending modulus is greater than the value of the samples from Italy, Germany, and Georgia. In the higher strain range, a comparatively high damping is revealed.

Figure 9 illustrates the respective averaged strain-dependent damping curves. It becomes clear once again that the damping of the Kiri wood samples from Georgia and Germany are very similar. To illustrate the difference in damping data, the data was taken at maximum strain amplitudes of 0.1 and 1 (in terms of ε_{max} x 1000, see also reference lines) and are shown in Table 3. It is evident that the samples from Spain have approximately double the values of strain-independent damping compared to the other samples. In the strain-dependent damping range, the samples from Italy exhibit lower damping than the samples from Georgia and Germany. However, the damping values of the samples from Spain at this maximum strain amplitude is approximately double that of the others.

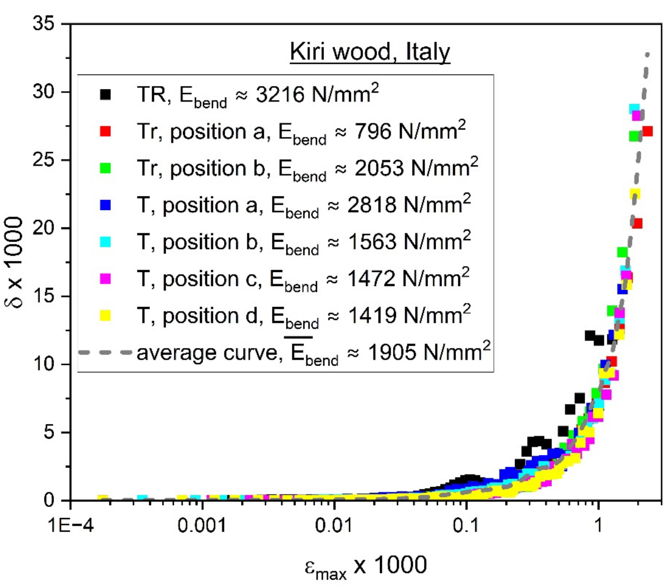

Figure 5. *Strain-dependent damping of Kiri wood from Italy in consideration of the fibre orientation. The calculated bending modulus* E_{bend} *is added*

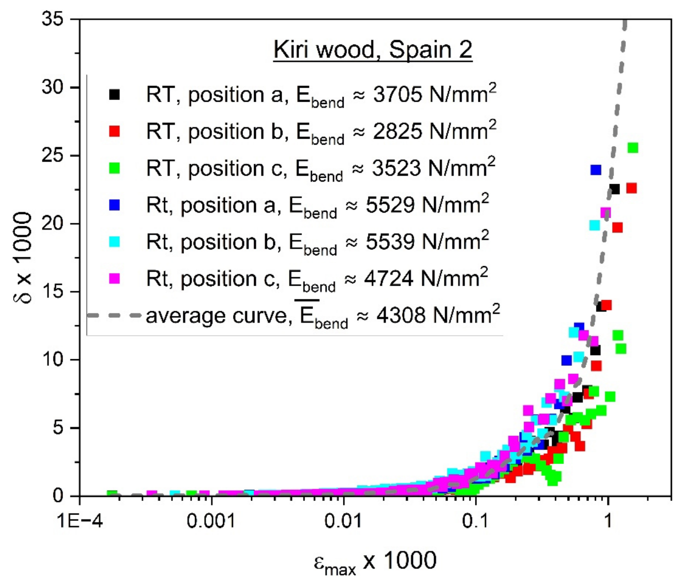

Figure 7. *Strain-dependent damping of Kiri wood from Spain (2) in consideration of the fibre orientation. The calculated bending modulus* E_{bend} *is added*

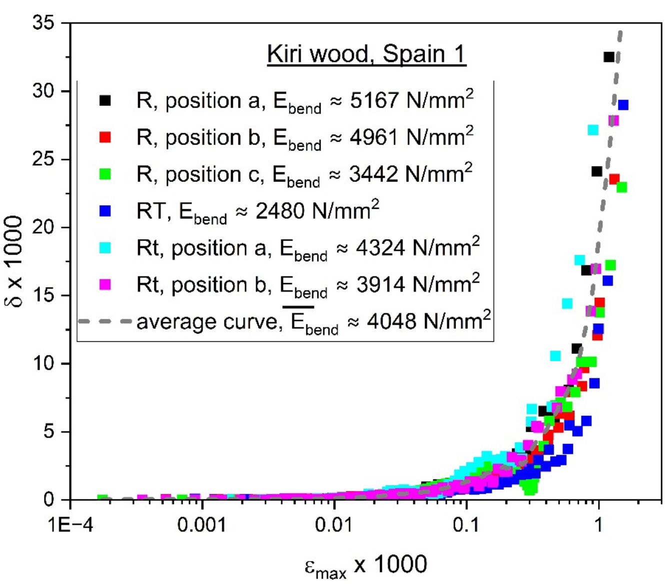

Figure 6. *Strain-dependent damping of Kiri wood from Spain (1) in consideration of the fibre orientation. The calculated bending modulus* E_{bend} *is added*

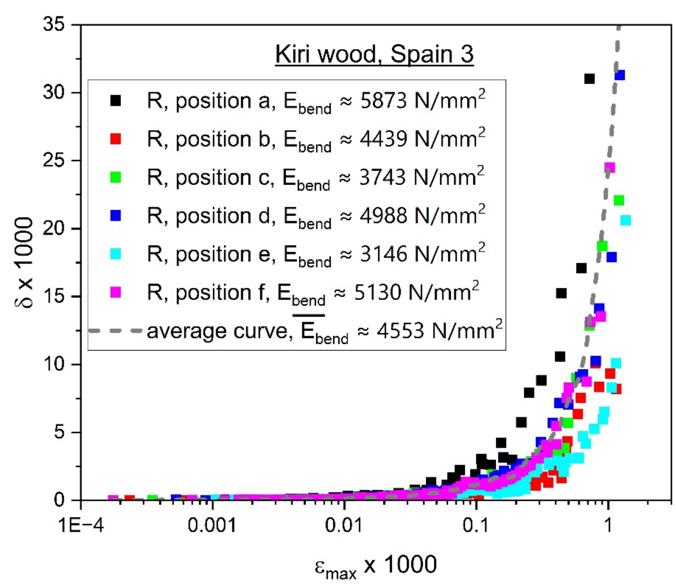

Figure 8. *Strain-dependent damping of Kiri wood from Spain (3) in consideration of the fibre orientation. The calculated bending modulus* E_{bend} *is added*

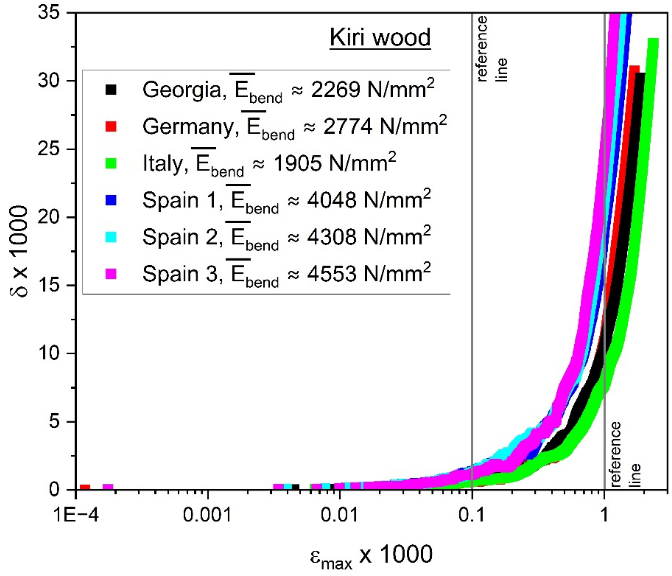

Figure 9. *Mean strain-dependent damping curves of Kiri wood. The calculated mean bending modulus* $\overline{E}_{bend}$ *is added*

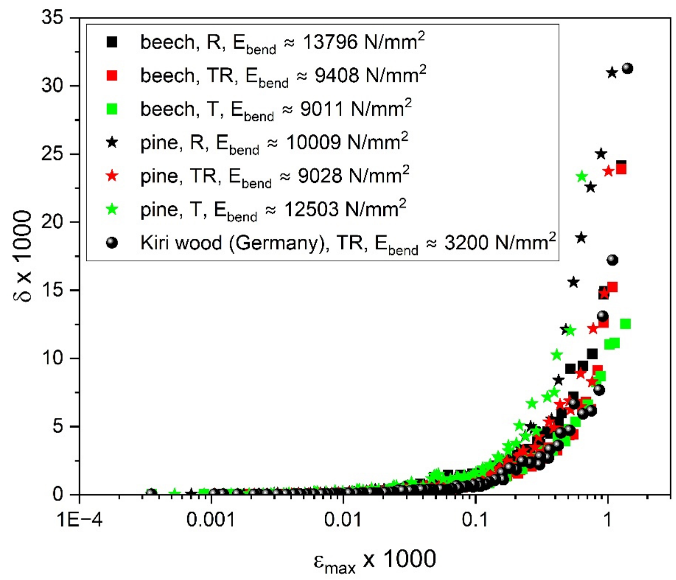

Figure 10. *Strain-dependent damping of different woods. The calculated bending modulus* E_{bend} *is added*

4. Discussion

According to Golovin [22], a damping categorization can be made on the basis of the damping value at ε_{max} of about 0.1% (see Table 3). Based on this, Kiri wood can be regarded as a medium damping material.

It is necessary to classify the results of the strain-dependent damping of Kiri wood. In this context, the results of the non-invasive German variant of Kiri wood are compared to the strain-dependent damping of the softwood pine and the hardwood beech. This comparison is shown in Figure 10.

It is obvious that the bending modulus of beech wood and pine wood depends on the fibre direction and ranges from approximately 9000 N/mm^2 to 13800 N/mm^2 for beech wood (literature value for American beech: 11900 N/mm^2 [23]) and between 9000 N/mm^2 and 12500 N/mm^2 for pine wood (literature value: 8500 N/mm^2 - 13700 N/mm^2 [23]). The observed differences in the bending modulus of the Kiri wood samples from different regions might be attributed to the influence of varying site conditions (e.g., nutrient or water content of the soil) leading to individual structural changes in the wood [24].

Kiri wood has an average bending modulus of around 3200 N/mm^2 and is therefore to be described as soft. According to literature, its bending modulus ranges from 2651 N/mm^2 to 4917 N/mm^2 [25]. Both beech wood and pine wood are used as tonewoods. The damping behaviour of Kiri wood is very similar to that of beech wood. So, it is not surprising that Kiri wood is used as tonewood, too. Its damping properties, combined with its climate friendliness and the possibility of local cultivation (resulting in a short logistics chain), make it suitable for areas requiring higher sound absorption, especially in the shipping industry.

As shown in Figures 3-8, all damping curves have the same shape, indicating a similar damping mechanism. Figure 11 illustrates the assumed mechanical reaction of the wood's honeycomb-like cell structure to an external force. It is surmised that the cell wall acts as a spring, with an external force causing displacement. The restoring force (referred to as "internal force") attempts to restore the cell wall's original shape. However, this mechanism represents elastic behaviour and cannot be considered the cause of the damping.

Table 3. *Comparison of damping data at different maximum strain amplitudes*

ε_{max} x 1000	ε_{max} in %	δ x 1000, Georgia	δ x 1000, Germany	δ x 1000, Italy	δ x 1000, Spain 1	δ x 1000, Spain 2	δ x 1000, Spain 3
0.1	0.01	0.74	0.61	0.63	1.36	1.33	1.16
1	0.1	10.52	10.92	7.83	19.19	21.41	24.46

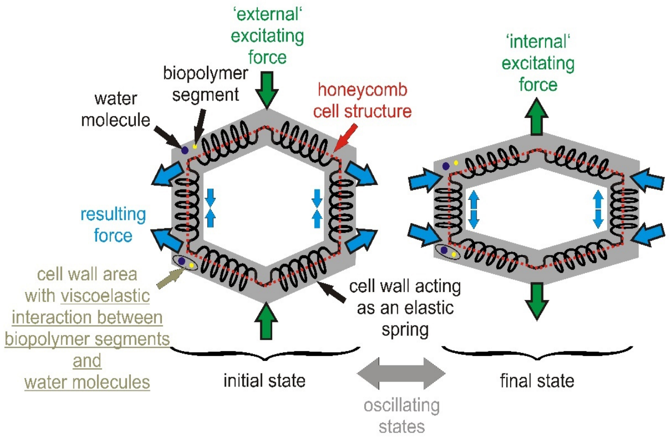

Figure 11. *Visualization of the effect of an external force on the honeycomb cell structure of Kiri wood*

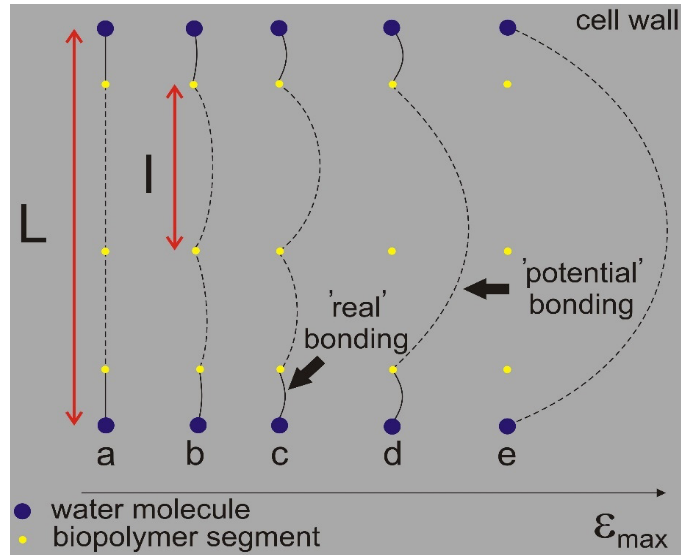

Figure 12. *Interaction between biopolymer segments with water molecules in the wood's cell wall (see also Figure 11). An unpinning mechanism takes place at increasing maximum strain amplitude* ε_{max}

The actual causes of the damping are the water molecules and segments of biopolymers present in the wood's cell wall. It is assumed that a primarily viscoelastic interaction occurs between the biopolymers and water molecules. However, a secondary viscoelastic interaction among the biopolymers cannot be ruled out. Therefore, wood damping is largely determined by the components present in the cell wall structure and their interactions.

In metals, the strain amplitude dependency of the loss tangent observed in this study is known from an unpinning process from obstacles (e.g., impurity atoms or precipitates) as explained in the Granato and Lücke [26] theory of dislocation damping. Following this approach, a similar mechanism is assumed here, where the obstacles are clusters consisting of connections of biopolymer segments with water molecules.

As shown in Figure 12, for small maximum strain amplitudes ε_{max}, it is presumed that mainly biopolymer segments exert a small movement (bowing out mechanism). If the maximum strain amplitude increases, weaker bonds between the biopolymer segments are occasionally broken. These bonds are referred to as 'potential' bonds, as they cannot be completely excluded. The stronger bond between the biopolymer segments and the water molecules (referred to as 'real' bonds) becomes progressively strained. Ultimately, this bond is also broken, leaving behind an unavoidable bond between the water molecules themselves. Meanwhile, new pairings of biopolymer segments with water molecules, as well as among the biopolymer segments themselves, have formed. The damping of wood is therefore significantly dependent on the moisture content and the proportion of biopolymers present in the cell structure. The lengths *L* and *l* declared in the figure (*L*: mean distance of the water molecules, *l*: mean distance of the biopolymer segments) can thus be interpreted as content statements concerning the respective water molecules and biopolymers.

This approach is based on studies of Becker and Noack [27]. They point out that groups of molecules from parts of cellulose, hemicellulose, and lignin (structural components of the wood cell wall) can move. Furthermore, water molecules connected to these groups by sorption forces influence the distance between molecules, their mobility, orientation, and the dipole moment of polar groups. In the wood fibre system, the potential adsorption sites are the hydroxyl groups and the carboxyl groups [28]. Amorphous wood polymers or segments have a higher affinity to form a bond with water [29]. Therefore, the moisture content has a significant influence on the wood damping. This was shown in a former own work [30].

Ashby has compiled a large number of material properties in the form of materials selection maps. Figure 13 shows such an "Ashby chart". In this chart, the damping of various materials is plotted against the Young's modulus. As there is hardly any damping data available for Kiri wood to date, and the vibration experiments carried out allowed the bending modulus to be determined, the damping data for the strain range listed in Table 3 was inserted in Figure 13.

When comparing the range determined for Kiri wood with that of Pine wood, a higher damping is expected for Pine wood, according to Figure 13. This result is confirmed by the damping data for Pine wood obtained in Figure 10 compared to Kiri wood.

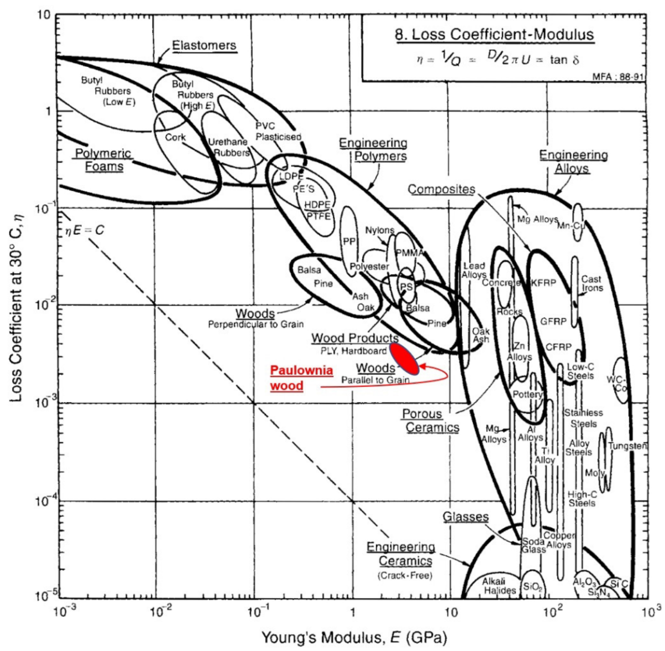

Figure 13. Material property chart "Ashby chart). The loss coefficient η is plotted versus the Young's modulus. Own damping data (taken from Table 3; note: η = δ/π) and data of the bending modulus (taken from Figure 9; note: bending modulus = Young's modulus) of Kiri wood are added. Adopted from [31] (modified)

Wood typically exhibits a rectangular cell structure, causing anisotropy in the mechanical properties. A round cell structure would result in isotropic mechanical properties. In the case of Kiri wood, the honeycomb shape of the cell structure can be seen as a mixture of rectangular and round shapes. Despite different fibre orientations, Kiri wood demonstrates a quasi-isotropic damping behaviour, allowing for more universal use.

5. Conclusion

A fast-growing timber which is designated as climate tree and demonstrably enables plantation cultivation is Paulownia wood. It is also known as Kiri wood. The usual varieties are considered invasive. A new non-invasive Paulownia variety is called Paulownia NordMax21® and is a German hybrid of Paulownia tomentosa and Paulownia fortunei. Its damping behaviour was investigated and compared with common Paulowina varieties harvested in Georgia, Italy and Spain.

The damping was measured as logarithmic decrement of freely decaying bending vibrations and determined as a function of the maximum strain amplitude. All damping curves could be divided into a strain-independent and a strain-dependent range where the latter one is interpreted as hysteretic damping. Such behaviour is well known for strain-dependent damping measurements of metals where pinning/unpinning of defects from pinning points in the structure (e.g., dislocations) can be found (Granato-Lücke model). A similar approach was introduced. It is assumed that biopolymer segments and water molecules form a bond. A weaker bond may also occur between biopolymer segments. With increasing maximum strain amplitude, these bonds are stressed and can fail (unpinning mechanism). This leads to viscoelastic material behaviour, which manifests itself in the form of damping.

It is therefore hardly surprising that moisture content significantly influences the wood damping. However, Kiri wood is the first choice in environments with changing humidity levels (e.g., like on board ships) due to its extremely low swelling and shrinking behaviour. Consequently, a relatively constant damping value is to be expected despite fluctuations in humidity.

The damping data, along with the determined bending moduli, were added to an existing "ashby chart". Although the damping of Kiri wood is lower than that of balsa wood, it shows less dependence on the fibre orientation (leading to a quasi-isotropic damping behaviour), which might be attributed to the honeycomb structure of the Kiri wood.

Since wood is a renewable resource, particularly with Kiri wood, it combines properties of sustainability, aesthetics, and functionality. Especially Kiri wood is lightweight, which means less energy is needed in transporting this material. The advantage of weight savings is particularly significant in different areas like: construction (e.g., tiny houses, wooden facades), mobility (e.g., model and glider aircraft, caravan construction) and lifestyle (e.g., furniture, home accessories such as vases and bowls). Kiri wood has enormous application potential in these areas and also opens up a large field of research.

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Footnotes

Authorship Contributions

Concept design: J. Göken, and N. Saba, Data Collection or Processing: J. Göken, Analysis or Interpretation: J. Göken, and N. Saba, Literature Review: J. Göken, and N. Saba, Writing, Reviewing and Editing: J. Göken, and N. Saba.

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