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(Research Article)

Hammer Excitation Vibration Technique on Southern Yellow Pine Bio-Composites

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Abstract

Wood-based bio-composites are materials that combine wood or wood-derived components with bio-based polymers, fibers, or other natural materials to form a composite material. These composites are designed to utilize renewable and sustainable resources, such as wood, in their composition. The Department of Mechanical Engineering at the University of Mississippi, The Department of Sustainable Bioproducts at Mississippi State University, and Alcorn State University focused on creating new wood-based bio-composites from agricultural and plant-based materials in response to the current trends toward natural-based composites. It is imperative to study the structural properties of newly developed bio-composites to find the potential capabilities and applications. The materials tested were made from southern yellow pine (SYP), a commercial urea-formaldehyde (UF Unibond) resin, and a polymeric methylene diphenyl isocyanate (pMDI) resin using a Dieffenbacher hot press. The dynamic and damping properties were determined using the hammer excitation vibration technique. The responses were obtained from the frequency domain for the fundamental natural frequency (fn).

The panel made using 4% pMDI resin (Material 1) demonstrated the highest average storage modulus (4.32 GPa), indicating superior stiffness and potential for use in load-bearing applications where structural integrity is essential. The panel made with 5.3% UF resin (Material 2) exhibited the highest average damping ratio (0.02), suggesting its effectiveness in reducing vibrations and providing damping in dynamic applications. Overall, these materials have distinctive attributes that cater to specific application requirements. Any of the three materials could be considered a viable option depending on the intended use.

Keywords: Wood-based bio-composites, damping, loss factor, storage modulus.

1. Introduction

In recent years, bio-composite materials have gained significant attention from both researchers and industry professionals. These materials possess the notable advantage of being carbon dioxide neutral, meaning they achieve a balance involving the release of carbon dioxide into the environment with the amount of carbon dioxide removed from the atmosphere [1]. Wood-based bio-composites, in particular, have emerged as a popular choice for various structural and non-structural applications. They offer advantages such as renewability, affordability, high strength-to-weight ratio, and the ability to customize their mechanical properties [2-5]. Consequently, wood-based bio-composites present a promising ecological alternative to conventional carbon, glass, and petroleum-based fiber composites.

To explore their potential further, this study focuses on investigating three wood-based bio-composites developed in collaboration with the Department of Sustainable Bioproducts at Mississippi State University and Alcorn State University. Composite materials play a crucial role in applications involving dynamic loading, such as energy absorption and noise attenuation. Therefore, it becomes essential to examine the damping and dynamic properties of these materials. These are newly developed material compositions and need to be evaluated because limited research exists on the dynamic and damping characterization of wood-based composites using the hammer excitation vibration technique.

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The hammer excitation vibration technique is a reliable and non-destructive method for quickly assessing the dynamic modulus of elasticity (E_d) and damping ratio (ξ) of wood-based bio-composites [8]. This investigation aims to evaluate the dynamic properties, including the storage modulus (E'), damping ratio (ξ), and loss factor (η), of the newly developed wood-based bio-composites with various constituent materials. Such knowledge will facilitate the selection of appropriate materials based on specific load application requirements.

2. Material and Methods

The three types of wood-based bio-composites (listed in Table 1) are made from Southern yellow pine particles (SYP), polymeric methylene diphenyl isocyanate (pMDI) resin (Rubinate 1840, Huntsman, The Woodlands, Texas), and commercial urea formaldehyde resin (Unibond 800).

Table 1. Wood-based bio-composites material composition

Material designation	Mass fraction (%) of raw material constituents			Density (kg•m-3)
	SYP	Urea formaldehyde	pMDI	
Material 1	96%	0%	4%	703
Material 2	94.7%	5.3%	0%	680
Material 3	92%	8%	0%	634

The panels used in this study were produced with a Dieffenbacher hot press system (Figure 1) measuring 915 mm x 915 mm located at Mississippi State University's Sustainable Bioproducts Laboratory. The hot press used hot oil to heat the platens and was operated and monitored by Pressman software from the Alberta Research Council. The panels were fabricated at approximately 190°C and cured for about four minutes. For testing, each panel had three samples cut at 304.8 mm long and 25.4 mm wide (Figure 2). The panels were created with a thickness of 13 mm.

Figure 1. Dieffenbacher hot press at Sustainable Bioproducts Laboratory of Mississippi State University

Figure 2. Representative image of material 3 bio-composite samples

3. Experimental Testing

The dynamic behavior of wood-based bio-composites in a cantilever beam configuration was assessed using hammer excitation at the Structure and Dynamics Laboratory located at the University of Mississippi. To conduct the tests, an accelerometer was positioned at the free end of the beam and connected to both an oscilloscope and a signal analyzer equipped with a conditioning amplifier (Figure 3). The impulse hammer was connected to the signal analyzer through the conditioning amplifier.

By lightly impacting the beam with the excitation hammer, the dynamic response of the system was initiated. Subsequently, the oscilloscope captured the logarithmic decrement and damped natural frequency derived from the dynamic response. Furthermore, the spectrum analyzer was used to record the natural frequencies (f_n) and damping ratio (ξ) of the beam.

3.1 Frequency domain analysis [2]: The storage modulus (E') measures the stored energy, representing the elastic portion, calculated using [6]

$$E' = \frac{4\pi^2 f_n^2 L^4 \rho A}{(\lambda_n L)^4 I} \quad (1)$$

The relationship described in this equation indicates that the natural frequency provides an assessment of the storage modulus (E').

In the equation, λ_n represents the eigenvalue associated with the nth mode, I correspond to the area moment of inertia of the beam's cross-section, ρ denotes the mass density of the beam, L represents the length of the beam, and A signifies the cross-sectional area of the beam.

For a fixed free (Cantilever beam) boundary condition [6]:

1st mode: $\lambda_1 L = 1.875$, 2nd mode $\lambda_2 L = 4.694$, 3rd mode $\lambda_3 L = 7.855$.

The loss factor (η) is a measure of intrinsic damping (resistance to vibration) given by:

$$\eta = \frac{E''}{E'} \quad (2)$$

Here, the symbol ξ represents the damping ratio, while E" represents the loss modulus, which quantifies the amount of energy dissipated in the system.

The frequency domain analysis involves examining mathematical functions or signals in relation to their frequencies.

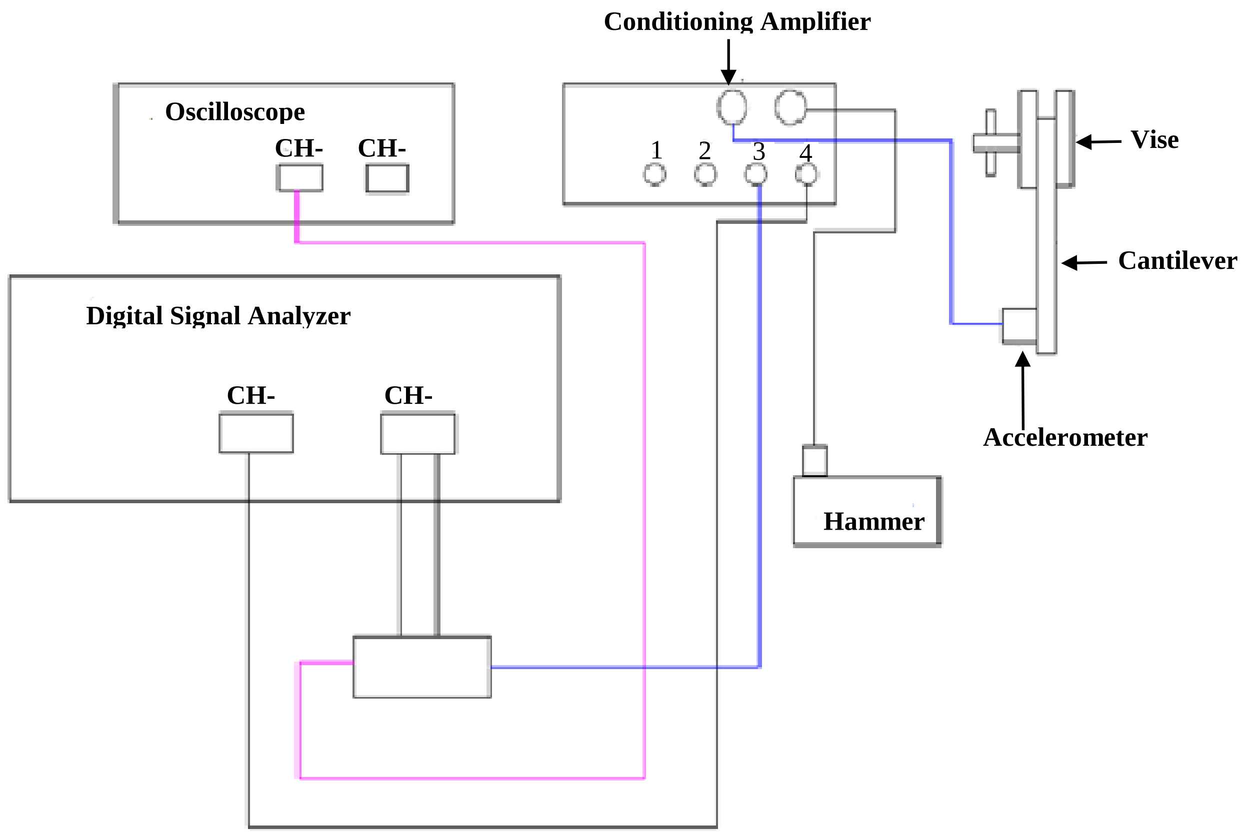

Figure 3. Schematic of experimental setup [2]

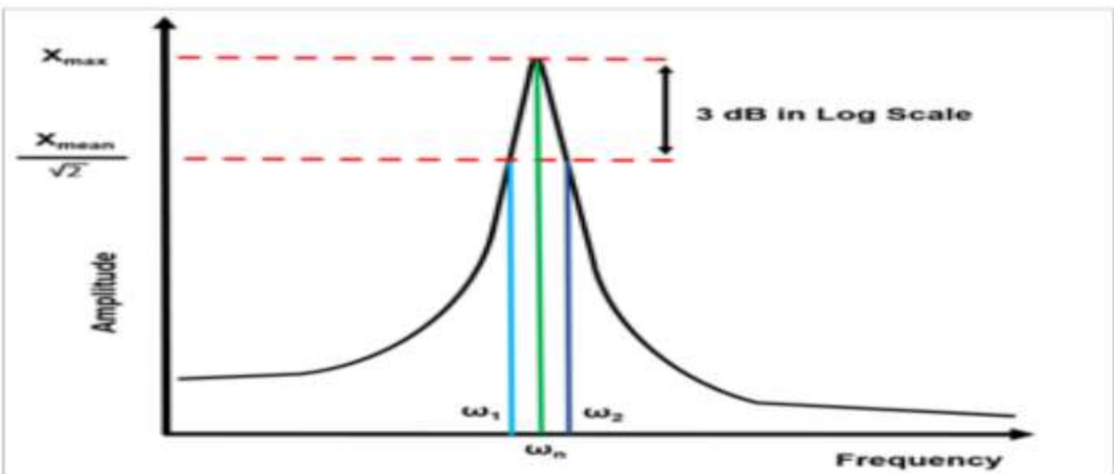

Figure 4. Damping measurement using half-power bandwidth method [2]

When analyzing the data in the frequency domain, each frequency corresponds to peaks along the horizontal axis representing specific frequency values. Damping characteristics can also be determined using the half-power bandwidth method [2], as demonstrated in Figure 4, which is based on the frequency domain data.

$$2\xi = \frac{(\omega_2-\omega_1)}{\omega_n} = \frac{f_2-f_1}{f_n} = \eta \qquad (3)$$

4. Results and Discussions

The experimental findings of three distinct wood-based bio-composites tested using the hammer excitation vibration technique are presented in Table 2. This table provides a summary of the average values, of three samples from each material, obtained from the experiments.

The average values of the fundamental natural frequencies (f_n) were found from the investigation of the wood-based bio-composites. In Figure 5, the average values of the fundamental natural frequency (f_n) are presented, along with their standard deviation, for the various types of wood-based bio-composites that were tested. The data illustrates distinct differences in the average natural frequencies (f_n) among the different materials.

The storage modulus (E') characterizes the ability of a composite material to store elastic energy when subjected to mechanical stress. It quantifies the material's stiffness and its capacity to recover the energy once the sample is de-stressed. The storage modulus reflects the material's elasticity or its ability to deform and then return to its original shape. The analysis shows that the average storage modulus (E') varied for the different types of wood-based bio-composites as shown in Figure 6.

Table 2. Mechanical properties (frequency response) of wood-based bio-composites (statistical significance of 5%)

Material	Natural frequency (f_n) (Hz)	Storage modulus (E') (GPa)	Damping ratio (ξ)	Loss factor (η)
4% MDI	53.83 ±2.37 (±4.40%)	4.32 ±0.62 (±14.25%)	0.01±0.00 (±16.98%)	0.03 ±0.01 (±16.98%)
5.3% UF	50.92 ±2.36 (±4.63%)	3.47 ±0.45 (±12.93%)	0.02 ±0.01 (±35.46%)	0.04 ±0.01 (±35.46%)
8% UF	47.50 ±4.61 (±9.71%)	2.89 ±0.81 (±28.05%)	0.01 ±0.00 (±31.33%)	0.03 ±0.01 (±31.33%)

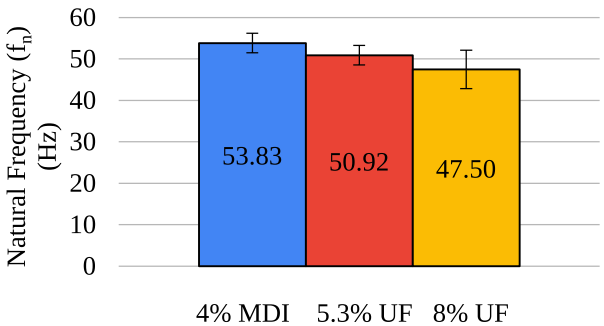

Figure 5. Natural frequency (f_n) of different wood-based bio-composites

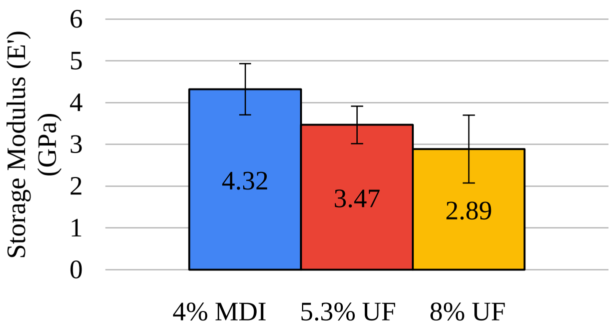

Figure 6. Storage modulus (E') of different wood-based bio-composites

From the results, we can observe that Material 1 has the highest average storage modulus (4.32 GPa), followed by Material 2 (3.47 GPa), then Material 3 (2.89 GPa). A higher storage modulus indicates that the material is stiffer and can store more energy when subjected to external forces. On the other hand, a lower storage modulus suggests that the material is less rigid and may deform more under applied loads. The significant difference in storage modulus values among the three materials could be attributed to variations in their composition, fiber arrangement, or processing techniques. Material 1 seems to possess the highest stiffness, making it potentially suitable for applications where structural integrity and resistance to deformation are crucial.

The damping ratio measures the material's ability to dissipate energy and resist oscillations. It indicates how quickly the material's vibrational motion will decay after being subjected to an external force. Higher damping ratios imply that the material can dissipate energy more effectively and exhibit stronger resistance to vibrations. The analysis shows that the average damping ratio (ξ) varied for the different types of wood-based bio-composites as shown in Figure 7.

Comparing the results, we can see that Material 2 has the highest average damping ratio (0.02), followed by Material 1 (0.01), and then Material 3 with the lowest damping ratio (0.01).

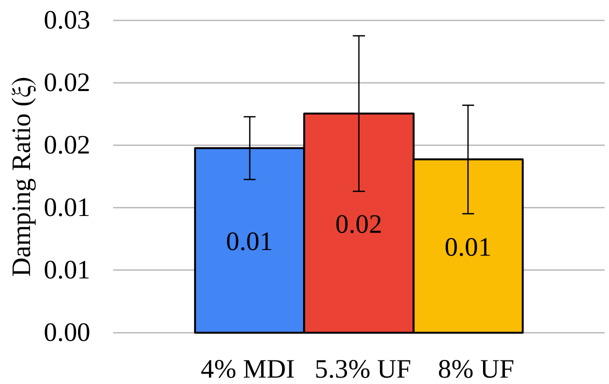

Figure 7. Damping ratio (ξ) of different wood-based bio-composites

A higher damping ratio suggests that the material has enhanced energy dissipation capabilities, making it suitable for applications where vibration damping and noise reduction are critical. On the other hand, a lower damping ratio might be preferable in scenarios where preserving energy and minimizing energy loss are essential, such as in structural components subjected to dynamic loads.

The loss factor (η) is another important parameter in characterizing the dynamic behavior of a material. It represents the amount of energy dissipation that occurs per cycle during mechanical vibrations. A higher loss factor indicates that the material dissipates more energy and exhibits greater damping capabilities. The analysis shows that the average loss factor (η) varied for the different types of wood-based bio-composites as shown in Figure 8.

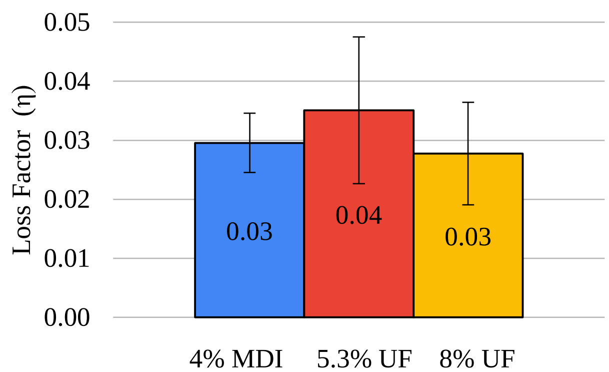

Figure 8. Loss factor (η) of different wood-based bio-composites

Comparing the results, we find that Material 2 has the highest average loss factor (0.04), followed by Material 1 (0.03), and then Material 3 with the lowest loss factor (0.03). Materials with higher loss factors are generally preferred in applications where damping and energy absorption are vital. Such materials can effectively attenuate vibrations and noise, making them suitable for applications like shock absorbers or vibration dampers. On the other hand, materials with lower loss factors are beneficial in applications that require high stiffness and minimal energy loss, like structural components or load-bearing elements.

5. Conclusions

In this study, we utilized the hammer excitation technique to investigate the dynamic response of three different wood-based bio-composite materials. The analysis focused on key mechanical properties: storage modulus (E'), damping ratio (ξ), loss factor (η), and natural frequency (f_n). These properties play crucial roles in determining the suitability of materials for various applications.

The storage modulus represents the material's ability to store elastic energy. In this category, Material 1 demonstrated the highest average storage modulus (4.32 GPa), indicating superior stiffness and potential for use in load-bearing applications where structural integrity is essential.

The damping ratio indicates a material's ability to dissipate energy during vibrations. A higher damping ratio implies better energy dissipation and vibration isolation capabilities. Material 2 exhibited the highest average damping ratio (0.02), suggesting its effectiveness in reducing vibrations and providing damping in dynamic applications.

The loss factor quantifies the energy loss during each vibration cycle. Material 2 demonstrated the highest average loss factor (0.04), indicating good energy dissipation and damping properties.

Overall, these materials have distinctive attributes that cater to specific application requirements. Any of the three materials could be considered a viable option depending on the intended use. Further studies, including real-world testing and validation, will be necessary to determine their applicability in specific industrial or engineering scenarios. Additionally, exploring composite mixtures and optimization techniques may lead to even more enhanced materials with a wider range of applications.

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