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Reassessing Tension Side Reinforcement in Modular Timber Beams: Insights from Experimental Modal Analysis in Forest Bridge Systems

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ABSTRACT

Timber extraction in Malaysia is normally taking place deep within the forest, where accessibility poses a significant challenge. The current practise forest bridge involves the construction of temporary log stringer bridges for short-term use, which are either dismantled or left to deteriorate after their intended period of usage. These temporary bridges are typically neglected post-logging, leading to degradation and collapsed due to strong water flow, erosion, and sedimentation. The adoption of modular and mobile bridge concepts is strongly recommended as these allow for easy transportation, installation at various sites, and reuse. This approach has the potential to reduce construction costs while facilitating post-harvesting activities for sustainable forest management practices. By implementing modular and mobile bridge concepts in the logging industry, the challenges of accessibility and post-harvesting activities can be effectively addressed. This study investigates the inherent frequencies of modular timber beams using a combined approach of experimental and simulation methods. Experimental modal analysis was conducted on physical beam specimens to determine their natural frequencies and mode shapes. This study aims to investigate the potential use of Experimental Modal Analysis in evaluating the structural behaviour of modular concepts, particularly when incorporating mechanical connectors in timber beams. Findings indicate that as the number of beam segments increases, natural frequency decreases due to enhanced flexibility and reduced stiffness. Reinforcement which are expected to enhance beam stiffness, showed inconclusive results, potentially due to its discontinuous nature along the beam length.

Keywords: Natural frequency; mobile bridge; stiffness; modular; timber beam

INTRODUCTION

HISTORICAL OVERVIEW AND CURRENT TRENDS IN TIMBER BRIDGE SYSTEMS

Girders (beams) are one of the structural members in the superstructure of a bridge system (Naser 2022). The use of timber in bridge construction has undergone considerable transformation, harnessing its versatile attributes, including high tensile strength and low density and it has become a preferred material for bridge decks (Rodrigues et al. 2013). Examining historical timber bridge designs provides valuable insights into contemporary maintenance and preservation techniques (Sert & Apaydın, 2017). The introduction of modern adhesives and engineered wood products, including glulam, has reaffirmed the status of timber in bridge constructions (Björngrim et al. 2016). Despite these advancements, concerns regarding timber bridge maintenance and longevity remain, leading to research on stochastic assessment and fault tree analysis for timber bridge deterioration (Owoeye & Abejide, 2015; Lokuge et al. 2016).

The modular system for bridge design demonstrates a trend towards simplicity at the construction site (Khirwizam & Rizuwan, 2020). The development of new materials has enabled the development of longer-span timber bridges with improved durability (Zhao et al. 2016). The structural performance of timber bridges has been improved through designs that utilize timber for compression and end-bearing, increasing load capacity (Alonso et al. 2014), and by applying innovative modular connection concepts. Fault tree analysis has proven to be a useful tool for assessing the risk and aiding the maintenance of timber bridge subsystems (Lokuge et al. 2016).

ROLE AND IMPORTANCE OF MODULAR TIMBER BEAMS IN BRIDGE CONSTRUCTION

The increasing importance of modular timber beams in bridge construction is owing to their structural efficiency and eco-friendly nature. As previously reported by Bertola et al. (2021), timber-UHPFRC structures contribute significantly to reducing environmental impacts and aligning with sustainable development goals. The mechanical properties of modular timber beams have been a focus, particularly in local timber materials for bridge frames, addressing shear, flexural strength, and load endurance, as explored by Sandhyavitri et al. (2020). Moreover, Shi et al. (2023) advanced this further with studies on timber-concrete composite beams, specifically examining steel-plate connections in prefabricated concrete slabs. In general, modular construction has been recognized for its ability to improve construction efficiency, cost-effectiveness, and sustainability. Jang et al. (2022) and John et al. (2022) have noted its benefits in terms of waste minimization and efficiency. Owing to its ease of assembly and design convenience, modular construction, also known as off-site or industrialized building construction, has become increasingly popular. This is consistent with the findings of Jiang et al. (2019) and Suleiman et al. (2021). Paliwal et al. (2021) and Musa et al. (2018) identified modular construction as a sustainable method for enhancing project cost, schedule, and quality while reducing site disruption and waste.

Li et al. (2018) recognized the economic benefits of modular construction, including improved design and construction efficiency. Wei et al. (2021) asserted that modular construction can enhance construction performance and productivity. The time-saving aspects of modular construction have been highlighted by Choi et al. (2020), Ghannad et al. (2019) and Gunawardena et al. (2014) particularly in terms of post-disaster housing and reduced construction schedules. Boafo et al. (2016) emphasized the advantages of modular construction over traditional construction methods in terms of speed, quality, material efficiency, worker safety, and environmental friendliness. The assembly's level of intricacy is contingent on the quantity and varieties of components being joined together through mechanical fastening and joining methods (Haider et al. 2024).

The efficiency, cost-effectiveness, sustainability, waste reduction, and improved project performance of modular construction make it an appealing choice for the modern construction industry. While the concept of modular construction has several advantages, several research studies have identified some drawbacks. According to Wang et al. (2019), the current modular connections have limitations, including construction challenges, potential weakening of the bearing capacity of beams or columns, and the risk of damage to decorations. Subramanya et al. (2020) also highlighted limitations in modular construction that make it difficult, despite its benefits over traditional construction methods. Sun et al. (2020) noted that although modular construction reduces on-site labor, it requires a substantial amount of skilled labor for manufacturing prefabricated modules, resulting in increased construction costs. Therefore, selecting the right materials is crucial for understanding their properties and addressing any performance-related issues (Riza et al. 2022).

TENSION SIDE REINFORCEMENT IN TIMBER BEAMS

The examination of tension-side reinforcements in timber beams is a crucial aspect of structural engineering, which investigates how various materials and techniques affect the strength and stiffness of the beam. The implementation of carbon fiber and glass fiber reinforcements significantly increased these properties. Glišović et al. (2015) emphasized the benefits of using fiber-reinforced plastic (FRP) owing to its high strain capacity, which allows tension laminates to reach the ultimate tensile strength and enhances beam performance.

The role of FRP in altering the failure mode and facilitating stress transfer in weaker sections, emphasizing the significance of proper reinforcement techniques. Kusnindar et al. (2018) demonstrated that specific reinforcement types could significantly enhance the bending strength and stiffness of timber beams, depending on the timber variety. The choice of reinforcement material, application method, and timber type are crucial for optimizing the performance of reinforced timber beams.

A moderate ratio of FRP composite reinforcement can effectively prevent tension failure in beams. Nevertheless, Yang et al. (2016) found that excessive amounts of reinforcement may result in a significant increase in the extreme fiber tensile strain at failure, changing the failure mode from brittle tension failure to ductile compression failure. This implies that although tension reinforcement can help address local defects, it does not eliminate the risk of failure.

Overall, although tension-side reinforcement can improve the structural behaviour of timber beams, it is essential to recognize its limitations and seek comprehensive solutions for both tension and compression failures.

DYNAMIC ANALYSIS AND EXPERIMENTAL MODAL ANALYSIS (EMA) IN STRUCTURAL ENGINEERING

Dynamic analysis techniques are essential in structural engineering for evaluating timber structures. These methods encompass a variety of approaches for analysing the dynamic behaviour and properties of timber buildings, bridges, and floors. In situ modal analysis, as demonstrated by Reynolds et al. (2016), is crucial for testing and comparing dynamic properties across different structural systems. Han et al. (2021) suggested the finite element method (FEM) to assess the mechanical behaviour of timber structures, including the performance of connections under various loads, such as wind-induced vibrations.

In the broader context of structural health monitoring (SHM), EMA is crucial for pinpointing changes in structural behaviour owing to damage or degradation by identifying natural frequencies and mode shapes (Ribeiro & Lameiras, 2019). Moreover, EMA provides deep insights into the dynamic performance of a system by underpinning other dynamic analyses, such as harmonic response and transient dynamic analysis (Wang et al. 2017). Jian et al. (2022) investigated the flexural performance of timber beams reinforced with Fiber Reinforced Polymers (FRP), focusing on the influence of FRP bars, sheets, and wraps. Similarly, Righetti et al. (2015) studied the bending strength and deformation properties of timber beams, particularly examining the Basalt FRP spike repair of wood beams. These studies demonstrated the effectiveness of the EMA in evaluating the mechanical behaviour of timber beams under various loading and strengthening scenarios.

Existing studies by Mironovs et al. (2023) demonstrated the widespread use of EMA in the dynamic testing and structural health monitoring of timber beams. Righetti et al. (2015) utilized EMA to evaluate the bending strength and deformation properties of timber beams. Mohamed et al. (2021) used a combination of EMA, torsion tests, and photogrammetric methods to determine the shear modulus of timber and glulam beams, highlighting its versatility in mechanical property assessment. Khelifa et al. (2016) and Qing et al. (2020) confirmed the efficacy of EMA in evaluating timber beam reinforcements with materials like CFRP and BFRP. Kržan et al. (2023) extended EMA's application to engineered wood products under various loads and conditions.

Previous research has consistently shown the benefits of tension-side reinforcement in enhancing the mechanical properties and performance of structural elements, especially in timber and reinforced-fiber frameworks. Cholkrer and Tantray (2020) reported that tension-side reinforcement leads to a more consistent correlation between resistance change and deflection. These findings collectively demonstrate the significant impact of tension-side reinforcement on the performance of the structural elements. The addition of tension reinforcement significantly improves stiffness, strength, and ductility, emphasizing its crucial role in structural engineering.

This research investigates the applicability of Experimental Modal Analysis (EMA) in assessing the structural performance of modular systems, specifically focusing on the influence of mechanical connectors on timber beams. By broadening the use of EMA, this study examines how the incorporation of mechanical connectors affects the functionality and durability of modular timber structures.

METHODOLOGY

EXPERIMENTAL MODAL ANALYSIS (EMA)

Experimental Modal Analysis (EMA) is a widely used technique for evaluating the dynamic characteristics of structures and materials. This primarily entails measuring and examining impulse or frequency response functions to ascertain modal parameters, including natural frequencies, mode shapes, and damping ratios. The EMA process includes data acquisition, signal processing, and modal parameter estimation. Signal processing methods, such as the Fourier transform and covariance-driven time-domain methods, were then used to derive modal properties from the measured data. Finally, estimation methods such as Bayesian or maximum likelihood estimation were employed to identify the modal parameters (Figure 1).

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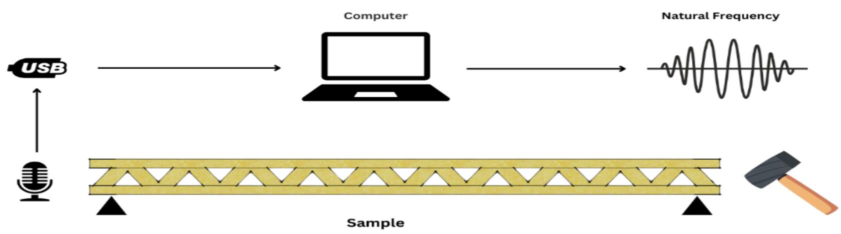

FIGURE 1. Experimental Modal Analysis (EMA) data collection flow

SAMPLE PREPARATION

In this study, I-shaped timber beams from the PERI Malaysia GT-24 category were employed. These beams were designed with precision and standardized length of 3 m. They featured carefully designed cross-sectional dimensions, measuring 0.08 meters in width and 0.24 meters in height. The flanges of these beams, which are an integral part of their structure, were 6 mm thick. The selection of these beams was strategic, as they combined the necessary robustness and flexibility for modular bridge construction. Their material composition and lattice web design were noteworthy, as they contributed to the capacity of the beam to support loads of up to 10 kN, which was a critical factor in the study of stiffness degradation.

The Chopped Strand Mat (CSM) is applied to the tension side of the beams to enhance their rigidity and load-bearing capacity. To achieve this, a 5 mm thick CSM was carefully wrapped around the bottom flange of each beam, ensuring a strong bond and improved durability. The application process was followed with precision to guarantee uniformity across all samples. The resin saturation process is also essential because it plays a critical role in determining the effectiveness of CSM as a reinforcing material.

The research strategy implemented a thorough separation of the beams into two clearly defined categories: control and testing for both sample with and without reinforcement (Figure 2). The control group comprised beams that retained their original form without any CSM reinforcement and served as a benchmark for comparison. The test group consisted of beams reinforced with CSM on the tension side. It is crucial to emphasize that in addition to the CSM reinforcement, both groups of beams exhibit identical specifications, including their dimensions, material properties, and manufacturing process. This uniformity is vital for ensuring that any observed disparities in performance or characteristics can be exclusively attributed to the existence or absence of CSM reinforcement. This precise delineation of the control and test groups is a fundamental aspect of the experimental methodology, providing a transparent and unbiased foundation for assessing the influence of CSM reinforcement on the beam stiffness and other mechanical properties.

The mechanical connectors of the bridge girder, made of 5 mm-thick steel plates, join each segment. These connectors determine the structural integrity and load-bearing capacity of the beams, particularly in terms of stiffness degradation and overall durability. They play a crucial role in modular beam construction by facilitating the transfer of loads and stresses between different segments, thereby enhancing the stability and strength of the structure and thus proper design and construction of the joints are essential to maintain structural integrity (Jamaludin et al. 2024). In this study, these steel plate connectors are not only structural components but also significant variables. Steel and timber beam act as a cohesive system when exposed to various types of loads. This type of structure derives its strength from both materials and resulting in an efficient and appealing structural design (Maaroof et al. 2022). These factors influence the overall stiffness, strength, and durability of the beams by altering their placement and number. This experimental setup allowed for an in-depth examination of the connectors' mechanical performance and their impact on the modular beam. Most importantly, steel connectors are vital for studying stiffness degradation. As their performance changes over time and under varying load conditions, it influences the overall structural behaviour of the beam. By closely monitoring these changes using reliable methods, valuable insights can be gained into the reliability of modular connection beams.

The use of segment lengths ranging from 0.6 meters to 3 m was intended to gain an understanding of scale effects and to assess the performance of the Mechanical Connector. In addition, this information can simulate real-world conditions in which modular connections are frequently used at varying lengths, thereby enabling a comprehensive and accurate analysis of modular bridge beams.

FIGURE 2. Sample without reinforcement (top) and with reinforcement (bottom)

EXPERIMENTAL SETUP

A plastic hammer was used in the experimental modal analysis to excite the signals. A microphone was used to record signals, which were connected to data-acquisition systems for recording and analysis. The collected data were processed using a modal analysis software. The integration of a Fast Fourier Transform (FFT) device is crucial for analysing the frequency-domain characteristics of the measured signals. The FFT device is typically integrated with a data acquisition system and signal processing software to analyse the frequency content of the measured responses. The FFT device was used to transform the time-domain signals obtained from the microphone into the frequency domain, allowing the identification of modal parameters and resonant frequencies (Figure 3).

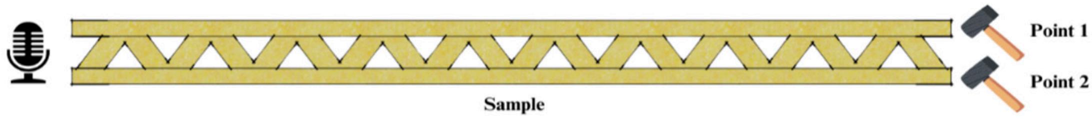

FIGURE 3. Data collection point for top and bottom flange

The FFT device is frequently incorporated into the data acquisition system, which comprises sensors designed to measure structural responses and a digital signal processing unit for real-time or postprocessing analysis. Additionally, the FFT device is crucial for processing the output signals from excitation sources, such as modal hammers or shakers, to analyse the frequency response functions and power spectra (Lee et al. 2016). This integration allows the identification of the dynamic characteristics of the structure under test and facilitates the comparison of experimental results with finite element analysis predictions. The experiment was conducted in a controlled environment, specifically a closed laboratory, to eliminate external noise and disturbances.

The sample beam was placed on a support stand positioned 15 cm from each end. Precise positioning of the sample is crucial for ensuring consistent boundary conditions for all beams. The speaker was placed along the direction of the beam to record the excitation signal with a consistent distance of 30 mm from the end of each beam. This uniform distance was essential to ensure the same excitation conditions across all samples. Ten excitation points were marked at specific points along the beam, where excitation occurred to excite the beam at consistent points for each test to ensure comparability of the results.

The data obtained from the speaker were transferred to the FFT device and subjected to subsequent analysis in LabVIEW. Owing to the limited resources of the embedded device, the natural frequency and mode shapes were calculated in the time domain using simplified FFT analysis. Analytical, semi-analytical, and numerical methods are typically used to determine the natural frequencies and mode shapes of the structures. It is essential to compare specific aspects of reinforced and non-reinforced beams, such as the shear capacity, strain distribution, and curvatures, to understand the structural behaviour of these beams.

RESULTS AND DISCUSSION

The field of structural engineering is constantly evolving, driven by the need for safer and more efficient construction methods (Yi et al. 2021). This paper presents valuable insights into the performance of modular timber beams in forest bridge systems through experimental modal analysis. Therefore, data collection was multifaceted to gather the natural frequency data collected from various points on the beams from different points and under varying conditions contributes to a comprehensive understanding of the vibrational behaviour across different scenarios (Huang & Baddour 2018).

Further statistical analysis revealed that the natural frequencies varied depending on the location and the loading conditions. The findings indicate the potential for reassessing tension side reinforcement in modular timber beams in forest bridge systems to optimize their performance under different loading scenarios. The natural frequency values along the longitudinal axis of a beam were measured to understand the behaviour of the structure (Su & Banerjee, 2015). Subsequent data gathering efforts have concentrated on examining how reinforcement, modular connections, and segment length variations relate to each other. To facilitate this exploration, nine specific locations on the top surface of the beam were identified for collecting natural frequency data.

This phase of data collection was crucial in determining how these factors interact and affect overall vibrational characteristics. The detailed natural frequency data collected from various points on timber beams has offered valuable insights into their vibrational behaviour under different loading conditions. All data were then tested using statistical methods to investigate the relationship between the natural frequency of modular timber beams and parameters such as flange location, reinforcement type, and the number of connectors. Analysis of Variance (ANOVA) was utilized to assess the statistical significance of the observed differences in mean natural frequencies across the varying levels of each parameter. These statistical analyses provided valuable insights into the relative importance of each factor in influencing the dynamic response of the modular timber beams.

SAMPLE

ETN131 and ETR136 samples, representing two distinct configurations of the same base material, exhibited distinct natural frequency properties, enabling a focused analysis of the impact of Chopped Strand Mat (CSM) reinforcement (Figure 4). ETN131 serves as the control sample, showcasing the material's inherent properties without any modifications. In contrast, ETR136 is specifically treated with CSM reinforcement applied to its bottom flange. This targeted reinforcement aims to enhance the beam's stiffness and load-bearing capacity. By comparing the performance of the reinforced ETR136 to the baseline established by ETN131, the study can effectively isolate and quantify the effects of CSM reinforcement on the material's vibrational behaviour and structural performance. ETN131 has a consistent average natural frequency of 28.13 Hz with low variability, as indicated by its minimal variance (0.029) and standard deviation (0.169745). This suggests the homogeneous nature of the samples or consistent testing conditions. In contrast, ETR136 showed a lower average frequency of 17.82167 Hz and greater variability, as evidenced by its higher variance (121.608 Hz) and standard deviation (11.027605 Hz) as in Table 1.

These differences could stem from fundamental variations in construction or treatment, such as reinforcement with Chopped Strand Mat (CSM), potentially affecting the stiffness and natural frequency. The use of CSM as a reinforcement in composite materials has been extensively researched for its potential effects on their stiffness and natural frequency (Sathishkumar et al. 2014).

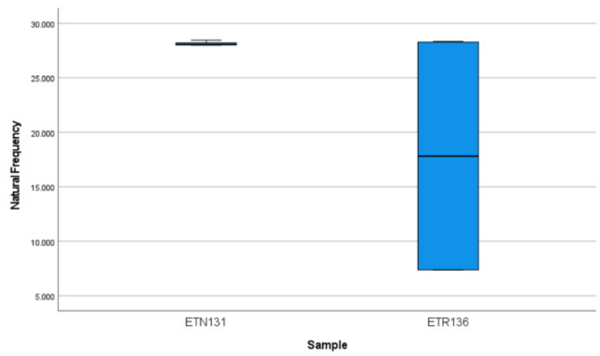

FIGURE 4. Natural Frequency for parameter Sample - Control

Across all samples (Figure 5), low standard deviations indicate closely clustered natural frequencies, implying uniformity and predictability. Most medians are approximately 28 Hz, suggesting a common dynamic characteristic. However, samples such as ETN313, ETN50.65, and ETR50.610 showed greater frequency spread, hinting at material or structural inconsistencies. Samples such as ETN21.52, ETN40.754, and ETR21.57, with tighter frequency distributions, suggest more uniformity and precision in their making. Outliers in some samples, particularly ETN50.65 and ETR40.759, highlight anomalies that require investigation to understand material or construction integrity

TABLE 1. Statistical result for parameter Sample - Control and Testing

	No	Sampel	Mean	Variance	Std. Deviation
Control	1	ETN 131	28.130	0.029	0.169745
	2	ETR 136	17.82167	121.608	11.027605
	No	Sampel	Mean	Variance	Std. Deviation
Testing	1	ETN 21.52	28.40667	0.045	0.212296
	2	ETN 313	28.55001	0.007	0.083149
	3	ETN 40.754	28.28168	0.033	0.181966
	4	ETN 50.65	27.92499	0.169	0.410833
	5	ETR 21.57	28.05834	0.003	0.051689
	6	ETR 318	27.85667	0.025	0.156774
	7	ETR 40.759	28.06333	0.012	0.111613
	8	ETR 50.610	27.92801	0.047	0.216364

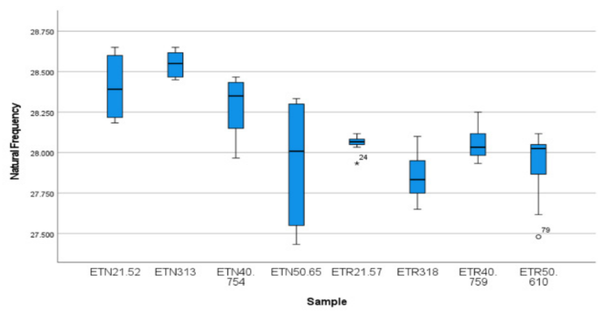

FIGURE 5. Natural frequency parameter Sample - Testing

FLANGE

The natural frequency and variability of the top and bottom flanges of a beam have been observed to exhibit distinct differences, indicating potential variations in structural properties or treatments. Specifically, the top flange demonstrated an average natural frequency of 28.18 Hz, with minimal variance (0.016) and standard deviation (0.126481) (Table 2), suggesting a consistent and uniform dynamic response as well as material properties (Zhang et al. 2020).

In contrast, the bottom flange's average natural frequency is much lower at 17.78 Hz, with high variance (120.547) and standard deviation (10.979399), implying a broader range of frequency values. This suggests a greater diversity in material properties or structural characteristics, due to inconsistent reinforcement or material quality variations (Figure 6). The analysis shows close average natural frequencies for both flanges around 28.18 Hz for the top and 28.09 Hz for the bottom. The bottom flange displayed a slightly higher variance, indicating marginally greater variability (Figure 7)

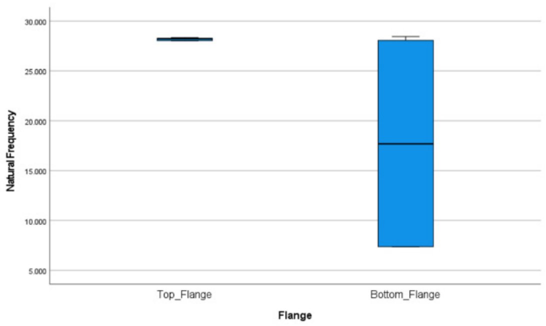

FIGURE 6. Natural frequency for parameter Flange – Control

TABLE 2. Statistical result for parameter Flange - Control and Testing

	No	Flange	Mean	Variance	Std. Deviation
Control	1	Top	28.17668	0.016	0.126481
	2	Bottom	17.77501	120.547	10.979399
	No	Flange	Mean	Variance	Std. Deviation
Testing	1	Top	28.17916	0.085	0.290710
	2	Bottom	28.08826	0.103	0.321536

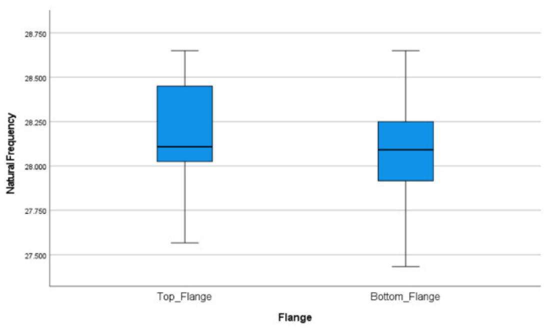

FIGURE 7. Natural frequency for parameter Flange - Testing

REINFORCEMENT

The comparison between the no reinforced and reinforced beams reveals distinct differences in their dynamic responses. The non-reinforced beams had an average natural frequency of 28.13 Hz with low variance (0.029) and standard deviation (1.69745), indicating uniform dynamic behaviour and consistent material or structural characteristics (Table 3).

TABLE 3. Statistical result for parameter reinforcement - Control and Testing

	No	Reinforcement	Mean	Variance	Std. Deviation
Control	1	No Reinforcement	28.13002	0.029	0.169745
	2	With Reinforcement	17.82167	121.608	11.027605
	No	Reinforcement	Mean	Variance	Std. Deviation
Testing	1	No Reinforcement	28.29084	0.114	0.337034
	2	With Reinforcement	27.97659	0.028	0.167037

In contrast, the reinforced beams demonstrated a lower average natural frequency of 17.82 Hz (Figure 8), along with a significantly higher variance (121.608) and standard deviation (11.027605). This suggests a lack of uniformity in their dynamic response, owing to inconsistencies in reinforcement application, varying impacts of the reinforcement on different beams, or an unexpected reduction in stiffness (Zhang et al. 2021).

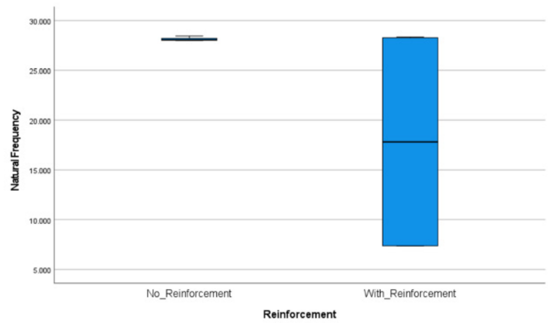

FIGURE 8. Natural frequency for parameter reinforcement - Control

The analysis shows that no reinforced beams have an average natural frequency of approximately 28.29 Hz with low variance, indicating consistency. However, reinforced beams show a slightly lower mean frequency of approximately 27.98 Hz and higher variance, indicating greater variability and unexpected outcomes, given that reinforcement typically increases stiffness and frequency (Figure 9).

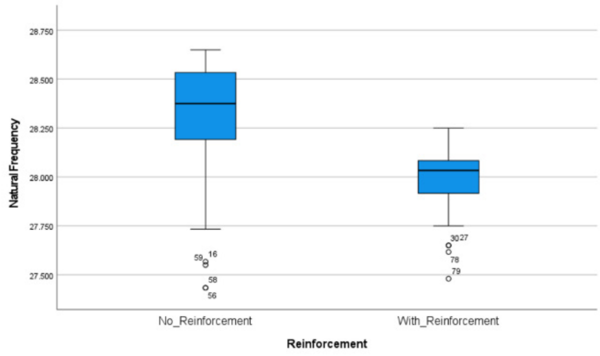

FIGURE 9. Natural frequency for parameter reinforcement - Testing

SEGMENT

The analysis of mean natural frequencies across different beam segments shows a gradual decrease from Segment 2 to Segment 5. Specifically, Segment 2 has a mean natural frequency of approximately 28.23 Hz, Segment 3 about 28.20 Hz, Segment 4 around 28.17 Hz, and Segment 5 notably lower at approximately 27.93 Hz (Table 4). This pattern suggests a trend where higher segment numbers, corresponding to various positions along the beam or variations in beam configuration, are associated with lower natural frequencies. The progressive decline in mean natural frequency from Segment 2 to Segment 5 could indicate changes in physical properties or conditions affecting the segments, which in turn impact their natural frequency. The particularly lower mean frequency for Segment 5 suggests that it may be structurally distinct from the other segments.

TABLE 4. Natural frequency for parameter No of Segment - Testing

No	Segment	Mean	Variance	Std. Deviation
1	2 Segment	28.23251	0.055	0.233547
2	3 Segment	28.20334	0.141	0.376062
3	4 Segment	28.17251	0.034	0.184748
4	5 Segment	27.92650	0.102	0.319574

Moreover, Figure 10 shows a discernible trend of decreasing median natural frequency from Segment 2 to Segment 5, implying potential changes in beam properties or effects of beam position along the segments. This observation might point to systematic variations in the beams' stiffness or damping characteristics across the segments. However, the variability in natural frequency is not uniform across all segments. Segment 4 exhibits the least variability, while Segment 3 shows the most.

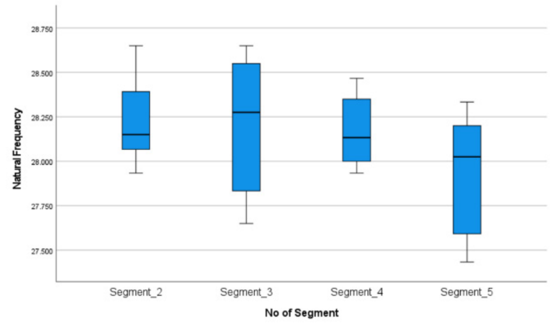

FIGURE 10. Natural frequency for parameter No of Segment - Testing

Overall, this consistent decrease in median natural frequency across segments suggests a systematic change in the properties of the beams. Understanding these variations is crucial for structural analysis and design, as it can influence the overall performance and suitability of the beams for specific applications.

CORRELATION

Statistical analysis of the data highlights several significant negative correlations with important implications in structural engineering. This trend could reflect systematic differences in the sample production or treatment. Additionally, the flange variable shows a similar negative correlation of -0.577, indicating that changes in flange design, material, or construction are linked to reduced natural frequencies. This suggests that the flange characteristics significantly affect the dynamic behaviour of the beam. A notable negative correlation of -0.572 (p-value = 0.008) (Table 5) with reinforcement indicates that reinforced beams have lower natural frequencies, contrary to the expectation that reinforcement increases the stiffness and natural frequency.

TABLE 5. Correlation results for Control Sample

	Sample	Flange	Reinforcement
Pearson Correlation	-0.572	-0.577	-0.572
Sig. (2-tailed)	0.008	0.008	0.008
N	20	20	20

Table 6 shows several relationships between the beam characteristics and their natural frequencies, which have important implications for beam design and reinforcement.

A significant negative correlation (-0.610, p < 0.001) between sample identifiers and natural frequency implies a systematic drop in frequency. However, the impact of the flange on the natural frequency was not statistically significant (-0.149, p = 0.189), indicating no direct linear relationship within the tested range. Notably, reinforced beams display lower natural frequencies (-0.513, p < 0.001), contrary to the expectation that reinforcement increases the stiffness and frequency. Furthermore, both an increased number of segments and connectors are associated with reduced natural frequencies (-0.347, p = 0.002 for both), suggesting that greater beam complexity may diminish stiffness and lower frequencies.

TABLE 6. Correlation results for Testing Sample

	Sample	Flange	Reinforcement	No. of Segment
Pearson Correlation	-0.610	-0.149	-0.513	-0.347
Sig. (2-tailed)	< 0.001	0.189	<0.001	0.002
N	80	80	80	80

CONTROL SAMPLE

The model analysis provides valuable insights into the factors influencing the natural frequency of beams, showing a robust correlation between the predictors and natural frequency. The multiple correlation coefficient (R) was 0.812, indicating a strong positive relationship between the model predictions and the observed values. The coefficient of determination (R Square) was 0.659, meaning that approximately 65.9% of the variance in natural frequency is explained by the independent variables, reinforcement, and flange (Table 7).

TABLE 7. Regression results for Control Sample

R	R Square
0.812	0.659

The high F-value (16.459) and significance value (p < .001) confirm the model's statistical reliability (Table 8). Table 9 shows negative coefficients for Flange (-10.402) and Reinforcement (-10.308), both significant (p < 0.001), indicate an inverse relationship with natural frequency. The similar magnitudes of these coefficients (-0.577 and -0.572) suggest that both factors have a comparable impact on natural frequency. This is contrary to expectations that increases in reinforcement and certain flange characteristics increase the stiffness and natural frequency. The specific flange modifications, intended to enhance stiffness, may have inadvertently led to stress concentrations or compromised the overall structural integrity. Similarly, the Chopped Strand Mat (CSM) reinforcement could have been hindered by suboptimal placement, poor bonding, or material variations. Additionally, the interplay between the flange changes and CSM reinforcement may have altered the load paths within the beam, resulting in unanticipated reductions in stiffness.

TABLE 8. ANOVA for Control Sample

Sum of Squares	df	Mean Square	F	Sig.
1072.284	2	536.142	16.459	<0.001

TABLE 9. Parameter significant relationship for Control Sample

Independent Variable	Unstandardized Coefficient	Sig.
Flange	-10.402	< 0.001
Reinforcement	-10.308	< 0.001

MODULARITY ON TESTING SAMPLE

The examination of the model, which incorporates factors such as the quantity of connectors, presence of reinforcement, and the flange, provides valuable insights into their relationship with the inherent frequency of a structure. The moderate positive correlation indicated by a multiple correlation coefficient (R) at 0.637 suggests that these combined factors moderately influence natural frequency in a linear manner (Table 10).

TABLE 10. Regression for Testing Sample

R	R Square
0.637	0.406

Table 11 shows an F-statistic of 17.300 strongly suggests significant fit to the data, making it evident that including predictors better explains variability in natural frequency compared to models without any predictors.

TABLE 11. ANOVA for Testing Sample

Sum of Squares	df	Mean Square	F	Sig.
3.041	3	1.014	17.300	<0.001

Quantification through coefficients illustrates impact on natural frequency: while having a slight decrease associated with an increase in flange variable (-0.091), its relationship lacks statistical significance (p = 0.097). On other hand, reinforcement demonstrates more substantial decrease (-0.314) and high statistical significance (p <

0.001) (Table 12), indicating stronger effect in reducing natural frequency compared to number connectivity's impact - essential knowledge for understanding implications related beam design changes affecting structures' dynamics and stability across various engineering applications.

TABLE 12. Parameter significant relationship for Testing Sample

Independent Variable	Unstandardized Coefficient	Sig.
Flange	-0.091	0.097
Reinforcement	-0.314	< 0.001
No of Connector	-0.095	< 0.001

This study examines the inherent frequencies of modular timber beams by employing both experimental and simulation methods.

Research findings indicate a limited scope of natural frequencies, influenced by material inconsistency. These results underscore a broader pattern: as the quantity of beam segments grows, indicating longer beams, the natural frequency tends to decrease due to enhanced flexibility and diminished stiffness. This pattern aligns with theoretical predictions and was consistently detected in both experimental and simulated datasets.

Although the theoretical benefits of incorporating Chopped Strand Mat (CSM) reinforcement to improve beam stiffness are well-documented, further investigation is needed to explore the practical implications of its use, particularly in applications with intermittent reinforcement configurations. Numerical simulations forecast a rise in the natural frequency for beams reinforced with CSM, aligning with theoretical predictions of heightened stiffness. Nevertheless, the experimental findings for reinforced beams were inconclusive, potentially due to the discontinuous nature of the reinforcement along the length of the beam.

Furthermore, the study highlights the vital function of connectors in maintaining natural frequencies and improving the system's overall rigidity and damping capacity. This implies that connectors could potentially reduce the beams' susceptibility to dynamic loads, resulting in a more reliable and predictable structural behaviour.

CONCLUSION

This study offers valuable information on the design principles of forest bridges, revealing that adjusting the beam segment lengths and reinforcement techniques can improve the beam dimensions and material usage. These advances are expected to enhance the durability and longevity of forest bridges. Our research reveals the intricate connection between beam reinforcement, especially with Chopped Strand Mat (CSM) improvement, and its mechanical behaviour. This investigation proves that Experimental Modal Analysis is a promising method for assessing structural behaviours in forest bridge systems. This highlights the need for further research on the vibrational characteristics and impact of modular connections on CSM-reinforced timber beams. The ultimate aim is to improve the structural integrity of forest bridge systems using innovative analysis and engineering techniques.

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DECLARATION OF COMPETING INTEREST

None.

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