

Investigation of the Modal Parameters of a Cricket Bat via Simulation and Experimental Modal Analysis

M.I.A. Ismayatim¹, M.S.A. Mohd Kahar, N.F.H. Ah Siak, M.A. Yunus¹ and M.N. Abdul Rani^{1*}

¹Structural Dynamics Analysis & Validation (SDAV),
Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM),
Shah Alam, Selangor, Malaysia.

*Corresponding email: mnarani@uitm.edu.my

ABSTRACT

The dynamic behaviour of a cricket bat significantly influences its overall performance, particularly in relation to ball rebound, power, control, and player comfort. Despite its importance, the relationship between bat structure and dynamic response remains insufficiently understood. This study aims to investigate the modal parameters of a cricket bat, with the goal of enhancing performance and reducing the risk of injury due to repeated impact during gameplay. To achieve this, an integrated approach involving Finite Element analysis (FEA) and Experimental Modal Analysis (EMA) are used to determine modal parameters such as natural frequencies, mode shapes and damping ratios. The FE model of the cricket bat is developed based on the actual dimensions of the physical cricket bat test. Normal modes analysis is then performed using MSC Nastran to compute the natural frequencies and mode shapes of the bat. These results are compared with the EMA results to evaluate the accuracy of the simulated results. The study shows notable differences in modal frequencies, with error ranging from 0.73% to 26.70%. These discrepancies highlight the complexity of reproducing bat dynamics accurately through FE models. The findings of the study indicate that the dynamic behaviour is highly sensitive to material properties, particularly Young's Modulus and density. This study provides valuable findings on the complex dynamic behaviour of cricket bats. The results can assist players in selecting bats that align with their playing style and support manufacturers in optimising bat performance, enhancing player safety, and improving overall player experience.

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INTRODUCTION

Cricket, like many other sports, is increasingly becoming a domain of technical refinement where the physics of equipment behaviour directly influences player performance. The cricket bat is a critical piece of sporting equipment that affects a player's ability to control shots, maximise energy transfer, and minimise vibration-induced discomfort. While traditionally crafted from English Willow wood and governed by the regulations of the Marylebone Cricket Club (MCC), the modern cricket bat is more than a static tool, the bat is a dynamic structure whose performance is reviewed by complex mechanical interactions during ball contact [1]. Understanding the response of the bat to dynamic loading conditions, especially in terms of its vibrational behaviour, is important for enhancing both playability and player's comfort.

The dynamic behaviour of a cricket bat is fundamentally characterised by its modal parameters, which are natural frequencies, mode shapes, and damping ratios. These modal characteristics determine how the bat vibrates when struck and directly influence performance attributes such as energy dissipation and player comfort. For example, impact near vibrational nodes reduce energy loss and shock to the hands, while off-node impacts can excite resonant modes, resulting in performance degradation and discomfort. Therefore, accurate identification and analysis of these modal parameters are critical for optimising bat design. Previous studies have shown that the effectiveness of experimental modal analysis and finite element modelling in characterising the dynamic behaviour of cricket bats [2], [3], [4]. However, comprehensive integration of both methods remains limited. The influence of modal parameters extends beyond immediate tactile feedback which also plays a vital role in structural design optimisation. Advanced techniques such as Finite Element Analysis (FEA) allow researchers to simulate the modal behaviour of bats under varying conditions which help the manufacturers make informed decisions regarding geometry, material selection, and weight distribution [1]. Similarly, EMA using accelerometers and impact hammers enables the identification of real-world vibrational modes and natural frequencies, providing critical validation data for analytical and numerical models [2], [3].

Although several studies have investigated cricket bat dynamics, most focus narrowly on experimental measurements or individual parameters without proposing an integrated analytical framework. There remains a significant lack of comprehensive research that combines analytical modelling of cricket bats with experimental validation. Moreover, few studies account for realistic boundary conditions that replicate actual playing scenarios, such as hand grip stiffness or bat support constraints. Without this integration, theoretical models risk inadequate validation, and experimental findings may not generalise beyond specific cases [3], [5]. This gap limits the predictive capability of analytical approaches and restricts innovation in cricket bat design.

The aim of this study is to investigate the modal parameters of a cricket bat by developing and validating an analytical model based on its modal parameters. The research seeks to determine key modal parameters, namely natural frequencies and mode shapes through both simulation and experimental modal analysis. The accuracy of the developed analytical model is evaluated by comparing the FE results with the EMA results. This integrated approach is intended to provide a robust framework for understanding the dynamic behaviour of cricket bats and to support future engineering decisions in the design and optimisation of cricket bats for improved performance and player comfort.

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This study contributes to the growing field of sports engineering by integrating numerical simulation and experimental validation to offer a deeper understanding of cricket bat dynamics. The outcomes of this study are intended to enhance the collective understanding of how modal properties may directly influence cricket bat performance and player experience, thereby benefiting manufacturers, players and researchers alike.

METHODOLOGY

Structural Modelling

A Classic MB Malik Sarfi English Willow cricket bat manufactured in India was used in this study. The geometric features of the cricket bat, including its edges, spine, and other pertinent elements, precisely were measured precisely using a Coordinate Measuring Machine (CMM), as shown in Figure 1. First, the z-coordinated along the bat's spine were measured using the CMM touch probe. Second, regions inaccessible to the probe were measured with the vernier calliper, which offers greater accurate than a standard ruler.

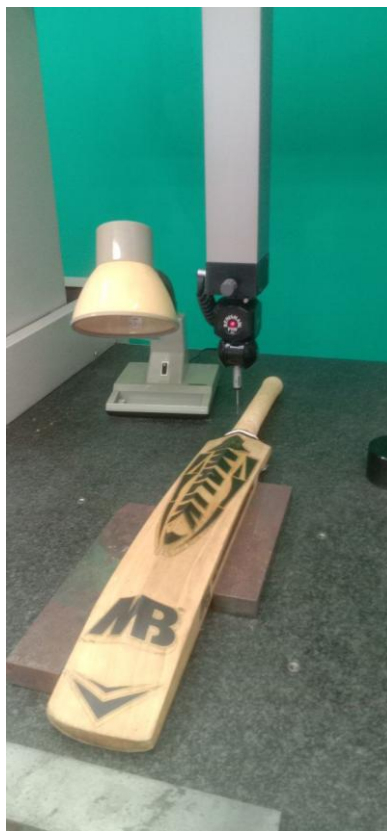


Figure 1. Coordinate measurements using CMM machine

Figure 2 shows the dimensional measurements of the blade and handle for the cricket bat. The lengths of the blade and handle were measured due to its superior accuracy compared to conventional measuring tools such as standard ruler. The combined use of these two measuring tools is ensures comprehensive and reliable geometric data for the subsequent CAD modelling process.

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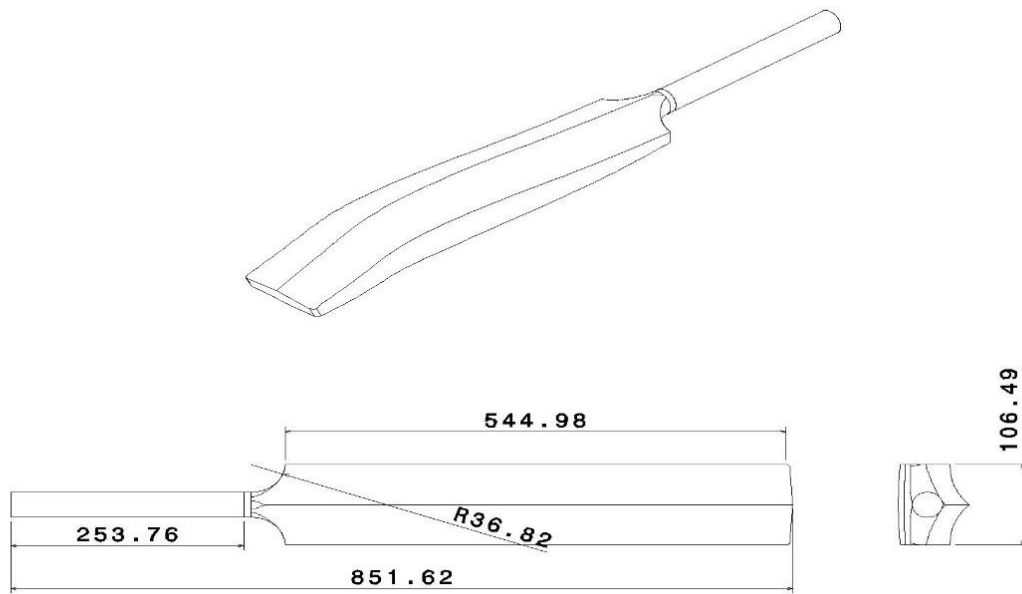


Figure 2. Detailed dimensions of the Cricket bat

The spine coordinates measured with the CMM were imported into CATIA to define the cricket body axis. The spine profile served as the foundation for constructing the cricket blade geometry, while the handle was created using the diameter measurements obtained from the vernier calliper, the. Finally, finishing features were added to closely replicate the physical cricket bat, using unique feature such as fillet and revolution to incorporate all important characteristics including the edges, spine profile, and general curvature. The resulting CAD model, shown in Figure 3, served as the foundation for subsequent analysis.

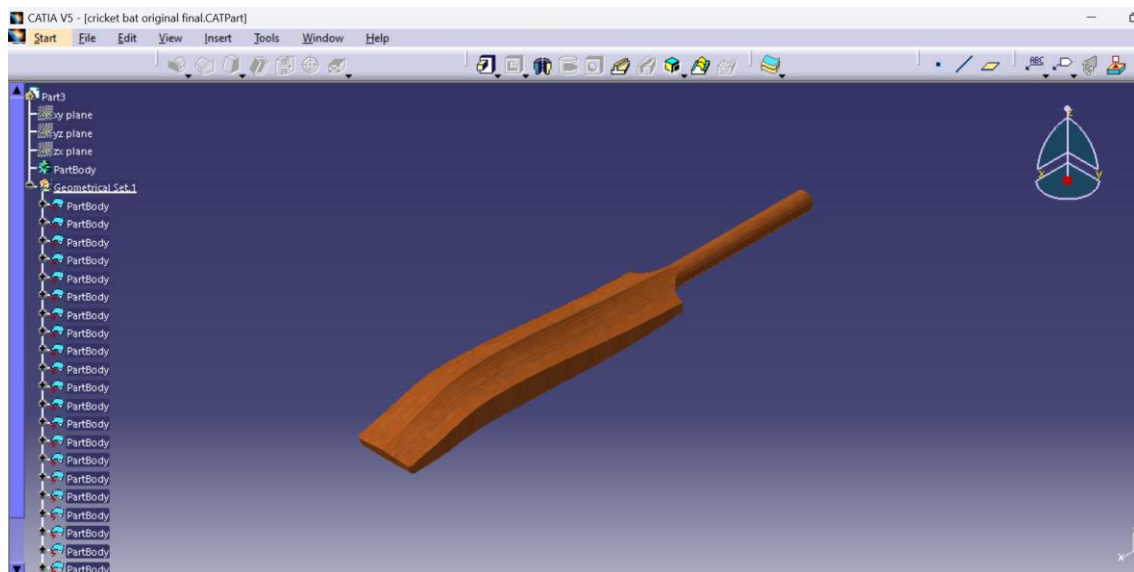


Figure 3. CAD model of the cricket bat

FE Modelling of the cricket bat

MSC Nastran was used to perform normal modes analysis (Figure 4) due to its user-friendly and robust pre-processing capabilities. The cricket bat 3D CAD model, initially developed in CATIA, was imported into MSC Patran for further analysis. The material properties of English Willow wood were assigned based on relevant literature values, including density, Young's modulus, and Poisson's ratio.

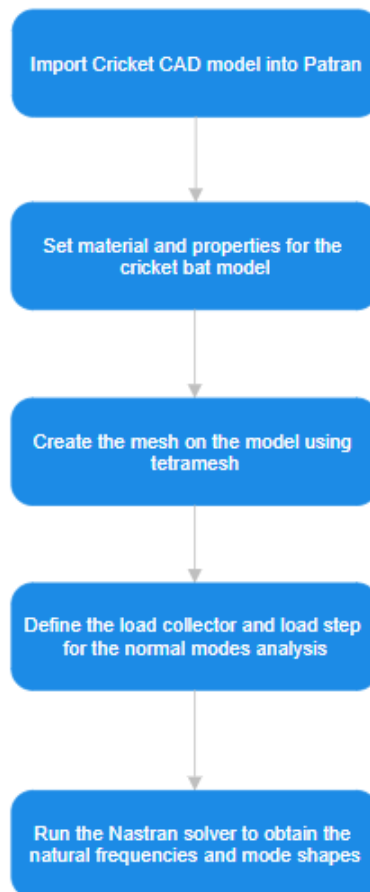


Figure 4. Flow chart for normal modes analysis of cricket bat

Meshing was carried out using tetrahedral (Tetra) elements for the 3D solid regions of the bat, complemented by R-trias elements for 2D surface representations as shown in Figure 5, ensuring the mesh conformed accurately to the complex geometry of the bat. Tetrahedral elements are ideal for automatically meshing irregular or curved 3D geometries like cricket bat because of their 4-nodes, pyramid-like shape allow them to fit into complex volumes without manual intervention. Following the meshing process, the EIGRL (Eigenvalue Real) card was defined to extract the desired number of natural frequencies and corresponding displacement mode shapes.

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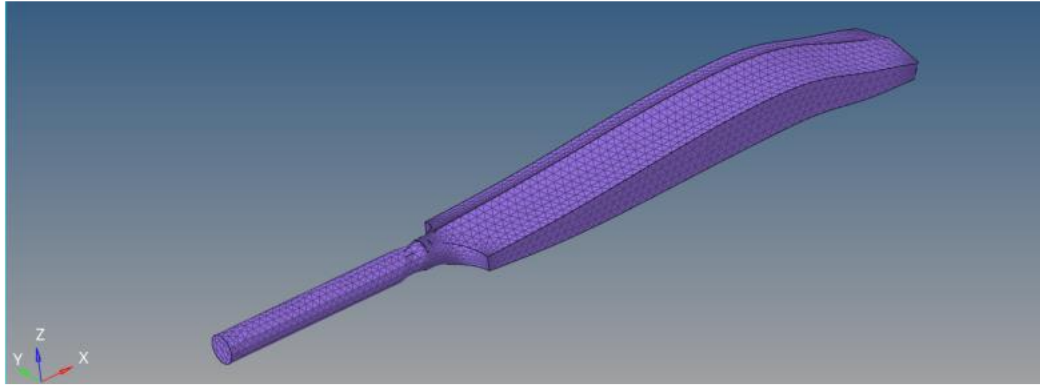


Figure 5. FE model of the cricket bat

Based on the composition material of the cricket bat, the FE model was assigned the relevant material properties of English Willow wood, including density (ρ), Poisson's ratio (ν), and modulus of elasticity (E). These properties are essential for ensuring realistic simulation of the dynamic behaviour of the bat. Following an intensive review of previous literature and experimental studies, the material parameters for English Willow were identified and are summarised in Table 1.

Table 1. Material property of English Willow Wood

Modulus of Elasticity, E	Poisson's Ratio, ν	Density, ρ
2050 MPa	0.35	$4.383 \times 10^{-10} \text{ Kg/mm}^3$

Modal analysis was executed using Nastran to compute the natural frequencies and associated mode shapes of the bat, based on the defined boundary conditions and material properties as shown in Table 1. The analysis calculated the first 10 natural frequencies and their corresponding mode shapes. Figure 6 shows the first mode of the bat, with its mode shape predominantly in the z-direction.

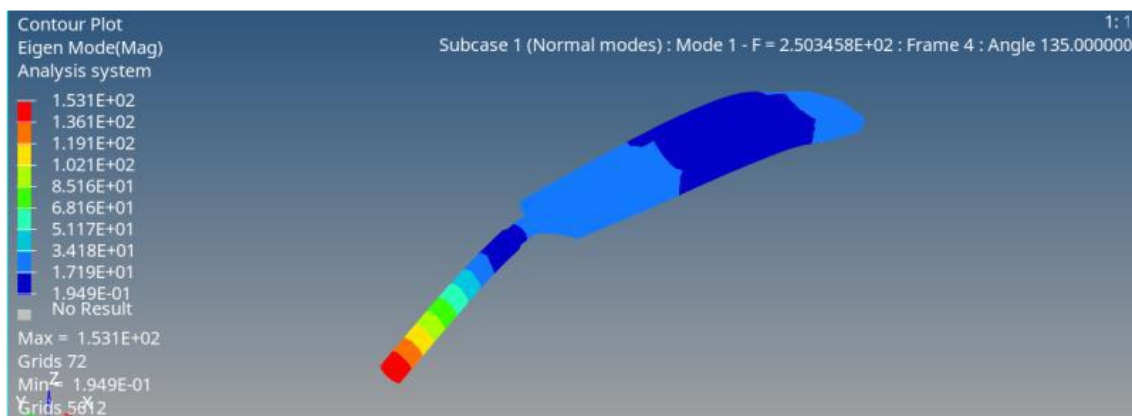


Figure 6. Simulated natural frequency and mode shape of the bat

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Convergence test

In this study, convergence tests were conducted using five different element sizes: 1 mm, 2 mm, 4 mm, 6 mm, and 8 mm. Normal modes analysis was performed for each mesh size, with the first five natural frequencies calculated in each case. The results showed that decreasing the element size led to improved correlation with the EMA results, indicating higher accuracy in representing the dynamic behaviour of the bat. Table 2 presents the variation in natural frequencies corresponding to each element size used in the FE models of the cricket bat.

Table 2. Natural frequencies of the cricket bat with different meshing sizes

Mode	Element size				
	1	2	4	6	8
1	125.09	219.75	222.27	225.34	229.91
2	152.22	267.03	269.52	272.73	278.34
3	358.11	629.5	634.93	641.79	654.22
4	588.72	1037.78	1042.48	1048.99	1066.47
5	653.10	1149.77	1161	1174.74	1204.06

The graph in Figure 7 shows the results of the convergence test for natural frequencies across different element sizes and modes. Regardless of element size, the natural frequencies converge to comparable values at higher modes (4 and 5) across all mesh sizes, suggesting mesh-independent and effective convergence. For lower modes (1 and 2), only minor differences are observed between meshes, indicating a low sensitivity to element size. While element sizes like 6 mm or 8 mm are sufficient for obtaining accurate frequencies, smaller sizes like 2 mm or 4 mm provide more reliable results at a higher computational cost.

However, based on this trend, the 1 mm mesh sizes provide higher accuracy, with differences between the FE and EMA results falling below 1%. This finding confirms the accuracy and dependability of the model. Therefore, a 1 mm mesh size is identified as the most appropriate choice. Providing highly accurate and reliable results for comparison with EMA, despite the increase computational cost.

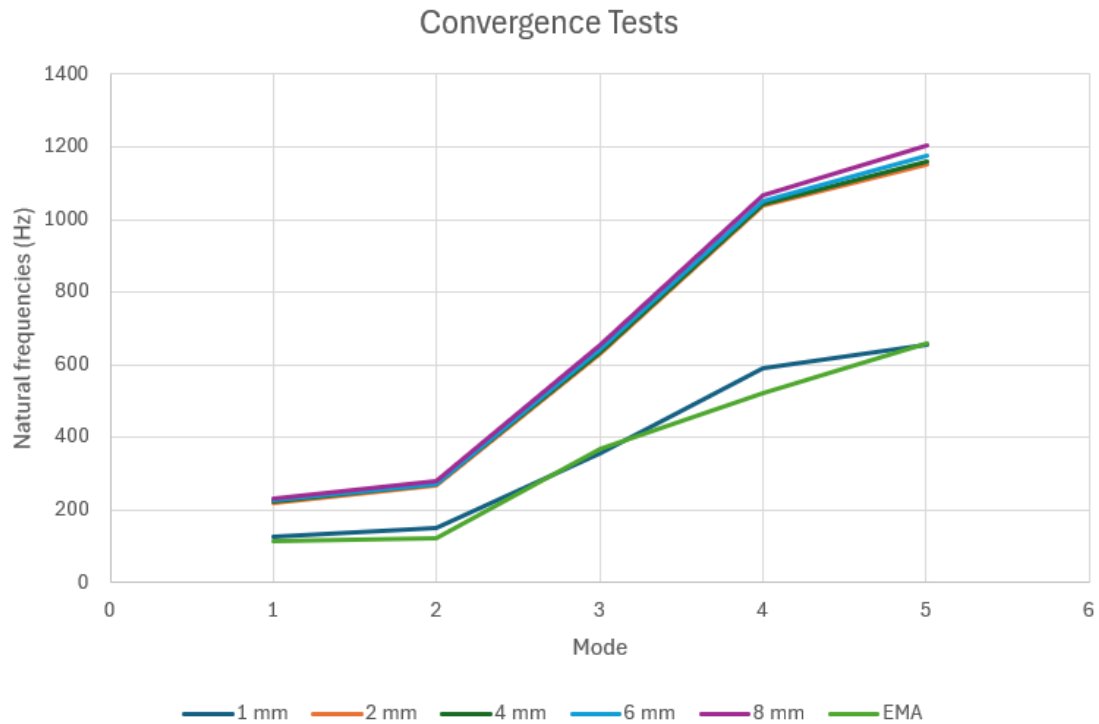


Figure 7. Convergence Test results

Experimental Modal Analysis (EMA)

EMA of the cricket bat was carried out using the roving accelerometer method to identify its modal parameters, namely natural frequencies and mode shapes. In this procedure, the bat was rigidly tied with a string at the end of the blade to approximate free boundary conditions, shown in Figure 8.

Five PCB 356A12 tri-axial accelerometers and a PCB Piezotronics Model 086C03 instrumented impact hammer were used to measure the modal parameters of the bat. The roving accelerometer approach was adopted in this measurement. The accelerometers were roved systematically across 15 predefined measurement points, with each separate ten excitations performed. Ten difference FRFs were measured using the LMS-Test Lab.

From the combined set of measured FRFs, the natural frequencies and mode shapes of the bat were extracted and used as the validation benchmark for FE models. Figure 9 shows the flow-chart of the measurement procedure of the modal parameters of the bat in this study.



Figure 8. EMA setup of the physical cricket bat

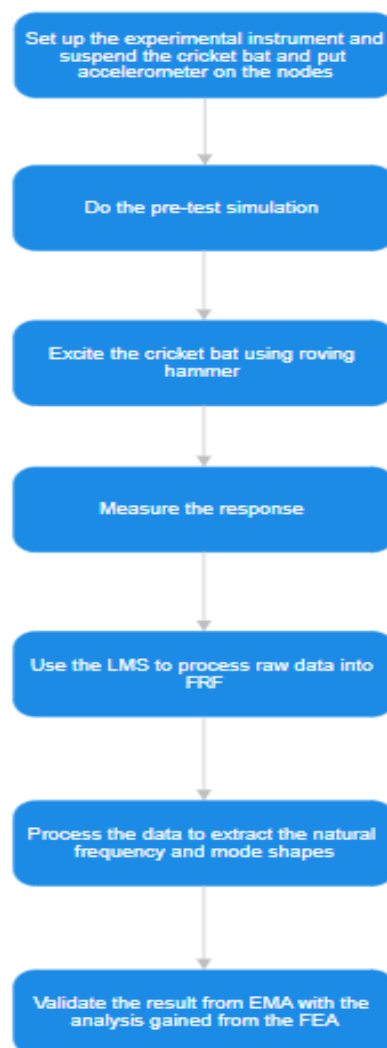


Figure 9. Flow chart for experimental modal analysis of a cricket bat

RESULTS AND DISCUSSION

The aim of this study is to determine the modal parameters of the cricket bat using both analytical and experimental approaches. MSC Nastran used for simulation, EMA was conducted to determine experimental data. The simulated modal parameters obtained from Nastran were compared with the EMA results to validate the FE model constructed and used in this study.

Percentage error between FEA and EMA

The comparison of natural frequencies obtained from FEA and EMA, as tabulated in Table 3, shows non-uniform discrepancies across modes, with the error percentage errors from 0.73% to 26.70%. These mode-dependent discrepancies indicate that the FE model has difficulty accurately reproducing the dynamic behaviour of the physical bat. This outcome is a common scenario observed in studies using FEA to predict the dynamic behaviour of structures, often arising from simplifying assumptions related to geometry, homogenous material properties, and simplified constraints [1], [3].

Table 3. Comparison of natural frequencies between FE and EMA (Element size = 1 mm)

Mode	FE (Hz)	EMA (Hz)	Error (%)
1	125.09	113.28	10.43
2	152.22	120.14	26.70
3	358.11	366.65	2.33
4	588.72	519.72	13.28
5	653.1	657.93	0.73
6	883.98	987.78	10.51
7	940	1038.69	9.50
Total Error (%)			73.48

Several factors may contribute to these discrepancies. First, the assumption of linear and isotropic material properties does not fully represent the complex, anisotropic, and heterogeneous nature of English Willow wood, the material commonly used for cricket bats. Studies have shown that wood exhibits directionally dependent mechanical behaviour, which significantly affects its vibrational response [3]. Furthermore, the suspended support from the experimental set-up can be affected by surrounding conditions that alter its effective boundary conditions. Even small deviations in boundary conditions have been shown to produce significant changes in natural frequency values in modal analysis studies [2], [4].

Despite these natural frequency differences, the comparison of mode shapes between FE and EMA show excellent agreement. EMA mode shapes were consistent in form and nodal location with FE counterparts, indicating that the FE model represents the essential dynamic behaviour of the bat. This particularly important because mode shapes play a key role in identifying the sweet spot and understanding how vibrations propagate through the structure. While the frequencies differ slightly, the similar mode shapes between FE and EMA demonstrate that the model can reliably predict locations of the bat where minimal or maximal vibration occurs [6].

Furthermore, the experimental measurements themselves are influenced by noise, sensor mass loading, and fluctuations of the excitation force. Notably, accelerometers

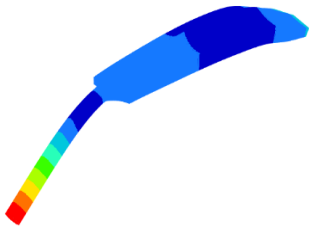
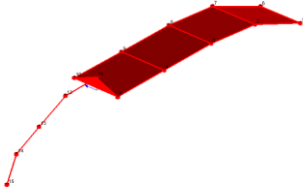
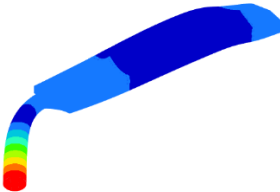
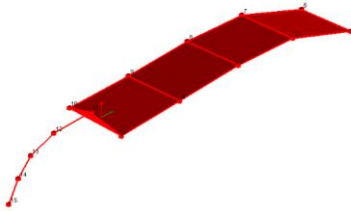
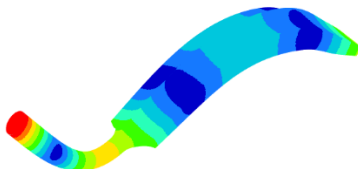
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have significant mass relative lightweight structures such as sports equipment, which can alter their dynamic behaviour [7]. These factors, together with variability in impact location and force application, likely contribute to the differences in EMA outcomes and highlight the need to carefully control these factors [2].

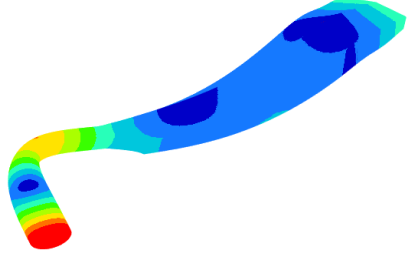
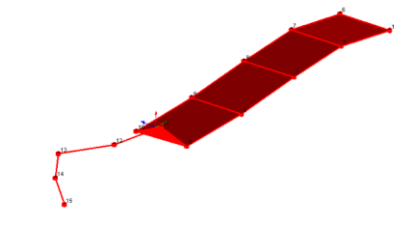
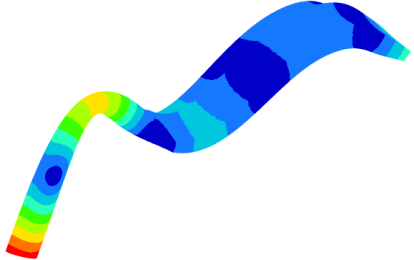
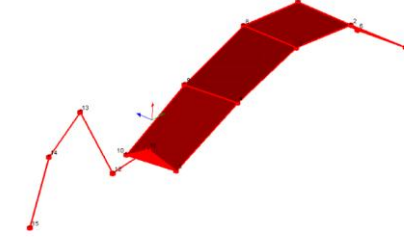
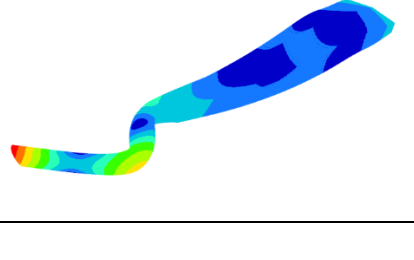
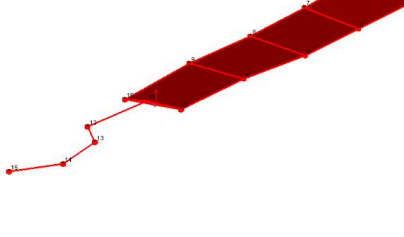
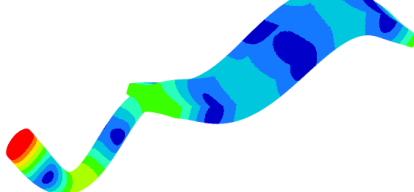
Comparison of mode shapes between FE and EMA

Table 4 shows the comparison of mode shapes between FEA and EMA, demonstrating excellent agreement. The mode shapes exhibit bending behaviour in both the y- and z-directions. By analysing the displacements patterns of these mode shapes, sweet spots (node locations) can be identified to minimise vibration transmission to the handle. The FE mode shapes were found to be similar in appearance and nodal position to the EMA counterparts, suggesting that the FE model accurately reproduces the dynamic deformations of the bat. This outcome aligns with similar findings in studies of bat and racket dynamics, where the ability to accurately identify mode shape, rather than simply matching frequencies, has been considered more important for assessing performance [1], [4].

Table 4. Comparison of mode shapes between FE and EMA

Mode	FE	EMA	Error (%)
1			10.43
2			26.70
3			2.33

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4			13.28
5			0.73
6			10.51
7			9.50

Considering these findings, the study has largely achieved its objectives. The FE model was relatively successful in reproducing the natural frequencies and demonstrated strong capability in representing the model shapes of the physical cricket bat. These results affirm the importance of validating simulation data with experimental data, especially for sports equipment where dynamic behaviour directly affects performance and user comfort [1], [3].

Future work may focus on refining the material modelling by incorporating orthotropic properties and more realistic damping estimates. Additionally, improving boundary condition modelling to more closely mimic experimental setups could reduce the margin of error [8]. Incorporating these refinements would enhance the predictive accuracy of the model and further support the optimisation of cricket bat design through FEA.

CONCLUSIONS

The numerical and experimental investigation of the modal parameters of the cricket bat has been presented and discussed. FEA and EMA were used to determine the modal parameters. The results indicate that the FE model showed limited capability in accurately predicting the natural frequencies with mode-dependent discrepancies observed. However, it demonstrated strong capability in reproducing the EMA- derived mode shapes, indicating that the model accurately represents the deformations of the mode shapes. These findings highlight the essential role of EMA validation in developing robust FE models for sports equipment design. Future work should focus on improving the accuracy of the predicted natural frequencies by adopting model updating approaches.

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REFERENCES

- [1] T. Kilpatrick, L. Mulcahy, and A. Blicblau, "Improving the performance of cricket bats: An experimental and modelling approach," *Sensoria: A Journal of Mind, Brain & Culture*, vol. 9, no. 1, pp. 47–50, 2013.
- [2] P. Jaramillo et al., "Sweet Spot or Sweet Zone? Modal Analysis of a Wooden Baseball Bat for Design Optimization," *Proc. of IMECE 2003*, ASME International Mechanical Engineering Congress, Washington, D.C., Nov. 2003.
- [3] S. Fisher, *Experimental and Finite Element Analysis of Cricket Bats*, PhD thesis, University of Bath, 2005.
- [4] A. Cross, "The sweet spot of a baseball bat," *American Journal of Physics*, vol. 72, no. 6, pp. 620–626, 2004.
- [5] D. Brody, "The mechanics of the baseball-bat collision," *American Journal of Physics*, vol. 51, no. 7, pp. 597–600, 1983.
- [6] H. Jansen, K. Sotthewes, J. Swigchem, H. Zandvliet, & E. Kooij, "Lattice boltzmann modeling of directional wetting: comparing simulations to experiments", *Physical Review E*, vol. 88, no. 1, 2013. <https://doi.org/10.1103/physreve.88.013008>
- [7] A. Sarrafi, Z. Mao, C. Niezrecki, & P. Poozesh, "Vibration-based damage detection in wind turbine blades using phase-based motion estimation and motion magnification", *Journal of Sound and Vibration*, vol. 421, p. 300-318, 2018. <https://doi.org/10.1016/j.jsv.2018.01.050>
- [8] S. Shi, L. Ma, K. Kang, J. Zhu, J. Hu, H. Maet al., "High-sensitivity piezoelectric mems accelerometer for vector hydrophones", *Micromachines*, vol. 14, no. 8, p. 1598, 2023. <https://doi.org/10.3390/mi14081598>