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Vibration Characteristics of Copper-Aluminium Composite Under Different Boundary Conditions: Experiment and Simulation

Prabhat Mahawar[1],*, Pankaj Sharma[2], Jai Kumar Sharma[3]

Abstract

The utilization of vibration analysis on the tapered beam significantly enhances the engineering investigation and design process. It is notable that the width of the tapered beam exhibits variation along its length, while the height remains constant. Experimental modal testing aims to determine modal factors such as natural frequency, damping, and mode shapes. A comparative study is presented in this paper, examining the vibrational characteristics of tapered beams composed of copper, stainless steel, and Copper-Aluminium composite under different boundary conditions. Both experimental and numerical approaches are employed for this purpose. The excitation of the beam is achieved using an impact hammer, while a laser vibrometer captures the ensuing response. Signal conversion from the time domain to the frequency domain is carried out using the Fast Fourier Transform in MATLAB software. A comparison is made between the experimental findings and the numerical results generated by COMSOL 5.6v, a finite element modeling software. Investigation and analysis of the modal properties of the tapered beams, particularly its natural frequency and mode shape, are essential for enhancing design robustness.

Keywords: Tapered beam, modal analysis, laser vibrometer, composite, impact hammer

INTRODUCTION

Today, alloys that consist of aluminum, copper, and magnesium exhibit a wide range of properties dependent on their precise formulation. Aluminum-copper alloys are often recognized for their increased strength and excellent wear resistance, thereby making them fitting for structural applications [1]. Aluminum-magnesium alloys are distinguished by their remarkable corrosion resistance and low density, which is particularly beneficial for applications in the aerospace and automotive sectors [2]. Although less prevalent, copper-magnesium alloys can provide improved strength and thermal conductivity. The specific properties of these alloys can vary based on their precise formulation and processing [3]. Also, aluminum metal matrix composites (MMCs) exhibit a wide range of enhanced characteristics when compared to pure aluminum. These characteristics include increased strength and rigidity resulting from the reinforcement phase, improved wear resistance, and enhanced thermal stability. The exact extent of these enhancements is dependent on the specific nature and amount of reinforcement materials utilized, as well as the properties of the matrix [4].

In the previous twenty years, experimental modal testing has gained significant prominence as a technique utilised to evaluate, optimise, and improve the dynamic characteristics of engineered

***Author for Correspondence**
Prabhat Mahawar

[1]Research scholar, Department of Mechanical Engineering, Rajasthan Technical University, Kota, Rajasthan, India
[2]Assistant Professor, Department of Mechanical Engineering, Rajasthan Technical University, Kota, Rajasthan, India
[3]Assistant Professor, Department of Mechanical Engineering, ITM Gwalior, Madhya Pradesh, India

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structures. The method involves the determination of the modal parameters of the structure, including but is not restricted to, parameters such as natural frequency, damping factor, and mode shapes. Modal testing involves the controlled application of an excitation or external force at many locations on the structure to create vibrations in the test structure. Tapered beams are frequently employed in structural applications because of their high stiffness-to-mass ratio. In comparison to prismatic beams, tapered beams have various benefits, including greater lateral stability, a larger shear-bearing capacity, and weight savings. Next, the vibration response data is gathered using an appropriate transducer. A more comprehensive analysis is conducted on the composed vibration data in order to extract the modal characteristics, which comprise the natural frequencies, mode shapes, and damping. Finite element analysis is widely employed in industry to accurately simulate engineering structures. However, when dealing with intricate engineering structures and components, the exclusive use of finite element modelling can result in inaccuracies owing to computer or method constraints. The integration of modal testing and finite element modelling is extensively employed to accurately ascertain the dynamic characteristics of complex structures while minimising errors.

Researchers have utilised experimental and Finite Element Method methodologies to undertake modal analysis for predicting the dynamic characteristics of engineering components. For example, Li et al [5]. and Banerjee et al [6]. determined the free vibration investigation of functionally graded (FG) tapered beams. The transfer matrix method was used by Boiangiu et al [7]. to study the free vibration of an Euler-Bernoulli beam whose cross-section changed. Bhattacharya et al [8]. presented a study on the investigation of free vibrations in a double-tapered spinning and bidirectional FG micro-beam under temperature conditions. The study utilised the modified couple stress theory. Mehrparvar et al. [9] conducted an investigation on the analysis of free vibration in a tapered Timoshenko beam using the Haar wavelet approach. El-Sayed and Mongy [10]. conducted a study on the investigation of the natural oscillation of a tapered beam using the variational iteration technique. The free vibration study of an axially functionally graded material (AFGM) tapered beam was conducted using the modified couple stress theory [11]. Singh et al [12]. conducted a study on the analysis of free vibrations in axially functionally graded tapered beams using the Timoshenko beam theory. Huang [13]. examined the analysis of the natural oscillation of an orthotropic rectangular plate with varying thickness. Tomovic et al. [14] demonstrated the study of the natural oscillation of tapered beams made of AFGM. Tian [15]. utilized a modified variational method to calculate the natural frequencies of a rotating double-tapered beam made of functionally graded material (FG). Jung Lee [16]. carried out an investigation on the analysis of free vibration in tapered Rayleigh beams utilizing the transfer matrix method. Attarnejad et al [17] employed the differential transformation method to explore the study of free vibration in an axially functionally graded tapered Timoshenko beam. Yavuz and Ozkol [18]. conducted a research on the investigation of the free vibration of a rotating double-tapered beam with a flexible root utilizing the differential quadrature method. Modal analysis of various models is obtained using the Fast Fourier Transformation (FFT) method. The dynamic characteristics of the modal are more effectively addressed by the experimental method [19]. The modal model of a linear time-invariant vibratory system was formulated through experimental modal analysis [20]. Non-destructive experimental modal testing of the tapered beam was performed employing the laser vibrometer to monitor and analyze the vibration response using an impact hammer to excite the beam [21]. Miguel et al. [22]. conducted an experiment to assess the modal properties of a cantilever steel beam, encompassing the natural frequency, damping, and mode shapes, and subsequently correlated the actual findings with theoretical and numerical outcomes. Prashant and colleagues [23]. conducted an experimental study to assess the modal characteristics of a rectangular beam, hence the outcomes derived from the experiment are contrasted with both theoretical and numerical results. An experimental modal analysis of a bladed wheel was conducted by Bertini et al [24]. using a laser Doppler vibrometer.

Sharma [25]. compared the natural frequency obtaioned through experiment, theoretical, and numerical measurements of beams in different boundary conditions. Similar kinds of work were also performed by Sharma and Parashar on cam shafts and milling machine arbor [26-27]. The laser vibrometer consists of two components: one is an electronic unit and other is a laser sensor head. The sensor is equipped with a CCD camera to enhance visualisation, while a separate electronic unit is responsible for signal processing [28]. Prasad et al. [29] ascertained the mode shape, frequencies and damping characteristics of beams made from various materials. This article examines the usage of steel, copper, brass, and aluminium as materials for beams. The beams are subjected to excitation by an impact hammer. Ayush Chandra anshi et al [30] conducted an examination on the resonance behavior of a tapered laminated composite beam. Previous studies have indicated that tapered composite beams exhibit notable stiffness-to-weight ratios and customizable design characteristics, rendering them advantageous in diverse engineering applications [31]. Vijaykumar et al [32] explored the dynamic response of composite beams with variations in width and thickness through modal testing. This investigation aims to identify the inherent frequencies and patterns of vibration, specifically focusing on evaluating structural integrity. Jayalin et al [33] provided an analysis of composite beams utilizing ansys software. These inquiries emphasize the importance of experimental modal analysis on tapered metal composite beams under varying dynamic loads. Nandwani et al [34] assessed the dynamic attributes of metal matrix composite material manufactured via microwave casting. The study proposes an experimental technique for modal analysis to assess the dynamic properties of the composite, featuring silicon carbide (SiC) reinforcement within the SS202 matrix. As SiC improves the material's mechanical properties, including strength and hardness, enhance wear resistance, contribute to better thermal stability, and provide reduced thermal expansion [35]. Arumugam et al [36] computed the thermal performance of tapered laminated composite beams. Employing classical laminated plate theory and higher-order shear deformation theory, the study investigates the thermal behavior of tapered composite beams. Mohanty et al [37] presented a study on the free vibration analysis of tapered laminated composite beams. The investigation delves into the impact of boundary conditions on the natural frequencies and vibration patterns of the beam [38].

Prior scholarly investigations have not employed laser vibrometers to ascertain the dynamic properties of tapered beams made from isotropic (copper, stainless steel (SS)) and copper-aluminium composite, including natural frequency and mode shape. Focus of this study is to investigate experimentally the free vibration of a tapered beam. Further, a comparison is made between the experimental outcomes and the numerical results generated using COMSOL software version 5.6.

EXPERIMENTAL MODAL TESTING OF TAPERED BEAM

The current research, compares the system's inherent frequencies of isotropic tapered beam with composite tapered beam with a special emphasis on the second mode. Additionally, the goal of this investigation is to look at how the system reacts when there's a moderate initial disturbance. Free vibration occurs in the absence of external forces and when the system undergoes an initial deflection. The experimental setup for the tapered beam, which had support only at the ends, was designed to provide clamped-free and clamped-clamped boundary conditions for all three tapered beams made of the copper, stainless-steel and copper-aluminium composite materials. The tapered beam is strategically constrained at one end and allowed to move freely at the opposite end in order to adhere to the clamped free (C-F) boundary condition, as illustrated in Figure 1(a). The clamped-clamped (C-C) boundary constraints are fulfilled by fixing both ends of the beam to a rigid frame, as shown in Figure 1(b). This is done in order to ensure that the beam is in a fixed position. When the test structure is attached to the sturdy frame, it ensures that there is sufficient isolation from potential ground disturbances from the outside.

Same experimental approach is used to obtain the natural frequencies of both the tapered beams (isotropic and composite), regardless of the boundary conditions or the materials. Initial agitation of the tapered beam is performed using an impact hammer at a number of different places. Within the tapered beam, movements happen on their own. The subsequent oscillations of the tapered beam are monitored utilising a Polytec laser vibrometer NLV-2500. Choosing the appropriate displacement module on the controller allows for the measurement of the time-dependent displacement as well as the effect of the laser light on the tapered beam. This is accomplished by selecting the module that corresponds to the displacement. In order to ensure accurate reflection, a tiny paper reflector is placed on the beam through which light get reflected back and received by laser head. This reflected light stores the information regarding vibrations in the form of wave signals. Electronic unit processes signals to enhance the visibility. Further, these received signals are manipulated and analyzed through the digital oscilloscope (NB207C1), to collect the data. The time-domain signals are stored on the USB disk of the digital oscilloscope.

The conversion from time domain to frequency domain is achieved through the application of Fast Fourier Transform. The goal of designing and constructing the experimental setup is to ascertain a beam's intrinsic frequency under various boundary conditions. The current experimental investigation focuses on studying the boundary conditions of clamped-clamped and clamped-free scenarios, as previously reported. The subsequent responses of the beams, subjected to vibration from an impact hammer, were measured using a vibrometer. The natural frequencies obtained through experiment and simulation for the isotropic tapered beams (stainless-steel and copper) and composite (copper-aluminium) tapered beam, are provided in Table 1.

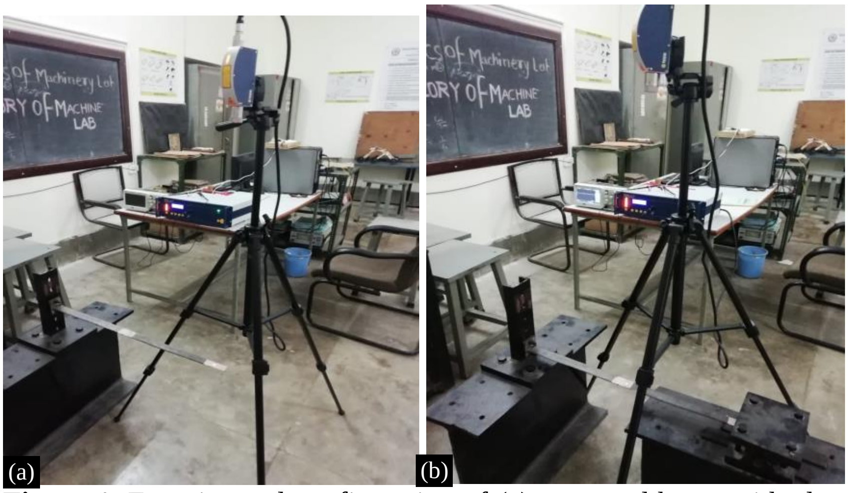

Figure 1. Experimental configuration of (a) a tapered beam with clamp-free and (b) a tapered beam with clamp-clamp boundary conditions.

Table 1. Experimental & Numerical Natural Frequencies of Tapered Beams.

End condition	Beam materials	Mode	Experimental (Hz)	Numerical (Hz)	Error (%)
Clamped-Free	Stainless - Steel	Mode 1	5.556	5.56	0.07
		Mode 2	35.555	33.159	6.7
Clamped -Clamped	Stainless - Steel	Mode 1	32.45	32.309	0.4
		Mode 2	---	89.207	---
Clamped-Free	Copper	Mode 1	4.23	4.1479	2.1
		Mode 2	27.08	23.771	12.2
Clamped -Clamped	Copper	Mode 1	24.053	23.192	3.5
		Mode 2	--	64.034	--
Clamped-Free	Composite	Mode 1	4.004	3.9765	0.75
		Mode 2	25.625	22.976	10.3
Clamped -Clamped	Composite	Mode 1	22.716	22.52	0.8
		Mode 2	68.148	62.16	8.7

The signal in the time domain has been transformed into the signal in the frequency domain by the implementation of FFT algorithm in MATLAB. Figure 2 illustrates the time domain and FFT response of an SS tapered beams equipped with clamps.

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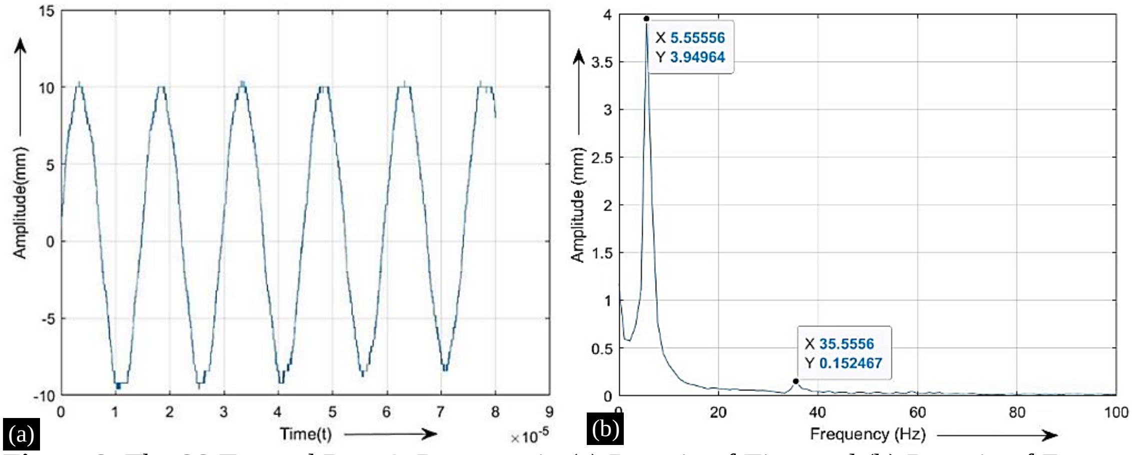

Figure 2. The SS Tapered Beam's Response in (a) Domain of Time and (b) Domain of Frequency for a C-F Beam.

A SS clamped-free (C-F) beam's FFT graph shows a first peak at 5.55 Hz, followed by a second peak at 35.55 Hz, which is the second natural frequency. Figure 3 shows the clamped-clamped (C-C) tapered beam's response in both domain of time and domain of frequency. The first peak corresponds to the natural frequency (32.45 Hz). However, an impact hammer cannot generate upper modes of a clamped tapering beam.

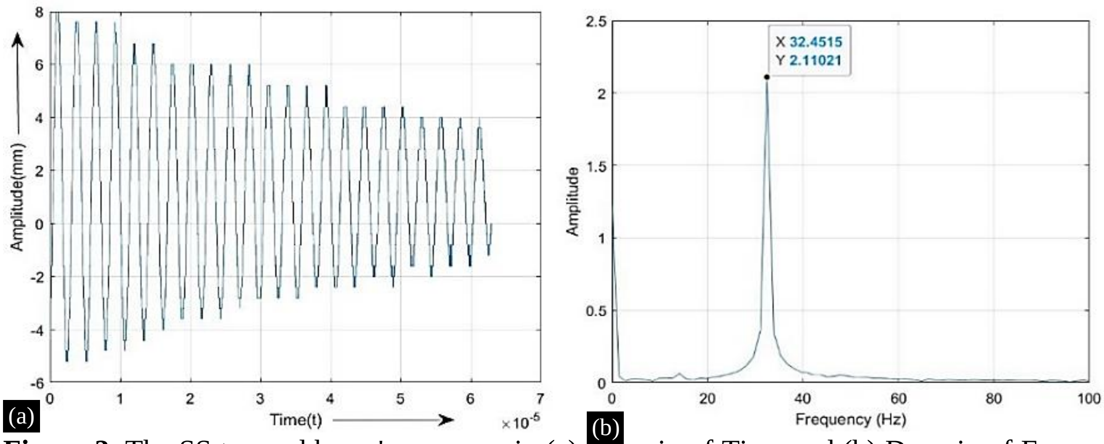

Figure 3. The SS tapered beam's response in (a) Domain of Time and (b) Domain of Frequency for a C-C Beam.

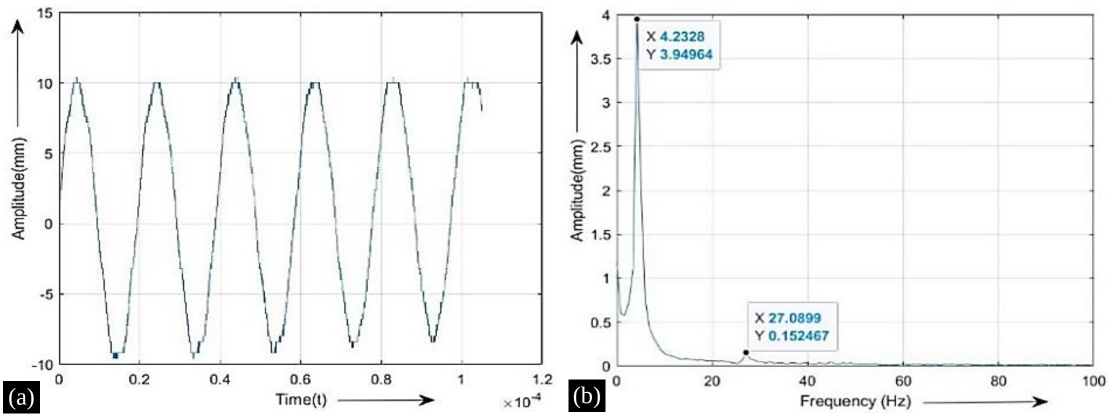

Figure 4. The copper tapered beam's response in (a) time domain and (b) frequency domain for a C-F beam.

A clamped-free copper tapered beam's FFT graph (Figure 4) shows two peaks: one at the first natural frequency of 4.23 Hz and the other at the second natural frequency of 27.08 Hz. The response of the clamped-clamped tapered beam in the domain of frequency and domains of time is shown in Figure 5. These Figures 6-7 show that the first peak is associated with the first natural frequency, which is 24.052 Hz. Nevertheless, the upper modes of a clamped tapered beam cannot be generated by an impact hammer.

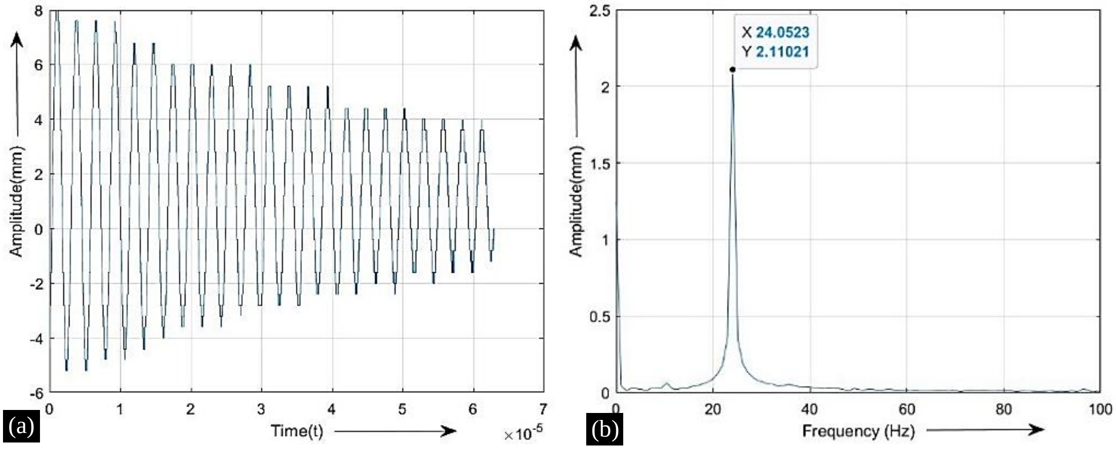

Figure 5. Response of tapered copper beam in (a) domain of time and (b) domain of frequency for a C-C beam.

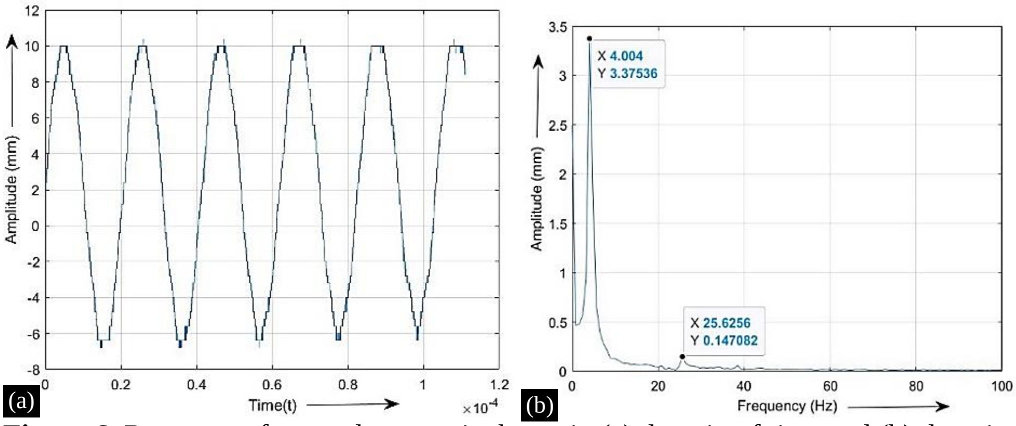

Figure 6. Response of tapered composite beam in (a) domain of time and (b) domain of frequency for a C-F beam.

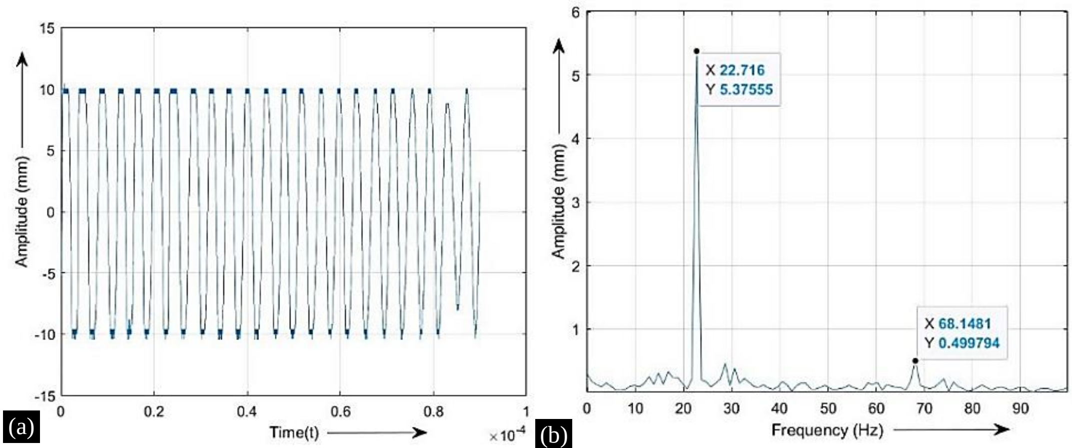

Figure 7. Response of tapered composite beam in (a) domain of time and (b) domain of frequency for a C-C beam.

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NUMERICAL MODELING OF TAPERED BEAMS

To verify the experimental outcomes, a finite element analysis of a tapered beam subjected to various boundary conditions is conducted using version 5.6 of the COMSOL multi physics software. The examination includes the consideration of CC and CF boundary conditions for both isotropic and composite tapered beams. Material and geometric specifications are detailed in Tables 2 and 3, respectively. Utilizing COMSOL, a three-dimensional CAD model of the tapered beams is developed. Subsequently, the software's modal analysis module is employed to determine the mode shapes and natural frequencies. Results observed in the bending mode of the tapered beam are presented in Table 1, obtained through COMSOL multiphysics software version 5.6. Numerically generated mode shapes under various boundary conditions are illustrated in Figures 8, 9, 10, 11, 12, 13, and 14.

The geometry of a tapered beams depicts in Figure 4. Here, L is the length, D & d are the width at extreme left and the extreme right of the beam and t is the thickness of beam. The composite is being comprised of two distinct materials that is metals and non-metal. The top and bottom layer is made up of two thinly coated copper and aluminium sheet having 0.5 mm thickness. The low density polyethelene (LDPE) non-metallic core having 2 mm thickness is sandwiched between two metallic coils.

Table 2 and 3 presents the material qualities and geometrical parameters of tapered beams. All geometric measurements are recorded in millimetres (mm). The symbol "E" represents Young's modulus, "ρ" denotes the density of the material, while "ν" represents Poisson's ratio.

Table 2. Material Properties [19].

Material properties	Isotropic (SS)	Isotropic (Copper)	Composite
E	190 [GPa]	120 [GPa]	30.21 [GPa]
P	7850 [Kg/m^3]	8950 [Kg/m^3]	0.335 [Kg/m^3]
N	0.265	0.35	2393

Table 3. Geometrical Parameters.

Parameters	Dimension
Length (L)	700 [mm]
Width at extreme left (D)	37 [mm]
Width at extreme right (d)	25 [mm]
Thickness (t)	3 [mm]

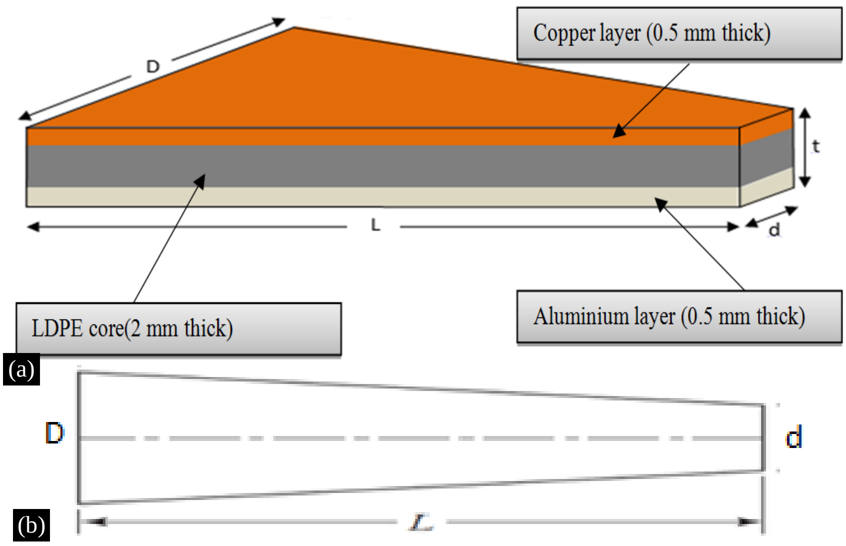


Figure 8. Geometry of (a) composite (b) isotropic tapered beams.

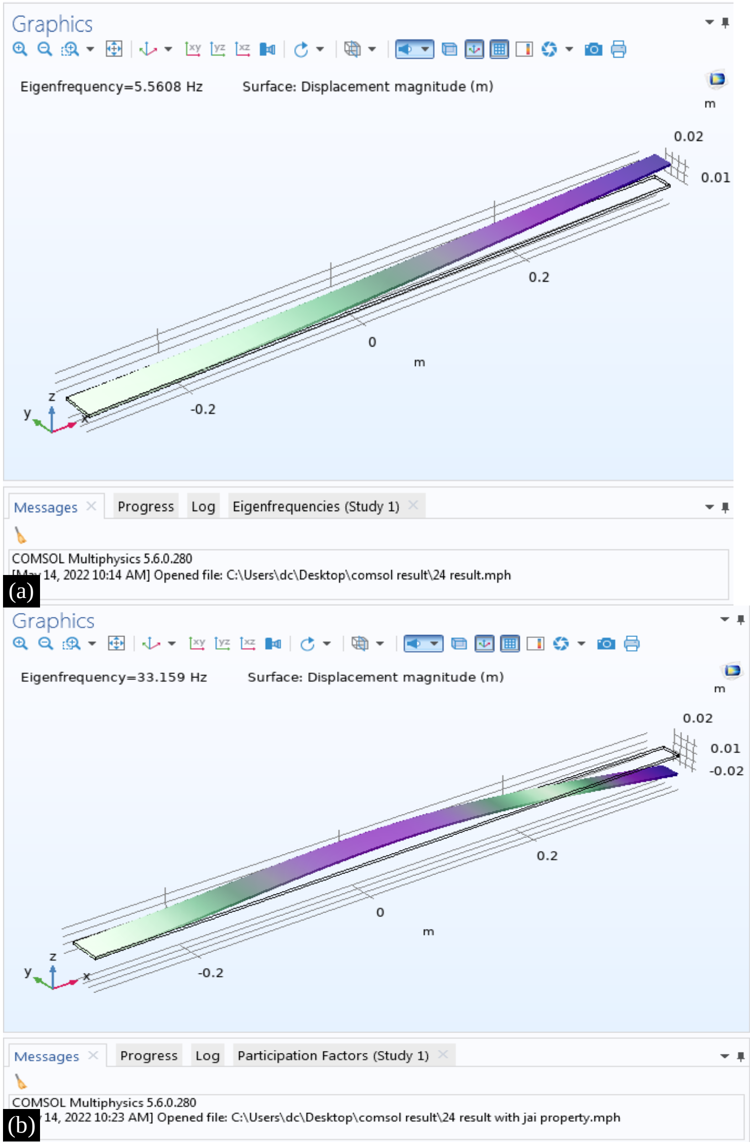
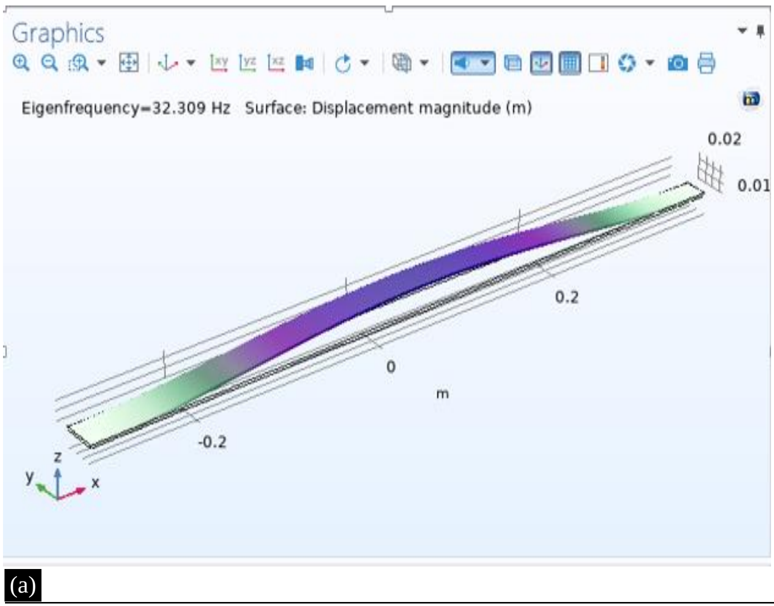
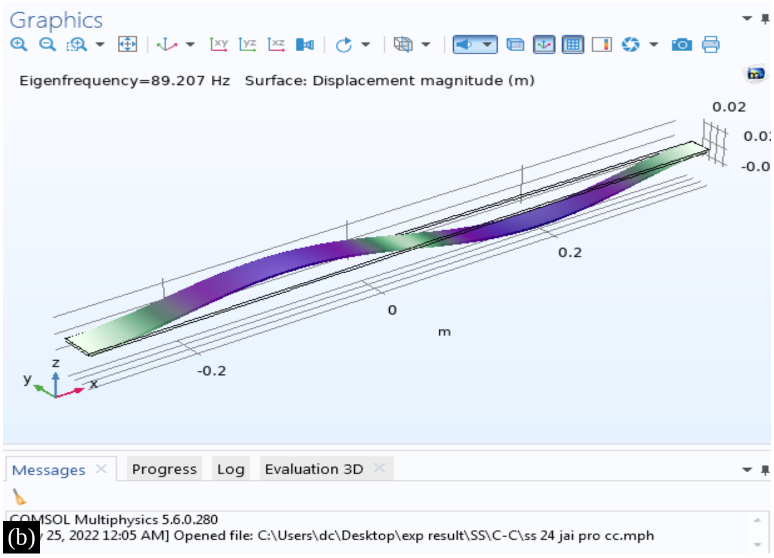


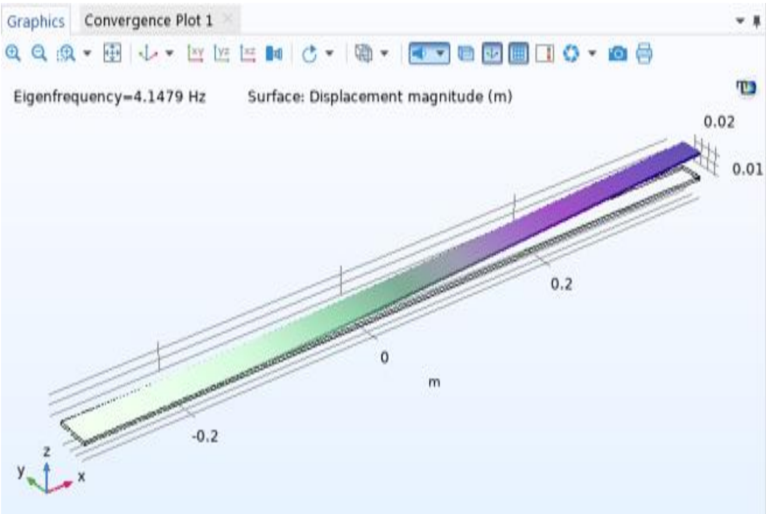
Figure 9. Mode forms and associated inherent frequency of clamp-free tapered stainless steel beam.



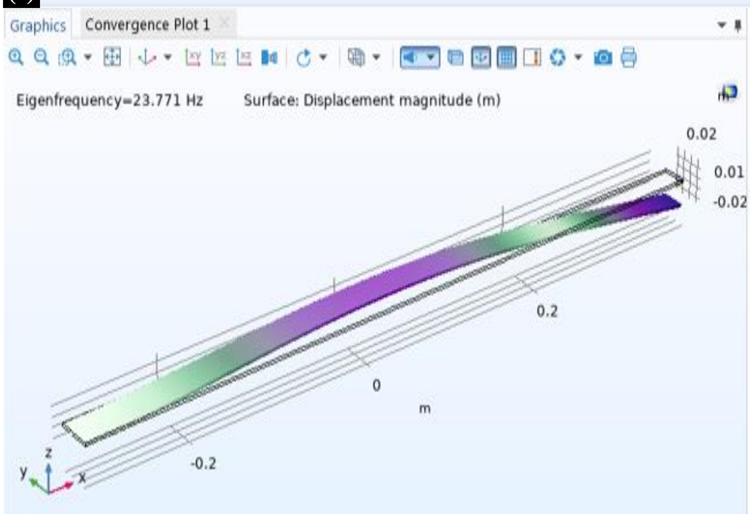


(b)

Figure 10. Mode forms and associated inherent frequency of clamped-clamped tapered stainless steel beam.



(a)



(b)

Figure 11. Mode forms of clamped-free tapered copper beam and associated natural frequency.

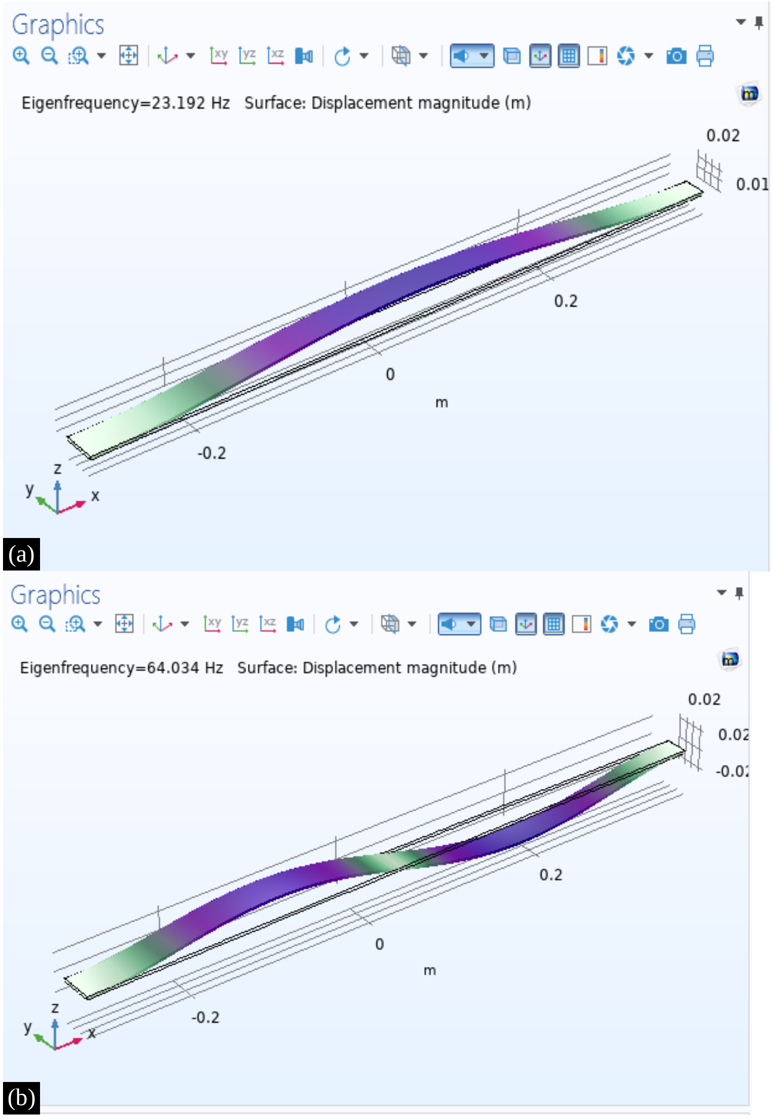
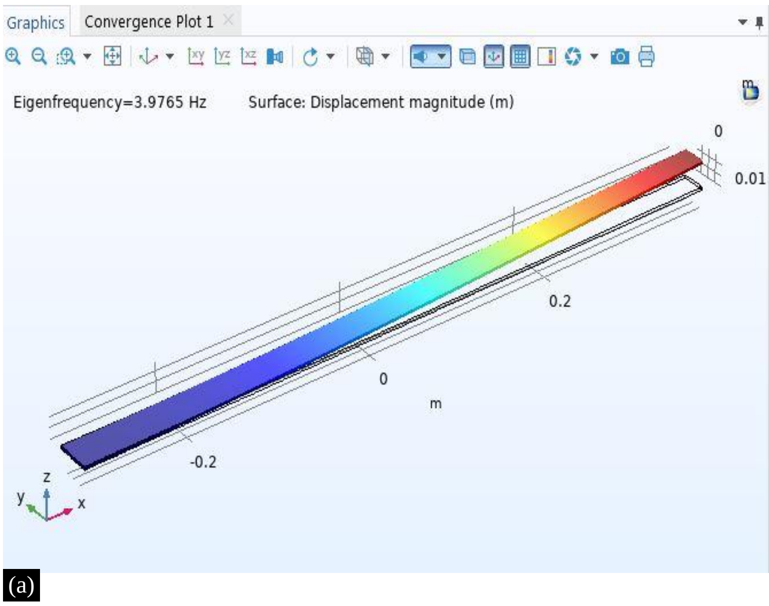


Figure 12. Mode forms of clamped-clamped tapered copper beam and associated natural frequency.



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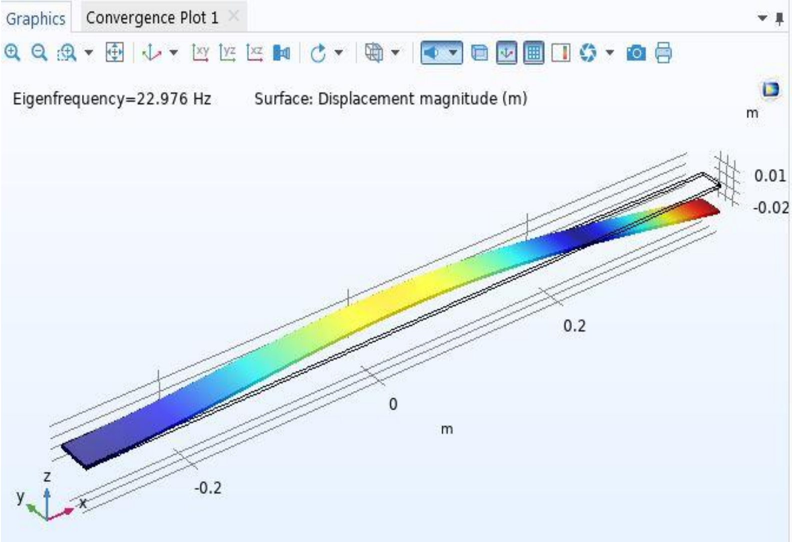
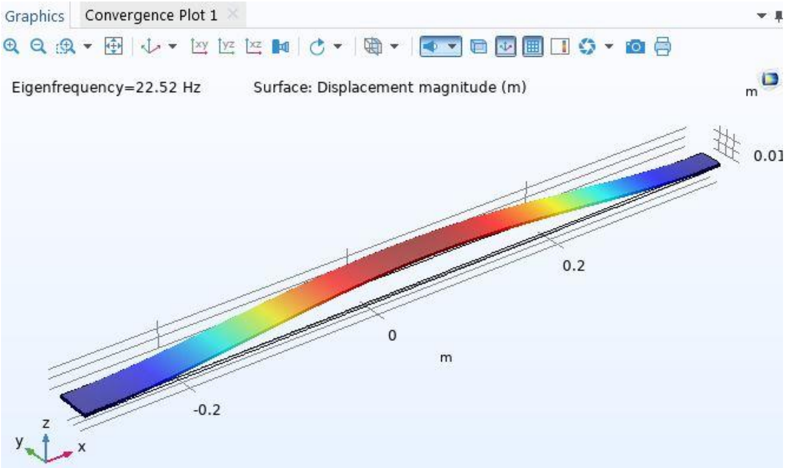
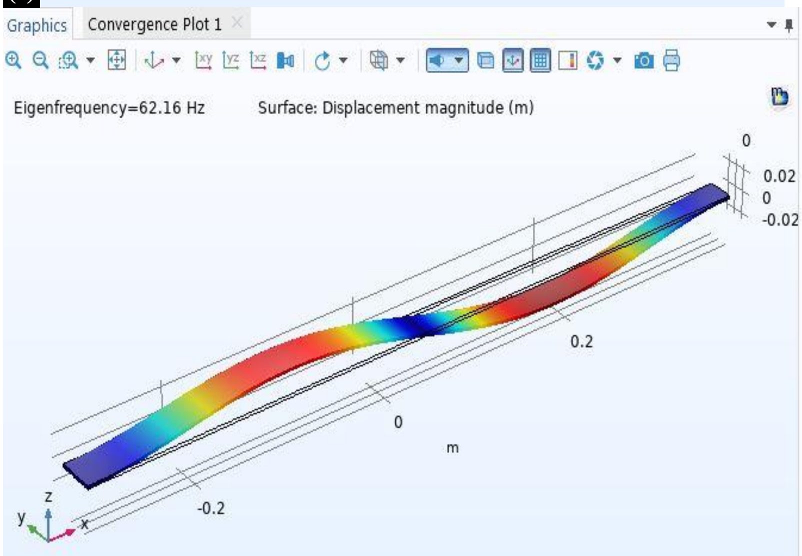


(b)

Figure 13. Mode forms of clamped-free tapered composite beam and associated natural frequency.



(a)



(b)

Figure 14. Mode forms of clamped-clamped tapered composite beam and associated natural frequency.

COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS FOR TAPERED BEAMS

The results obtained from both computational and experimental methods for tapered beams with CF and CC boundary conditions are shown in Table 1. It is clear that the impact hammer excitation method could not be used in the experiment to excite the higher modes of the tapered beams. The upper mode of a tapering beam can be found using the sine sweep test under CF and CC conditions. It is a very useful method. There is a significant correlation between the numerical and experimental results for the tapered beams. The physical dimensions of the tapering beam and variations in material attributes data, like the Young's modulus, lead to error in the results. Table 1 illustrates the closeness of the results obtained through FEM numerical analysis and experimental analysis. The obtained values are comfortably within the acceptable range.

CONCLUSION

The present research presents, the natural vibration properties of a tapered beams subjected to specific boundary conditions, such as CF (clamped-free) and CC (clamped-clamped). Initially, computations are executed for both the isotropic (stainless-steel and copper) and composite tapered beams. The initial assessments are carried out utilizing a laser vibrometer, followed by validation using COMSOL software version 5.6. Throughout the experimental assessment, the beam is excited by an impact hammer. The correlation between the findings obtained from experimental observations and computational simulations is clear and significant. The effectiveness of the experimental modal analysis performed with a laser vibrometer is validated through numerical approaches. The utilization of a sine sweep test proves to be a robust method for identifying the dominant mode of vibration for a tapered beam under either clamped-free or clamped-clamped boundary conditions. As indicated by the outcomes, both the modes for composite tapered beam (4Hz, 25.635Hz) are slightly lower in comparison to isotropic tapered stainless-steel (5.556Hz, 35.556Hz) & copper (4.23Hz, 27.08Hz) beams under CF condition. In case of CC condition, the obtained natural frequencies for composite tapered beam (22.716Hz) is also found to be lower in comparison to isotropic tapered beams (stainless-steel (32.45Hz), copper (24.053Hz)). Preliminary results indicate that composite tapered beams made of copper and aluminium are more suitable for vibrational applications than isotropic tapered beams. Detailed applications require extensive research.

Declaration of Competing Interest

The authors assert that no aspects of the research conducted in this investigation were susceptible to influence from any recognized conflicting financial concerns or interpersonal connections.

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