Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

Araştırma Makalesi / Research Article
e-ISSN: 2149-3367 **DOI: https://doi.org/10.35414/akufemubid.1519102**
AKÜ FEMÜBİD **25** (2025) 015903 (206-214) AKU J. Sci. Eng. **25** (2025) 015903 (206-214)

Free Vibration Analysis of 3D-printed ABS, PET-G and PLA Curved Beam: Effects of Opening Angle, Curvature Radius, and Part Thickness

***Makale Bilgisi / Article Info**
Alındı/Received: 19.07.2024
Kabul/Accepted: 14.09.2024
Yayımlandı/Published: xx.xx.xxxx

3B Baskı ile Üretilen ABS, PET-G ve PLA Eğrisel Kirişlerin Serbest Titreşim Analizi: Açılma Açısı, Eğrilik Yarıçapı ve Parça Kalınlığının Etkileri

Sinan MARAŞ[1], Çağın BOLAT[2*]

[1] *Ondokuzmayıs University, Faculty of Engineering, Deaprtment of Mechanical Engineering, 55270, Samsun, Turkey*
[2] *Samsun University, Faculty of Engineering and Natural Sciences, Department of Mechanical Engineering, 55420, Samsun, Turkey*

Öz

Yaygın olarak kullanılan üç boyutlu (3B) baskı şeklinde adlandırılan eklemeli üretim, işleme, dövme, kaynak ve toz sinterleme gibi geleneksel üretim tekniklerinin aksine, karmaşık nesneleri hızla üretme kabiliyeti ile öne çıkmaktadır. Günümüzde eklemeli üretim, işlevsel ve hafif son ürünler oluşturmak için sıklıkla kullanılmaktadır. Bu nedenle, bu tür malzemelerden oluşan yapıların tasarım sürecinde serbest titreşim analizi büyük önem taşımaktadır. Bu çalışmanın amacı, kelepçeli-kenetlenmiş sınır koşullarına sahip PET-G, PLA ve ABS malzemelerinden yapılmış 3B yazıcı kullanılarak üretilmiş eğrisel kirişlerin açılma açısı, eğrilik yarıçapı ve kalınlık gibi parametrelerdeki değişikliklerin yapının düzlem içi titreşim karakteristikleri üzerindeki etkilerini araştırmaktır. ANSYS sonlu elemanlar programı kullanılarak modellenen eğrisel kiriş yapısının titreşim parametreleri belirlenmiştir. Önerilen modelin doğruluğunu ve uygulanabilirliğini doğrulamak için sayısal sonuçlar literatürdeki bulgularla karşılaştırılmıştır. Sonuç olarak, 3B yazıcı ile üretilmiş eğrisel kirişlerin malzeme ve geometrik özelliklerindeki değişikliklerin yapının doğal frekanslarını önemli ölçüde etkilediği bulunmuştur.

***Anahtar Kelimeler:** Serbest titreşim; Eğri kirişler; Eklemeli imalat; Sonlu elemanlar yöntemi.*

Abstract

Additive manufacturing, commonly referred to as 3D printing, stands out for its ability to rapidly produce complex objects, contrasting with conventional manufacturing techniques such as machining, forging, welding, and powder sintering. Today, additive manufacturing is often used to create functional and lightweight final products. Therefore, free vibration analysis is crucial in the design process of structures composed of such materials. The objective of this study is to investigate the effects of variations in parameters such as opening angle, curvature radius, and thickness of 3D-printed curved beams made of PET-G, PLA, and ABS materials, which have clamped-clamped boundary conditions, on the in-plane vibration characteristics of the structure. The vibration parameters of the curved beam structure have been determined to use modeled the ANSYS finite element program. Numerical results have been compared with findings from the literature to validate the accuracy and applicability of the proposed model. Consequently, it has been found that changes in the material and geometric properties of 3D-printed curved beams significantly influence the natural frequencies of the structure.

***Keywords:** Free vibration; Curved beams; Additive manufacturing; Finite element method.*

1. Introduction

Unlike straight beams and plates, the vibration characteristics of composite curved beams, which are used in fields such as aerospace, automotive, and defense industries, are more complex to analyze. Therefore, studying the dynamic analysis of these structures is crucial. Numerous studies have been conducted to explore the complexities of curved beam vibrations. Some researchers focused on finite element mesh refinement for in-plane and out-of-plane vibrations of variable geometrical Timoshenko beams, emphasizing superconvergent vibration modes (Wang 2023). Another project team investigated the out-of-plane free vibration and forced harmonic response of curved beams with different boundary conditions (Mao *et al.* 2020). Also, the effect of porosity distribution on the vibration and damping behavior of inhomogeneous curved sandwich beams was studied (Taşkın and Demir 2023). In addition, the out-of-plane vibrations of curved uniform and tapered beams with additional mass was also analyzed in the scholarly archives (Özyiğit *et al*. 2017).

Additive manufacturing, also known as 3D printing, was initially preferred for prototyping, but nowadays it is generally used to create functional and lightweight final products (Stano and Percoco 2021, Mishra and Das 2021, Ergene *et al*. 2023). Additive manufacturing facilitates the layer-by-layer production of industrial components using raw materials and energy sources (Layani *et al.* 2018, Ma

**Sorumlu Yazar/Corresponding Author: Çağın BOLAT* *e-posta/e-mail: cagin.bolat@samsun.edu.tr*

et al. 2021, De Agostinis *et al.* 2021). Vibration analysis of 3D printing materials is a crucial area of study that focuses on understanding the vibrational behavior of structures fabricated using additive manufacturing technologies. Several research studies have been investigated different aspects of vibration analysis in the context of 3D printing materials such as PET-G, PLA, and ABS. For example, many researchers examined how varying printing parameters affect the thermal and mechanical characteristics of 3D-printed PLA and PETG through fused deposition modelling (Hsueh *et al.* 2021). These studies provide valuable data on material behavior under different loading conditions, offering essential insights into how printing parameters affect the mechanical response of 3D-printed structures, which is crucial for vibration analysis. Additionally, in these studies, it has been demonstrated that the modal testing of 3D-printed samples, in conjunction with finite element analysis (FEA), effectively predicts the natural frequencies of intricate thin-walled structures. These approaches provide valuable insights into how additive manufacturing processes influence the vibrational behavior of printed components. (Grammatikopoulos *et al.* 2021). Similarly, experimental and finite element investigations were done on tapered beams made from 3D-printed PET-G. They compared the natural frequency values of PET-G beams with those reinforced with carbon fiber (Ergene *et al*. 2023). The findings revealed that carbon fiber reinforcement led to higher natural frequency values compared to PET-G beams, emphasizing the influence of material composition on vibrational characteristics. Furthermore, the vibration and deflection responses of 3D-printed composites reinforced with carbon fiber and polylactic acid were investigated, highlighting how different material compositions can influence natural frequencies and damping properties (Kannan *et al*. 2023).

Moreover, some researchers conducted experiments to establish a connection between material properties investigations, field experiments, shaking table tests, and FEM modeling to accurately determine the natural frequencies of 3D-printed models (Boron *et al*. 2023). This integrated approach provides a comprehensive understanding of how material properties impact the vibrational behavior of printed structures. Furthermore, how infill parameters affect the natural frequencies of ABS specimens fabricated using extrusion-based 3D printing was also scrutinized (Parpala *et al*. 2021). The study emphasized the significance of infill patterns in controlling structural vibrations. Additionally, the mechanical properties of recycled ABS printed with an open-source FDM printer integrated with ultrasound vibration were examined, showing significant improvements in flexural, compression, and tensile strength (Maidin *et al*. 2022).

In exploring the mechanical properties of curved lattice structures, it is essential to consider the diverse research findings and insights available in the field. Lattice structures, known for their lightweight nature and high strength, offer unique mechanical characteristics that can be further enhanced through curvature and innovative design approaches. In another work, a nonlinear mechanics model of bio-inspired hierarchical lattice materials consisting of horseshoe microstructures was explored (Ma *et al*. 2016). The study emphasizes the hierarchical triangular lattice material's sharp transition in the stress-strain curve and high stretchability, highlighting the influence of lattice topology and microstructure geometry on mechanical behavior. The mechanical response of TiAl6V4 lattice structures manufactured by selective laser melting was also explored, providing insights into the mechanical properties of lattice structures under quasistatic and dynamic compression tests (Merkt *et al*. 2015). Understanding the mechanical behavior of lattice structures fabricated through advanced manufacturing techniques is essential for optimizing their performance in various applications. the additive manufacturing and mechanical properties of lattice-curved structures was analyzed, mapping the response of these structures under tensile loads to different stages and deformation mechanisms (Cuan-Urquizo *et al*. 2019). This research sheds light on the deformation behavior of curved lattice structures, including stages such as straightening, stretching, and fracture, offering valuable insights into their mechanical responses. the manufacturing and characterization of 3D miniature polymer lattice structures using fused filament fabrication was evaluated, highlighting the control of cell geometry and the absence of additional post-processing requirements (Guerra Silva *et al.* 2021). Understanding the mechanical properties of lattice structures fabricated through specific additive manufacturing processes is essential for optimizing their performance and functionality. To gain a comprehensive understanding of the mechanical behaviors of 3D printing curved beams, it is crucial to consider various factors that influence their performance. The orientation of the print, as highlighted by some researchers (Süsler and Kazancı 2023), indeed plays a significant role in determining the mechanical properties of 3D-printed parts, especially in complex structures like curved beams. Additionally, the selection of the build configuration is paramount before adjusting other process parameters to ensure optimal performance. In the realm of 3D printing, the use of continuous fibers for reinforcement has shown promising results in enhancing the mechanical properties of printed beams. Studies have demonstrated that the incorporation of continuous fibers, such as carbon fibers, can lead to a substantial increase in flexural properties, stiffness-to-mass ratio, and load-to-mass ratio of 3D-printed beams (Zhang *et al.* 2024). In another effort, the importance of continuous fiber reinforced thermoplastic composites (CFRTPCs) in industrial applications was emphasized but note limitations such as high mold costs and constraints in manufacturing complex constructions, which can impact the mechanical behaviors of curved beams (Yang *et al.* 2017). Besides, the flexural properties of sandwich beams with auxetic cores was delved, highlighting the importance of evaluating the flexural behavior, energy absorption, and stiffness of 3D-printed polymeric sandwich beams (Najafi *et al.* 2022). Understanding how different core structures, such as square node anti-tetra chiral, arrowhead, and re-entrant auxetic cores, affect the mechanical properties is crucial in optimizing the design of curved beams. Similarly, the structural behavior of 3D printed concrete beams with various reinforcement strategies was evaluated, shedding light on how reinforcement techniques can impact the mechanical properties of beams (Gebhard *et al.* 2021). Understanding the interaction between the printing material and reinforcement is vital in ensuring the structural integrity of curved beams. Certain Project teams discuss the manufacturing and mechanical testing of curved sandwich beams with zero-Poisson's ratio honeycomb cores, highlighting the unique properties of curved corrugated sandwich beams and their mechanical behavior (Cao *et al.* 2023).

When reviewing published studies on 3D-printed curved beams produced by Fused Filament Fabrication (FFF), it is noted that although there are few studies, these structures are generally experimentally investigated for their mechanical behavior. The free vibration analysis of 3D-printed curved beams, including the determination of natural frequencies, mode shapes, and damping characteristics, is crucial in the design phase. Therefore, the free vibration analysis of these materials is essential for engineering design. This study aims to investigate the effects of curvature radius, curvature angles and thickness on the free vibration behavior of 3D-printed curved beams using the ANSYS finite element package by numerically.

2. Material and Methods

2.1 Verification of the numerical model

To assess the accuracy and relevance of the proposed model, numerical results were compared with those from the study reported in the literature (Malekzadeh and Setoodeh 2009). The properties of the layered composite beam used in the comparison are: the ratios E_1/E_2 are 15 and 40, G_{12} is 0.5E2, the density is 1500 kg/m³, the length-to-thickness ratio (L/h) is 100, the width (b) is 0.025 m, the length (L) is 1 m, and the beam angles (θ) are 60° and 180°.

Table 1 presents the natural frequency values obtained for a layered composite curved beam with a [0°/90°] stacking sequence under clamped-free boundary conditions. The non-dimensional natural frequency $\bar{\omega}_i$ is defined as $\bar{\omega}_i = \omega_i \left(L^2/h\right)\sqrt{12\rho/E_1}$. Comparison with the results of Malekzadeh and Setoodeh's (2009) study shows that our findings demonstrate good agreement.

As a second example, the natural frequency values of a laminated composite curved panel from a work (Hajianmaleki and Qatu 2012) were compared with those obtained using a finite element software package. The material and geometric properties of the laminated composite beam are as follows: E_1=138 Gpa, E_2=8.96 Gpa, ν_{12}=0.3, G_{12}=7.1 Gpa, ρ = 1580 kg/m³, L=1 m, b=0.025 m and h=0.05 m. Table 2 presents the natural frequency values for four-layer composite curved beam with a 0°/90°/90°/0° stacking sequence under clamped-clamped boundary conditions. Non-dimensional natural frequency is presented as $\bar{\omega} = \omega a^2 \sqrt{12\rho/E_1 h^2}$. Table 2 demonstrates that the current results closely match those from Hajianmaleki and Qatu's study.

Table 1. . Natural frequencies (Hz) of clamped-free curved beams made of laminated cross-ply [0°/90°] composites

Method	$\mathbf{E_1/E_2 = 15}$			$\mathbf{E_1/E_2 = 40}$		
	θ=60°					
	ω_1	ω_2	ω_3	ω_1	ω_2	ω_3
GDQ	24.171	115.726	313.280	32.984	148.176	384.031
Ansys	24.820	117.620	311.820	33.783	143.460	356.570
	θ = 180°					
	ω_1	ω_2	ω_3	ω_1	ω_2	ω_3
GDQ	28.241	78.294	237.939	38.161	99.246	289.980
Ansys	31.467	83.668	247.720	43.391	101.260	282.940

Table 2. Natural frequencies of the laminated composite curved beam under clamped-clambed boundary condition (Hz) according to FEM (Hajianmaleki and Qatu 2012) and performed ANSYS in this work

Modes	0°/90°/90°/0°			
	a/R=0.2		a/R=1	
	3D FEM	Ansys	3D FEM	Ansys
1	421.00	413.25	938.19	963.75
2	895.25	867.45	854.89	985.11
3	1527.72	1414.90	1590.41	1868.60
4	2211.30	2040.00	2166.21	2660.20
5	2917.60	2725.50	2919.77	3576.70

2.2 Parametric study

Following the validation of the theoretical model, ANSYS software was used to conduct a free vibration analysis on a 3D-printed curved beam. This finite element methodology is a useful tool for engineers and researchers to improve their analyze capacity and is also tried for lots of other applications (Erdoğan et al. 2023; Depboylu et al. 2023).

The beam was assumed to be made of ABS, PLA, and PET-G materials. In Figure 1, the curved beam is characterized by a curvature radius R, width b, thickness t, and curvature angle θ. The x and z axes denote the primary axes of the beam's cross-section, while the y axis represents the tangent to the curve's axis. In this study, the mechanical properties of ABS, PLA, and PET-G materials are based on the data from the literature research (Bolat *et a*l. 2023). Table 3 lists the material properties of the 3D-printed curved beam. Also, it is known that the printing orientation, load direction, and test speed are another critical factors affecting the mecjanical properties of the PLA, ABS, and PETG printed via additive manufacuring (Yılmaz et al. 2022; Bolat and Ergene 2023). In this study, the examined curved beam has clamped-clamped boundary conditions, and the beam width is b=0.025m.

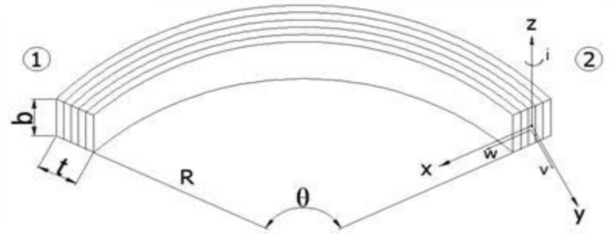

Figure 1. Geometric properties of the curved beam (Günyar *et al.* 2012).

The numerical analysis was conducted using ANSYS software. The model was developed and evaluated with the SHELL 281 element, which features 8 nodes. Each node possesses 6 degrees of freedom, encompassing translations and rotations along the x, y, and z axes. This element's geometry is well-suited for analyzing thin shell structures (Russo et al. 2019). The modeled curved beam consists of 198 elements and 673 nodes. Figure 2 shows the ANSYS model of a 3D-printed curved beam with a radius length of 0.1 m and an opening angle of 30 degrees. In this study, the configurations considered for examining the effects of variations in geometric and material properties on the natural frequencies of 3D-printed curved beams are presented in Table 4.

Table 3. Material properties of the 3D-printed curved beam (Bolat *et al.* 2023)

Mat.	ρ(kg/m^3)	σ_{UTS}(Mpa)	E(Mpa)	ν(-)
PLA	1240	50	1500	0.36
PETG	1290	46	2100	0.40
ABS	1040	48	1250	0.35

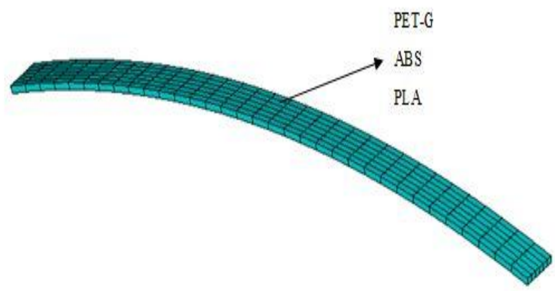

Figure 2. ANSYS model of 3D printed curved beam

Table 4. The configurations of 3D-printed curved beam according to curvature angle (θ), curvature Radius (R), and thickness (t)

Material	θ	R	t
PLA	30°	0.10 m	0.002 m
PET-G	60 °	0.30 m	0.004 m
ABS	90 °	0.50 m	0.006 m

3. Results and Discussions

Figure 3 shows the effect of opening angle variation on the natural frequencies of 3D-printed curved beams. As seen in Figure 3, as the opening angle increases, the rigidity of the curved beams decreases, leading to a reduction in the first, second, and third natural frequencies.

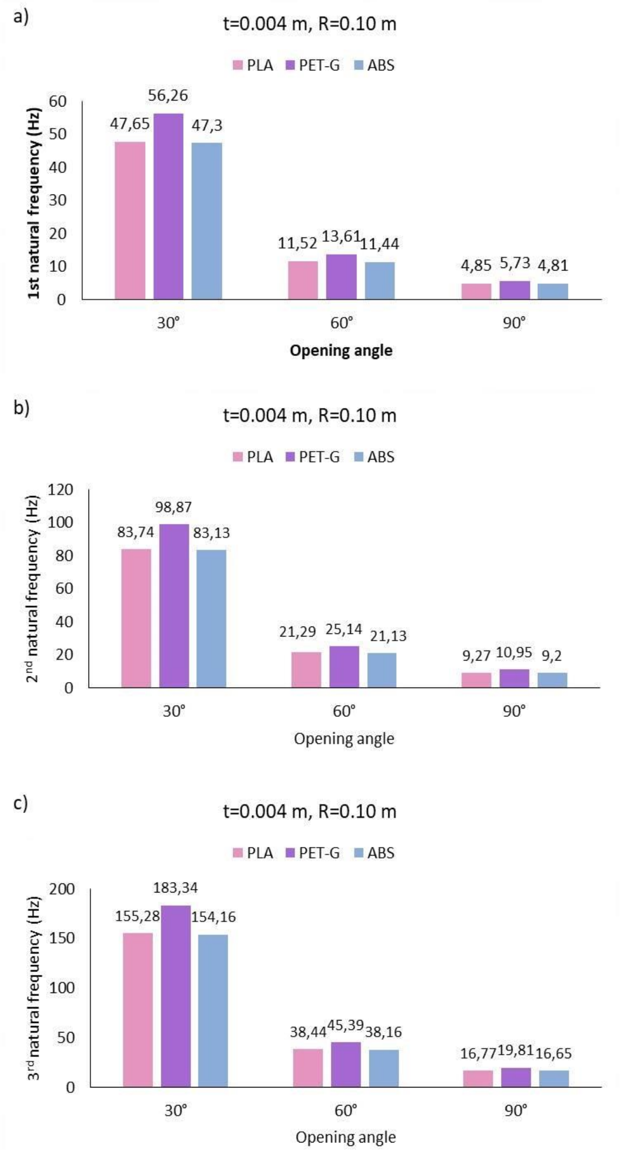

Figure 3. The effect of opening angle variation on the natural frequencies of 3D-printed curved beams: a) 1st frequency b) 2nd frequency c) 3rd frequency

Additionally, the natural frequency values are ranked from highest to lowest for PET-G, PLA, and ABS materials, respectively. It is observed that the natural frequency values of curved beams made of PLA and ABS materials are quite close to each other. This can be interpreted as the fact that the natural frequencies of materials with very similar mechanical properties are close to each other, as can be seen from the values given in Table 3. The variation of natural frequencies of 3D-printed curved beams with respect to radius length has been investigated. As seen in Figure 4, it is observed that as the radius length increases, the natural frequencies of the beams decrease. The natural frequencies in Figure 4 are ranked from highest to lowest for PET-G, PLA, and ABS materials. From the literature efforts (Bolat and Ergene 2023; Yao et al., 2019) , it is seen that PLA is advantageous for the tensile properties or ABS has lower density but when the usage purpose of the printed samples changes, other alternative filament materials can be selected as happened in this study.

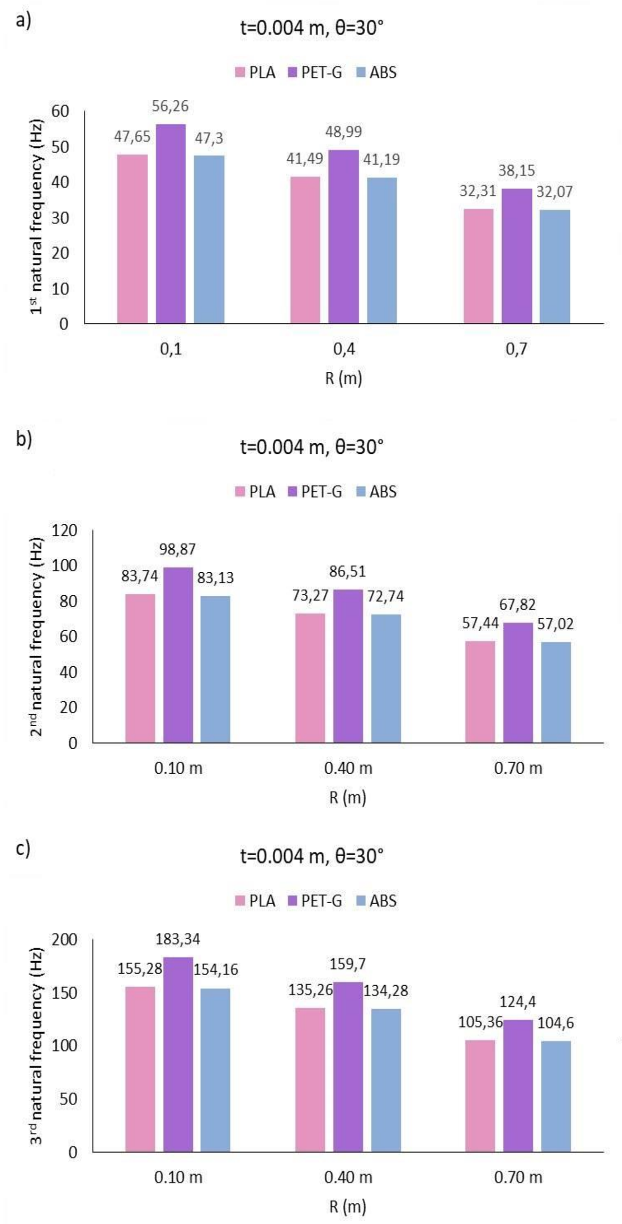

Figure 4. The effect of radius variation on the natural frequencies of 3D-printed curved beams: a) 1st frequency b) 2nd frequency c) 3rd frequency

The effect of thickness variation on the first, second, and third natural frequencies of 3D printed curved beams is examined in Figure 5. Upon examining Figure 5, it can be observed that as the thickness of the curved beam increases, the structure's rigidity increases, resulting in a rise in natural frequencies. The highest natural frequencies are obtained from the curved beam made of PET-G material, while the lowest natural frequencies are obtained from the curved beam made of ABS material. This case can be explained by the warpage risk of the ABS materials (Ramian et al., 2021). Another point is that, as can be seen from Figure 3 to Figure 5, curved beams made of PLA and ABS materials have similar natural frequency values. The mode shapes of a few curved beams with various geometric properties and materials are presented as examples in Figures 6, 7, and 8 to visualize the vibration modes.

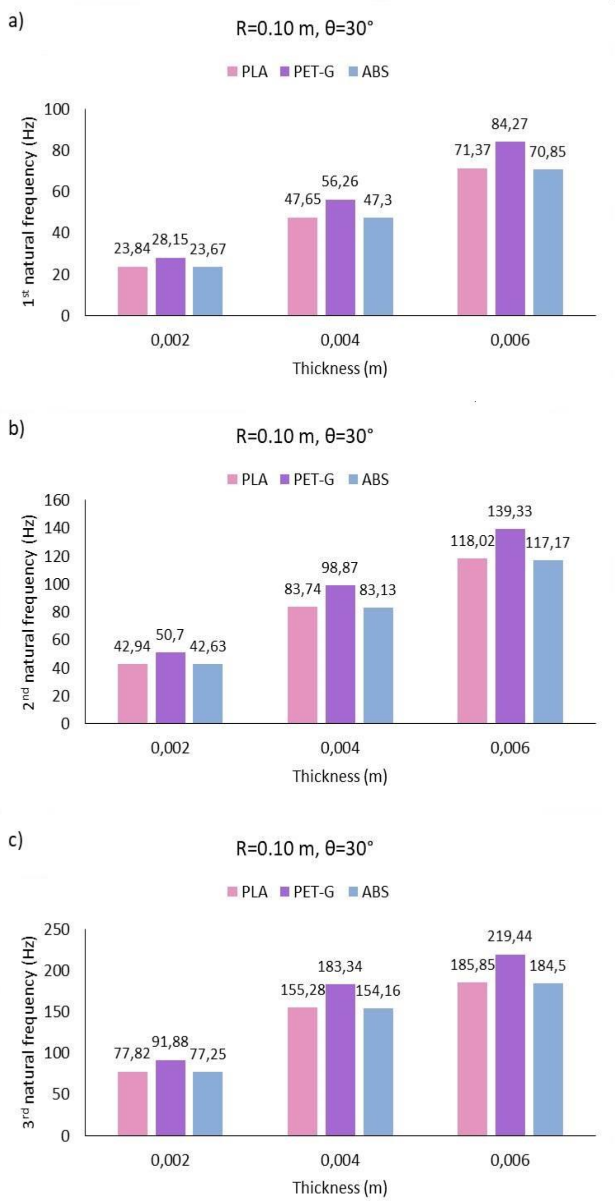

Figure 5. The effect of thickness variation on the natural frequencies of 3D-printed curved beams: a) 1st frequency b) 2nd frequency c) 3rd frequency

The mode shapes and natural frequencies of the curved beam consisting of PET-G material with geometric properties of R=0.1 m, θ=30°, and t=0.004 m are shown in Figure 6. Similarly, Figure 7 presents the mode shapes and natural frequencies of the curved beam made of ABS material with geometric properties R=0.7 m, θ=90°, and t=0.006 m. Likewise, the mode shapes and their corresponding frequencies of the curved beam made of PLA material with geometric properties R=0.1 m, θ=60°, and t=0.004 m are shown in Figure 8.

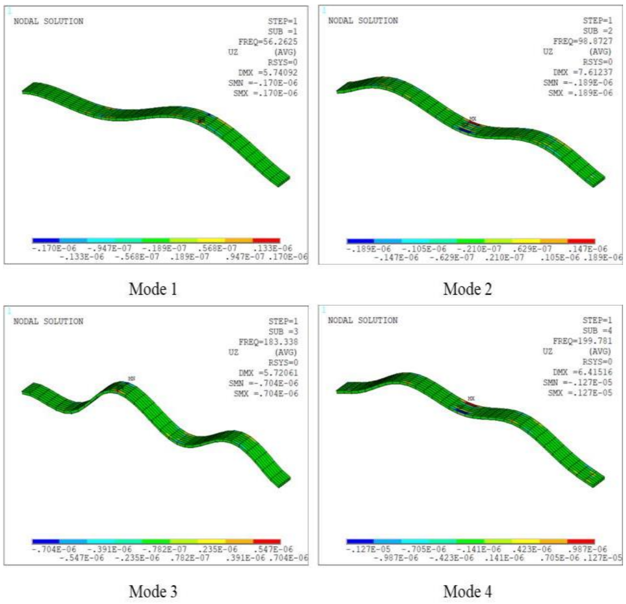

Figure 6. Mode shapes with natural frequencies for PET-G beam (R=0.1m, θ=30° and t=0.004 m)

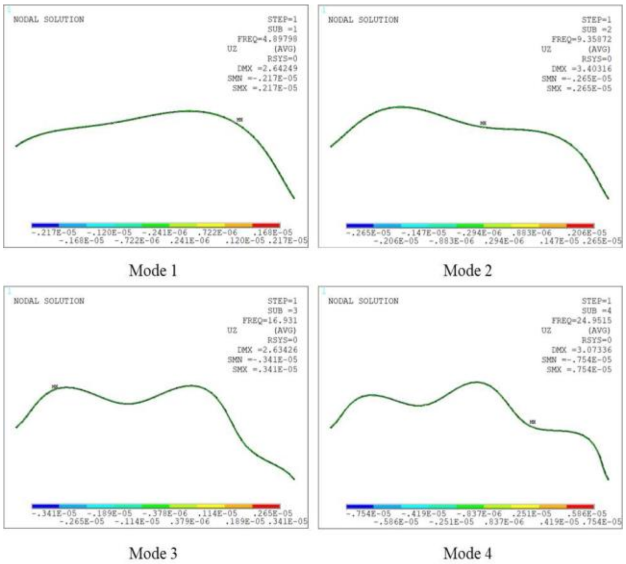

Figure 7. Mode shapes with natural frequencies for ABS beam (R=0.7m, θ=90° and t=0.006 m)

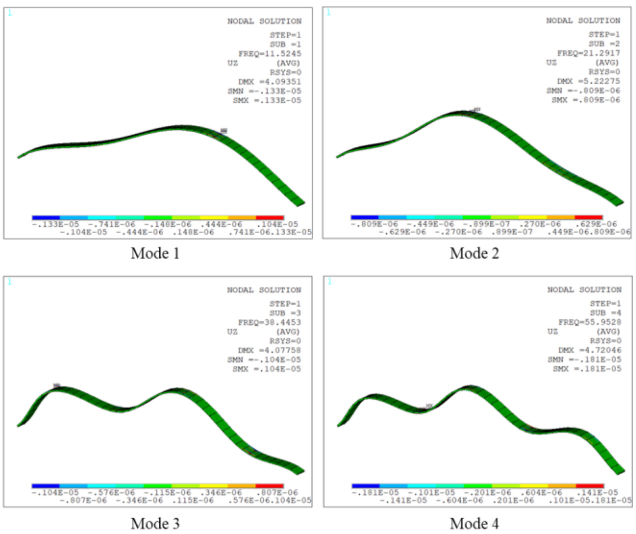

Figure 8. Mode shapes with natural frequencies for PLA beam (R=0.1m, θ=60° and t=0.004 m)

4. Conclusions

In this study, the free vibration analysis of 3D-printed curved beams with clamped-clamped boundary conditions was numerically investigated. The effects of varying the opening angle, curvature radius, and thickness of curved beams made of PET-G, ABS, and PLA materials on the natural frequencies of the structure were examined. The accuracy of the presented method was validated by comparing the data obtained from previous studies. The most important findings from the numerical analyses can be summarized as follows:

- The natural frequencies increase for 3D-printed curved beams with smaller opening angles.
- As the radius of 3D-printed curved beams increase, the natural frequencies decrease.
- The highest natural frequencies are observed in curved beams made of PET-G material, while the lowest natural frequencies are observed in curved beams made of ABS material.
- The natural frequencies of curved beams made of ABS and PLA materials are very close to each other.

In conclusion, the selection of material and geometric parameters for 3D-printed curved rods is of great importance, depending on their intended application. By choosing the appropriate material and geometric parameters, the natural frequencies can be kept away from the operating frequency, thus avoiding situations such as resonance, which can cause damage to structures.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author 1: Conceptualization, investigation, data curation, software, validation, writing – review, methodology, and editing and supervision.
Author 2: Conceptualization, investigation, resources, methodology, writing – review and editing

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability
Datasets are available on request. The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation

5. References

Bolat, Ç., Ergene, B. and Ispartalı, H., 2023. A comparative analysis of the effect of post production treatments and layer thickness on tensile and impact properties of additively manufactured polymers. *International Polymer Processing*, **38**, 244-256. https://doi.org/10.1515/ipp-2022-4267

Bolat, Ç., and Ergene, B., 2023. An Experimental Effort on Impact Properties of Polylactic Acid Samples Manufactured by Additive Manufacturing. *Düzce Üniversitesi Bilim Ve Teknoloji Dergisi*, **11**, 998-1013. https://doi.org/10.29130/dubited.1075259

Boron, P., Chelmecki, J., Dulinska, J.M., Jurkowska, N., Ratajewicz, B., Stecz, P. and Tatara, T. 2023. On the Possibility of Using 3D Printed Polymer Models for Modal Tests on Shaking Tables: Linking Material Properties Investigations, Field Experiments, Shaking Table Tests, and FEM Modeling. *Materials*, **16**, 1471. https://doi.org/10.3390/ma16041471

Cao, H., Bao, W., Bai, C., Yan, Q., Wang, B., Yang, Y. and Fan, H., 2023. Manufacturing and mechanical testing of curved sandwich beams with zero-Poisson's ratio honeycomb cores. *Polymer Composites*, **44**, 8849-8856.
https://doi.org/10.1002/pc.27742

Cuan-Urquizo, E., Martínez-Magallanes, M., Crespo-Sánchez, S.E., Gómez-Espinosa, A., Olvera-Silva, O. and Roman-Flores, A., 2019. Additive manufacturing and mechanical properties of lattice-curved structures. *Rapid Prototyping Journal*, **25**, 895-903. https://doi.org/10.1108/RPJ-11-2018-0286

De Agostinis, M., Olmi, G. and Arcidiacono, G., 2021. Mechanical characterization of parts fabricated by additive manufacturing. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Scienc*e, **235**, 1701-1702. https://doi.org/10.1177/0954406220948759

Depboylu, F.N., Poyraz, Ö., Yasa, E. and Korkusuz, F., 2023. Lazer-Toz Yatağında Füzyon ile Üretilen Ti6Al4V Gyroid Yapıların Basma Dayanımlarının Nümerik Modellenmesi. *Afyon Kocatepe Üniversitesi Fen Ve Mühendislik Bilimleri Dergisi*, **23**, 270-283. https://doi.org/10.35414/akufemubid.1171673

Erdoğan, H., Sayrugaç, A., and Yalçın, B., 2023. Tarımsal İlaçlamada X tipi Katlanabilen ve Geleneksel Kanatlarda Oluşan Gerilme-Gerinimin Tahmini ve Taguchi Analizi. *Afyon Kocatepe Üniversitesi Fen Ve Mühendislik Bilimleri Dergisi*, **23**, 797-810. https://doi.org/10.35414/akufemubid.1264988

Ergene, B., Atlıhan, G. and Pinar, A.M., 2023. Experimental and finite element analyses on the vibration behavior of 3D-printed PET-G tapered beams with fused filament fabrication. *Multidiscipline Modeling in Materials and Structures*, **19**, 634-651. https://doi.org/10.1108/MMMS-11-2022-0265

Ergene, B., and Bolat, Ç., 2023. Simulation of fused deposition modeling of glass fiber reinforced ABS impact samples: The Effect of fiber ratio, infill rate, and infill pattern on warpage and residual stresses. *Hittite Journal of Science and Eng*ineering, **10**, 21-3. https://doi.org/10.17350/HJSE19030000287

Gebhard, L., Mata-Falcón, J., Anton, A., Dillenburger, B. and Kaufmann, W., 2021. Structural behaviour of 3D printed concrete beams with various reinforcement strategies. *Engineering Structures*, **240**, 112380. https://doi.org/10.1016/j.engstruct.2021.112380

Grammatikopoulos, A., Banks, J. and Temarel, P., 2020. Prediction of the vibratory properties of ship models with realistic structural configurations produced using additive manufacturing. *Marine Structures*, **73**, 102801. https://doi.org/10.1016/j.marstruc.2020.102801

Guerra Silva, R., Torres, M.J., Zahr Viñuela, J. and Zamora, Z.G., 2021. Manufacturing and characterization of 3D miniature polymer lattice structures using fused filament fabrication. *Polymers*, **13**, 635. https://doi.org/10.3390/polym13040635

Günyar, A., Öztürk, H. and Sabuncu, M., 2012. Tabakalı Eğri Çubukların Dinamik Kararlılık Analizi. *Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi*, **14**, 43-55.

Hajianmaleki, M. and Qatu, M.S., 2012. Static and vibration analyses of thick, generally laminated deep curved beams with different boundary conditions. *Composites Part B: Engineering*, **43**, 1767-1775. https://doi.org/10.1016/j.compositesb.2012.01.019

Hsueh, M.H., Lai, C.J., Wang, S.H., Zeng, Y.S., Hsieh, C.H., Pan, C.Y. and Huang, W.C. 2021. Effect of printing parameters on the thermal and mechanical properties of 3d-printed pla and petg, using fused deposition modeling. *Polymers*, **13**, 1758. https://doi.org/10.3390/polym13111758

Kannan, S., Manapaya, A. and Selvaraj, R., 2023. Frequency and deflection responses of 3D-printed carbon fiber reinforced polylactic acid composites: Theoretical and experimental verification. *Polymer Composites*, **44**, 4095-4108. https://doi.org/10.1002/pc.27382

Layani, M., X. Wang, and Magdassi, S., 2018. Novel materials for 3D printing by photopolymerization. *Advanced Materials*, **30**, 1706344. https://doi.org/10.1002/adma.201706344

Ma, Q., Rejab, M., Kumar, A.K., Fu, H., Kumar, N.M. and J. Tang, J., 2021. Effect of infill pattern, density and material type of 3D printed cubic structure under quasi-static loading. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, **235**, 4254-4272. https://doi.org/10.1177/0954406220971667

Ma, Q., Cheng, H., Jang, K.I., Luan, H., Hwang, K.C., Rogers, J.A., Huang, Y. and Zhang, Y., 2016. A nonlinear mechanics model of bio-inspired hierarchical lattice materials consisting of horseshoe microstructures. *Journal of the Mechanics and Physics of Solids*, **90**, 179-202. https://doi.org/10.1016/j.jmps.2016.02.012

Maidin, S., Ting, K. and Sim, Y., 2022. Investigation of mechanical properties of recycled ABS printed with open source FDM printer integrated with ultrasound vibration. *International Journal of Integrated Engineering*, **14**, 57-63

Malekzadeh, P. and Setoodeh, A., 2009. DQM in-plane free vibration of laminated moderately thick circular deep arches. *Advances in Engineering Software*, **40**, 798-803. https://doi.org/10.1016/j.advengsoft.2009.01.011

Mao, H., G. Yu, W. Liu, and Xu, T., 2020. Out-of-Plane free vibration and forced harmonic response of a curved beam. *Shock and Vibration*, **2020**, 8891585. https://doi.org/10.1155/2020/8891585

Merkt, S., Hinke, C., Bültmann, J., Brandt, M. and Xie, Y., 2015. Mechanical response of TiAl6V4 lattice structures manufactured by selective laser melting in quasistatic and dynamic compression tests. *Journal of Laser Applications*, **27**. https://doi.org/10.2351/1.4898835

Mishra, D. and Das, A.K., 2021. Linear model analysis of fused deposition modeling process parameters for obtaining the maximum tensile strength in acrylonitrile butadiene styrene (ABS) and carbon fiber polylactic acid (PLA) materials. *Multidiscipline Modeling in Materials and Structures*, **17**, 915-930. https://doi.org/10.1108/MMMS-09-2020-0239

Najafi, M., Ahmadi, H. and Liaghat, G., 2022. Investigation on the flexural properties of sandwich beams with auxetic core. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **44**, 61. https://doi.org/10.1007/s40430-022-03368-3

Özyiğit, H.A., M. Yetmez, and Uzun, U. 2017. Out-of-plane vibration of curved uniform and tapered beams with additional mass. *Mathematical Problems in Engineering*, **2017**, 8178703. https://doi.org/10.1155/2017/8178703

Parpala, R.C., Popescu, D. and Pupaza, C., 2021. Infill parameters influence over the natural frequencies of ABS specimens obtained by extrusion-based 3D printing. *Rapid Prototyping Journal*, **27**, 1273-1285. https://doi.org/10.1108/RPJ-05-2020-0110

Ramian, J., Ramian, J. and Dziob, D., 2021. Thermal deformations of thermoplast during 3D printing: warping in the case of ABS. *Materials*, **14**, 7070. https://doi.org/10.3390/ma14227070

Russo, A., Sellitto, A., Saputo, S., Acanfora, V. and Riccio, A., 2019. A numerical–analytical approach for the preliminary design of thin-walled cylindrical shell structures with elliptical cut-outs. *Aerospace*, **6**, 52. https://doi.org/10.3390/aerospace6050052

Stano, G. and Percoco, G., 2021. Additive manufacturing aimed to soft robots fabrication: A review. *Extreme Mechanics Letters*, **42**, 101079.

https://doi.org/10.1016/j.eml.2020.101079

Süsler, S. and Kazancı, Z., 2023. Delamination Strength Comparison of Additively Manufactured Composite Curved Beams Using Continuous Fibers. *Polymers*, **15**, 3928. https://doi.org/10.3390/polym15193928

Taşkin, M. and Demir, Ö., 2023. Effect of porosity distribution on vibration and damping behavior of inhomogeneous curved sandwich beams with fractional derivative viscoelastic core. *Engineering Computations.* **40**, 538-563. https://doi.org/10.1108/EC-04-2022-0269

Wang, Y., 2023. Finite element mesh refinement for in-plane and out-of-plane vibration of variable geometrical Timoshenko beams based on superconvergent vibration modes. *Engineering Computations*, 2023. **40**, 22-40. https://doi.org/10.1108/EC-01-2022-0015

Yang, C., Tian, X., Liu, T., Cao, Y. and Li, D., 2017. 3D printing for continuous fiber reinforced thermoplastic composites: mechanism and performance. *Rapid Prototyping Journal*, **23**, 209-215. https://doi.org/10.1108/RPJ-08-2015-0098

Yao, T., Deng, Z., Zhang, K., and Li, S., 2019. A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations. *Composites Part B: Engineering*, **163**, 393-402. https://doi.org/10.1016/j.compositesb.2019.01.025

Yılmaz, C., Ali, H.Q., and Yıldız, M., 2022. Application of Classical Lamination Theory to Fused Deposition Method 3-D Printed Plastics and Full Field Surface Strain Mapping. *Afyon Kocatepe Üniversitesi Fen Ve Mühendislik Bilimleri Dergisi*,**22**, 342-352. https://doi.org/10.35414/akufemubid.1018774

Zhang, X., P. Sun, Y. Zhang, F. Wang, Y. Tu, Y. Ma, and Zhang, C., 2024. Design and Optimization of 3D-Printed Variable Cross-Section I-Beams Reinforced with Continuous and Short Fibers. *Polymers*, **16**, 684. https://doi.org/10.3390/polym16050684