Archives of Materials Science and Engineering

Volume 116
Issue 2
August 2022
Pages 49-56

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

DOI: 10.5604/01.3001.0016.1189

Experimental investigation for non-linear vibrations of free supported and cantilever FFF rectangular plates

E. Abdeddine *, A. Majid, Z. Beidouri, Kh. Zarbane
Laboratory of Advanced Research in Industrial and Logistic Engineering (LARILE),
National Higher School of Electricity and Mechanics, Hassan II University of Casablanca,
Km7 Route El Jadida, Casablanca, Morocco
* Corresponding e-mail address: e.abdeddine@ensem.ac.ma
ORCID identifier: https://orcid.org/0000-0002-0385-3928 (E.A.)

ABSTRACT

Purpose: The aim of this paper is to investigate experimentally the effect of large vibration of a cantilever and a fully free rectangular plate made by a Fused Filament Fabrication process. Furthermore, this investigation attempts to compare our measurements and those obtained in the literature experimentally.

Design/methodology/approach: For this purpose, a test rig was designed and manufactured for all experimental trials. The plate was excited randomly and harmonically at large displacement respectively, to obtain the linear and non-linear frequencies parameter.

Findings: The non-linear dynamic behaviour of our structure at forced vibration is figured by exciting the plate at large displacement. The dependence of frequency and amplitude vibration are examined for the first, second, and third mode shapes. The non-linear dynamic behaviour of cantilever plates is compared with literature to illustrate the convergence of our results by using our specific mechanical properties, printing parameters, and process. Furthermore, the non-dimensional comparison is shown by 33.38%, 5.83%, and 20.58% for the first, second, and third mode shapes, respectively.

Research limitations/implications: Experimental tests will be performed on a 3D-printed metal plate to improve the present work.

Practical implications: This work is intended to determine the dynamic proprieties of our parts in order to manufacture a safe and comfort machine.

Originality/value: Actually, the dynamic behaviour of our 3D printing plates is compared with the obtained in the case of the isotropic plate for the aim to predict the convergence of both structures.

Keywords: Fused Filament Fabrication, Non-linear dynamic behaviour, Geometrically non-linear, Non-linear transverse vibration

Reference to this paper should be given in the following way:

E. Abdeddine, A. Majid, Z. Beidouri, Kh. Zarbane, Experimental investigation for non-linear vibrations of free supported and cantilever FFF rectangular plates, Archives of Materials Science and Engineering 116/2 (2022) 49-56. DOI: https://doi.org/10.5604/01.3001.0016.1189

PROPERTIES

1. Introduction

Fused Filament Fabrication (FFF) is a polymer filament deposition procedure which is used to fabricate parts. As with the other additive manufacturing techniques, FFF applies the content of the printed component layer by layer, just where it is required, which allows for resource-saving, lower raw material costs and less waste. While showing advantages over conventional production methods, FFF printed parts often have inferior mechanical properties.

Recent research has been focusing on the study of different parameters of additive technologies [1,2]. This includes the study on body parts in order to determine the dimensional accuracy of the surface roughness of polymer dental parts [3] and the one on the mechanical properties so as to verify whether they match with the real bone structure strength [4]. In addition, other investigations have been directed towards the mechanical properties analysis of 3D printed aluminium components [5] and the verification of these 3D printers' accuracy [6].

Dynamic study of 3D printed samples using numerical techniques or experimental procedures can be found in the literature [7-10], in which the influence of print strength on the vibration characteristics of lattice structure bars using a fused deposition modelling (FDM) AM printer was particularly examined. In fact, the vibration scanning was employed to determine the natural frequencies of two samples with strong and nearly solid print strength [11]. Meanwhile, several studies focusing specifically on the mechanical behaviour of uniaxial tensile specimens under static loading have already established some relationships between the process parameters and the final results. However, FFF technology is intended for the production of finished parts for use in machinery or transportation. Dynamic loading is the most common scenario in such cases and needs to be taken into account [12]. The dynamic behaviour analysis of printed mechanical structures has gained importance in recent years [10,12,13]. Indeed, these printed structures (solid parts) offer good mechanical performance and a reduced weight [14], unlike the isotropic and composite components.

Njim et al. [15] investigated the free vibration characteristics of the functionally graded sandwich plate with uniform distribution of porosities varying smoothly through the core thickness direction. Njim et al. created a mathematical model based on CPT principles and the Ryleigh-Ritz approximate technique to identify the natural frequencies. And the results were validated using numerical software. While Kadum et al. [16] developed a numerical analysis to optimize the natural frequencies of sandwich plate functionally graded plate with porosity using Multi-Objective Genetic Algorithm methods. A convergence between the results obtained analytically and the numerical ones using ANSYS software was established, which also led to performing different effects on multiple parameters such as power-law index, porous metal type, porosity ratio, and length-to-thickness ratios [17]. that lead to investigate the optimized natural frequencies.

Al-Shammari et al. [18] studied experimentally and numerically the behaviour of thin, rectangular plates with fully clamped and fully simply supported boundary conditions and varying different working conditions such as the radius of the central hole of a plate, the aspect ratio of the plate, length of cracks, and numbers of cracks. In order to determine the effect of each parameter on the natural frequencies.

In the references [19,20] investigated analytically on graded sandwich plates and beams, respectively. [20] used Euler-Bernoulli beam theory and the Finite element method, a comparison was established, and given the accuracy of the natural frequencies results by increasing the number of layers [19]. The analytical formulations were formulated based on the classical plate theory. And validated using experimental techniques to verify the accuracy of the analytical solution. These later showed that the natural frequencies increase with increasing porosity factors, also increasing the core surface height increased the natural frequencies.

The present research is aimed at investigating the non-linear dynamic behaviour of an FFF plate. Testing specimens are printed and then carried out to an experimental process by exciting those specimens using an electrodynamic shaker. Afterwards, the data are collected by an accelerometer that is glued on the specimens. Moreover, the experimental results are compared with literature data obtained with a rectangular cantilevered plate and those applied on isotropic plates in the case of a fully free boundary conditions, presented in reference [21].

2. Experimental plan and methodology

2.1. Fabrication of specimen

First, the rectangular flat plate was parametrically modelled using "CATIA V5" After that, the latter files were imported into the 3D Slicer Software "deaMaker" where the printing parameters were set, and the printer orientation was considered. Figure 1 illustrates the printing process of the FFF plate.

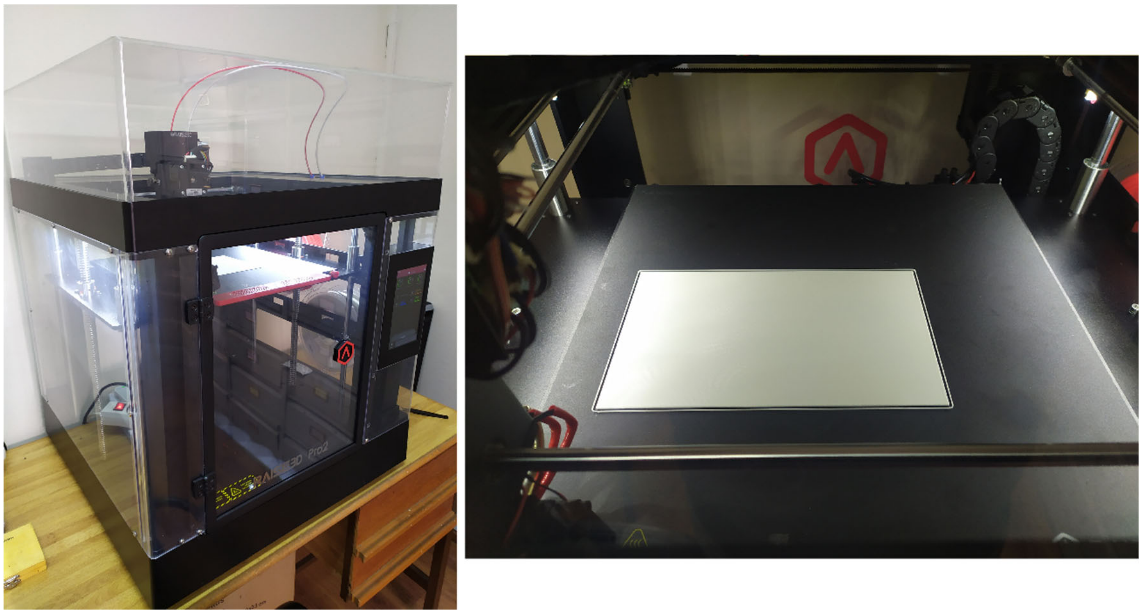

Fig. 1. Schematic diagram of the experimental vibration

Table 1.
Printing parameter and process

Plate's boundary conditions	Print head travel speed	Printing time	Plate temperature	Nozzle temperature	Nozzle diameter
Cantilever	90 mm/s	1 h 22 m	60°C	205°C	0.4 mm
Full Free	90 mm/s	2 h 47 m	60°C	205°C	0.4 mm

Table 2.
Physical and mechanical properties of PLA

Category	Density	Poisson's ratio	Tensile strength	Ultimate strain	Elastic modulus	Glass transition temperature	Melting temperature
Unit	g/cm^3		MPa	%	GPa	°C	°C
Value	1.2	0.33	46.6	1.90	2.636	61	150

The printing head travel speed is set up at 90 mm/s with a nozzle diameter equal to 0.4 mm, and temperature up to 205°C. With the last parameter set up, the printing process took 1 hour and 22 minutes. For the second case, experimental tests were conducted on a rectangular FDM plate with dimensions 200 mm × 120 mm × 1 mm (L x W x H); the printing process took 2 hours and 47 minutes. Table 1 summarizes the printing setting and Table 2 presents the mechanical characteristic of the used filament during the manufacturing process. Those results were carried out by Raise3D on testing specimens and printed under the same condition for our experience simples. The quality of the plate depends on many parameters that need to be considered, including the material and FFF factors [22,23]. This study used the optimal process and parameters proposed in the latter reference, which led to good results.

2.2. Test rig and instruments

In the experimental analysis on the printed simples, a coil was glued at the plate's bottom that provides the transverse harmonic excitation. We have supposed that the coil did not add stiffness and additional mass to the plate. The electronic apparatuses used during the test led to analyse the dynamic response of this structure. These later are given in Table 3.

In the following experiments, the sampling rate is set to 48000 Hz, and the Hilbert filter was used as a filter type for our acquisition signal.

Table 3.
Devices used

Accelerometer	Accelerometer
Brüel&Kjær	Brüel&Kjær
Power Amplifier	Power Amplifier
InterM L800	InterM L800
Sine wave generator	Sine wave generator
Metrix GX310	Metrix GX310

2.3. Experimental analysis for cantilever plate

In accordance with reference [24], the studied structure is a flat rectangle with a length of 130 mm, a width of 50 mm, and a thickness of 2.4 mm.

The experimental setup is depicted in Figures 2 and 3. Experiments have been carried out to highlight the dynamic behaviour response of the FFF cantilever plate and to compare the obtained results with those found in the literature. In this context, the plate was randomly excited to determine the natural frequency and then to perform the modal analysis. Regarding to analyse the non-linear dynamic behaviour, the plate was excited by using an electrodynamic shaker. It should be noted that the excitation amplitudes were varied step by step around the linear frequency of the first mode shape in order to examine the effect of geometrically non-linear.

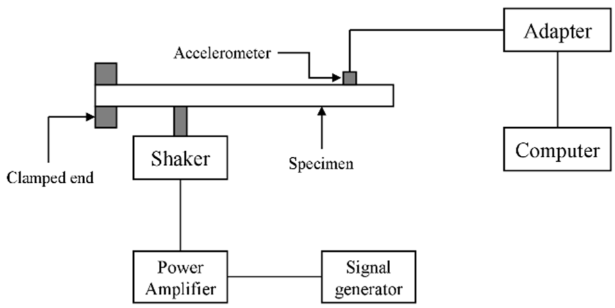

Fig. 2. Schematic diagram of the experimental vibration

2.4. Experimental analysis for full free plate

In order to investigate experimentally the dynamic behaviour of our structure, the configuration of fully free plate presented in Figure 4 has been adopted during the test. A similar laboratory setup is used in the previous work [25]. Furthermore, the theoretical formulation adopted was validated in the later work, and was used to treat plates and rods [26,27].

The fully plate was supporting by using threads and were acting to pull the plate at the all four corners. Coil-magnet as electrodynamic exciter is used to excite the plate. The coil is feeding by the alternating current generated by a sine wave generator and amplified via an amplifier. Afterwards, data are collected by an accelerometer that is glued on the plate's centre and analysed by the "StudioVib" software.

Fig. 3. Test rig for determining the dynamic characteristics for cantilever plate

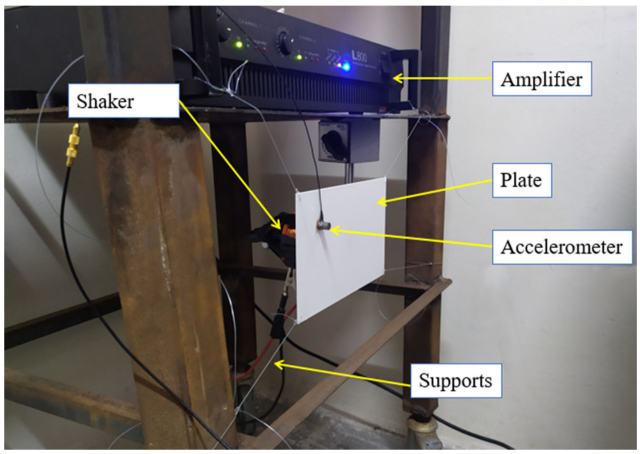

Fig. 4. Laboratory set-up and acquisition devices for the free plate

3. Results and discussions

For the first case of the free support plate, the investigation was made to illustrate the convergence of the numerical results found in literature and our experimental study. In addition, this later is to understand or to estimate the dynamic behaviour of FFF plates just by studying the isotropic plates. For that, the nonlinear dynamic behaviour is compared for both investigations. In the second case of cantilever plate, the analysis is made to compare the nonlinear dynamic behaviour of two FFF plates with different printing parameters and process. Also, to figure out the effect of these parameters.

3.1. Cantilever FFF plate

Referring to the Jiang study [24], the numerical of cantilever plate is based on Kirchhoff hypothesis used to approximate the mode shape of the plate under the studied cantilever boundary condition.

This model is solved using Ritz method by the energy variation principle, which could obtain the results by transforming functional extremum problem to the extremum problem of multivariate function.

The projected natural frequency and mode shapes are compared to the measured ones in order to verify the theoretical model [24] (Tab. 4). As shown in Table 4, a discrepancy between natural frequencies of the literature (theoretical and experimental data) and those obtained experimentally (Fig. 5) through this work was noticed. In the case of the first and third mode shapes, the error is higher compared to what has been demonstrated in the literature, while the value is improved for the second mode shape. Hence, this difference is related to the different setting parameters of the printing plates, such as the printing speed, the extruder temperature, and the contour layer and printing orientations along with the infill patterns; a concentric infill was used in [24]. In contrast, our printing process used a rectilinear infill pattern (Fig. 6). Additionally, it is necessary to add the operating conditions, such as the exact position of the shaker point. Due to the layer-by-layer process procedure, 3D printed materials behave with anisotropic properties, which add a significant difference.

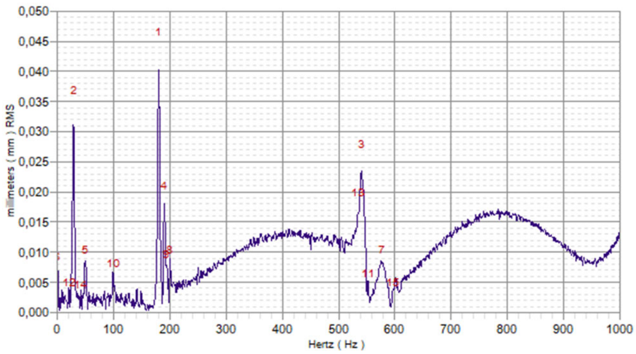

Fig. 5. The average measured frequency response curves of the dynamic test

a) b)

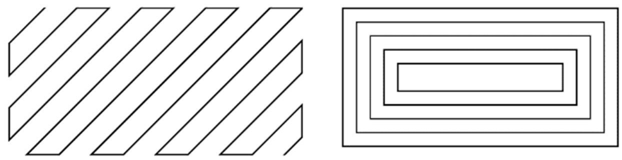

Fig. 6. Infill patterns of the printing process: a) rectilinear, b) concentric

In order to investigate the non-linear dynamic behaviour, the plate was excited by varying the displacement amplitude excitation. The results depicted in Table 5 show the dependence of frequency and the displacement amplitude. Both results are increased, which indicates a hardening type of non-linear behaviour with an increase in the non-linear frequency parameter. we can conclude the important of the nonlinear theory in order to investigate these structures by taking into account the parameter that involves the nonlinearity geometric. A backbone illustrates this geometrical nonlinearity effect in Figure 7.

Table 4.
The predicted and measured natural frequencies of the samples

	Mode Shape		
	1st	2nd	3rd
Measured natural frequency (Hz) [24]	18	154.9	384.8
Predicted natural frequency (Hz) [24]	19.3	170.1	429.4
Measured natural frequency (Hz) [Present]	28.97	180.63	540.69
Error (%) of measured natural frequency [Present]	37.87%	14.24%	28.83%
Error (%) of predicted natural frequency [Present]	33.38%	5.83%	20.58%
Error (%) of Measured and predicted natural frequency in [24]	7.22%	9.81%	11.59%

Table 5.
Frequency response of the first mode shape

Shaker amplitude	Frequency, Hz	Amplitude
1	30.04	0.093
2	31.04	0.115
3	32.01	0.125
4	33.98	0.148

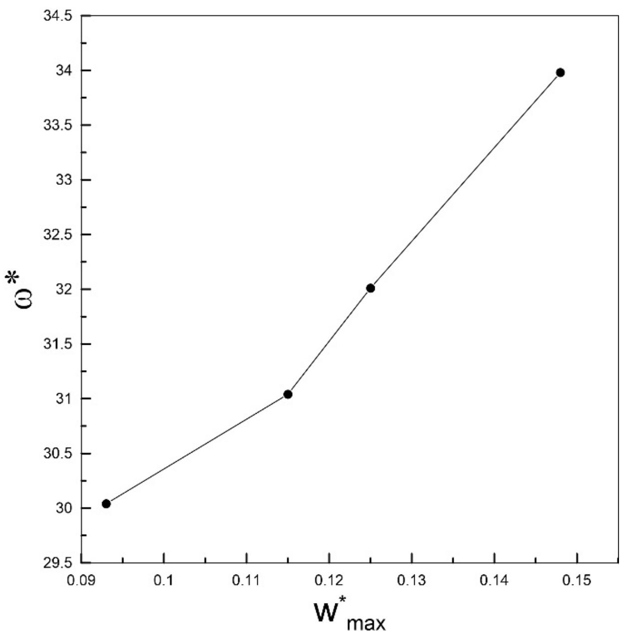

Fig. 7. Backbone curves corresponding to the first non-linear transversal mode shape of a Cantilever FFF plate

3.2. Free rectangular FFF plate

Alijani et al. [21] investigated numerically fully free plate using the nonlinear higher-order shear deformation theory and by Geometric imperfections are taken into account the effect of geometric imperfections. Furthermore, the bifurcation analysis was obtained by pseudo-arc-length continuation.

Experimental tests were conducted to understand the dynamic behaviour of FFF fully free plate and to compare it to the literature results made on isotropic plates. The main of this investigation was to predict the non-linear dynamic behaviour of the FFF plates. First, the plate was randomly excited to identify the natural frequency and perform the modal analysis (Tab. 6). Then, in the non-linear tests, the plat was excited by a shaker where the excitation is varying with small steps around the linear frequency in order to obtain a large amplitude vibration response.

Table 6.
Comparison of the first and second natural frequency of a free plate

Number of modes	Present study, Hz	Alijani et al. [21], Hz
1	39.08	23.28
2	56.07	33.1

In the non-linear analysis, the amplitude was both increased and decreased in order to analyse the geometrically non-linear phenomena. The results are summarized in Table 7, and are in a good agreement with those obtained in [21]. On the basis of the given results, it can be deduced that the research on the dynamic behaviour of the FFF plate has been successful. A backbone illustrates the geometrical nonlinearity in Figure 8.

Table 7.
Comparison of normalized response resonance of the first mode shape

Amplitude vibration	Present study	Alijani et al. [21]
0.117	0.97	1.02
0.804	1.04	1.06
0.865	1.05	1.12
1.165	1.09	1.17
1.404	1.12	-
2.252	1.22	-

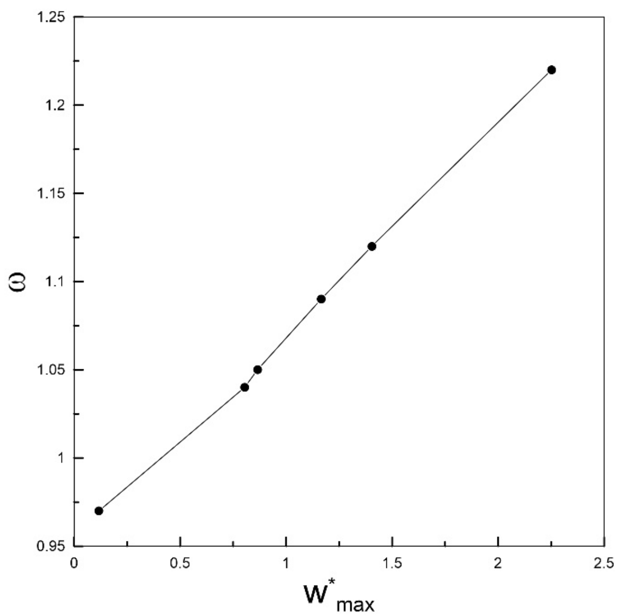

Fig. 8. Backbone curves corresponding to the first non-linear transversal mode shape of a free rectangular FFF plate

4. Conclusions

In the present paper, the dynamic mechanical properties of a cantilever boundary condition rectangular plate via an FFF process have been analysed on the basis of building and test parameters. A sample has been built with a fixed nozzle diameter, the number of contours, the distance between rasters, and speed printing. Tests have been carried out using different experimental ranges of amplitude, which exhibit a hardening type of non-linear behaviour. The obtained results confirmed that studied dynamical properties depend on the building and test parameters compared to the literature. Hence, experimental tests will be performed on a 3D-printed metal plate in order to improve the present work.

References

[1] L.A. Dobrzański, L.B. Dobrzański, A.D. Dobrzańska-Danikiewicz, M. Kraszewska, Manufacturing powders of metals, their alloys and ceramics and the importance of conventional and additive technologies for products manufacturing in industry 4.0 stage, Archives of Materials Science and Engineering 102/1 (2020) 13-41. DOI: https://doi.org/10.5604/01.3001.0014.1452

[2] M. Mrówka, M. Szymiczek, J. Lenża, Thermoplastic polyurethanes for mining application processing by 3D printing, Journal of Achievements in Materials and Manufacturing Engineering 95/1 (2019) 13-19. DOI: https://doi.org/10.5604/01.3001.0013.7620

[3] T.D. Dikova, D.A. Dzhendov, D. Ivanov, K. Bliznakova, Dimensional accuracy and surface roughness of polymeric dental bridges produced by different 3D printing processes, Archives of Materials Science and Engineering 94/2 (2018) 65-75. DOI: https://doi.org/10.5604/01.3001.0012.8660

[4] P.G. Ikonomov, A. Yahamed, P.D. Fleming, A. Pekarovicova, Design and testing 3D printed structures for bone replacements, Journal of Achievements in Materials and Manufacturing Engineering 101/2 (2020) 76-85. DOI: https://doi.org/10.5604/01.3001.0014.4922

[5] P. Baras, J. Sawicki, Numerical analysis of mechanical properties of 3D printed aluminium components with variable core infill values, Journal of Achievements in Materials and Manufacturing Engineering 103/1 (2020) 16-24. DOI: https://doi.org/10.5604/01.3001.0014.6912

[6] J. Taczała, W. Czepułkowska, B. Konieczny, J. Sokołowski, M. Kozakiewicz, P. Szymor, Comparison of 3D printing MJP and FDM technology in dentistry, Archives of Materials Science and Engineering 101/1 (2020) 32-40. DOI: https://doi.org/10.5604/01.3001.0013.9504

[7] F. Ali, B.V. Chowdary, Natural Frequency prediction of FDM manufactured parts using ANN approach, IFAC-PapersOnLine 52/13 (2019) 403-408. DOI: https://doi.org/10.1016/j.ifacol.2019.11.083

[8] O.A. Mohamed, S.H. Masood, J.L. Bhowmik, Experimental Investigations of Process Parameters Influence on Rheological Behavior and Dynamic Mechanical Properties of FDM Manufactured Parts, Materials and Manufacturing Processes 31/15 (2016) 1983-1994. DOI: https://doi.org/10.1080/10426914.2015.1127955

[9] D. Jiang, D.E. Smith, Anisotropic mechanical properties of oriented carbonfiber filled polymer composites produced with fused filament fabrication, Additive Manufacturing 18 (2017) 84-94. DOI: https://doi.org/10.1016/j.addma.2017.08.006

[10] S.K. Chaitanya, K.M. Reddy, S.N.S.H. Ch, Vibration Properties of 3D Printed/Rapid Prototype Parts, International Journal of Innovative Research in Science, Engineering and Technology 4/6 (2015) 4602-4608. DOI: https://doi.org/10.15680/IJIRSET.2015.0406087

[11] M.S. Azmi, R. Ismail, R. Hasan, M.R. Alkahari, T. Tokoroyama, Vibration analysis of FDM printed lattice structure bar, Proceedings of Sakura Symposium on Mechanical Science and Engineering, Nagoya University, Japan, 2017, 33-35.

[12] M. Domingo-Espin, S. Borros, N. Agullo, A.A. Garcia-Granada, G. Reyes, Influence of Building Parameters on the Dynamic Mechanical Properties of Polycarbonate Fused Deposition Modeling Parts, 3D Printing and Additive Manufacturing 1/2 (2014) 70-77. DOI: https://doi.org/10.1089/3dp.2013.0007

[13] S. Jiang, M. Zhan, M. Sun, W. Dai, C. Zhao, Experimental and Theoretical Analysis on the Dynamic Characteristics of Fused Filament Fabrication Plates, Shock and Vibration 2019 (2019) 1219435. DOI: https://doi.org/10.1155/2019/1219435

[14] O.A. Mohamed, Analytical modeling and experimental investigation of product quality and mechanical properties in FDM additive manufacturing, PhD Thesis, Swinburne University of Technology Hawthorn, Victoria, Australia, 2017.

[15] E.K. Njim, S.H. Bakhy, M. Al-Waily, Analytical and numerical free vibration analysis of porous functionally graded materials (FGPMs) sandwich plate using Rayleigh-Ritz method, Archives of Materials Science and Engineering 110/1 (2021) 27-41. DOI: https://doi.org/10.5604/01.3001.0015.3593

[16] E.K. Njim, S.H. Bakhy, M. Al-Waily, Optimization design of vibration characterizations for functionally

graded porous metal sandwich plate structure, Materials Today: Proceedings (2021) (Available online). DOI: https://doi.org/10.1016/j.matpr.2021.03.235

[17] E.K. Njim, S.H. Bakhy, M. Al-Waily, Analytical and Numerical Investigation of Free Vibration Behavior for Sandwich Plate with Functionally Graded Porous Metal Core, Pertanika Journal of Science and Technology 29/3 (2021) 1655-1682. DOI: https://doi.org/10.47836/pjst.29.3.39

[18] M.A. Al-Shammari, M.A. Husain, M. Al-Waily, Free vibration analysis of rectangular plates with cracked holes. AIP Conference Proceedings 2386 (2022) 040023. DOI: https://doi.org/10.1063/5.0066908

[19] E.K. Njim, S.H. Bakhy, M. Al-Waily, Free vibration analysis of imperfect functionally graded sandwich plates: Analytical and experimental investigation, Archives of Materials Science and Engineering 111/2 (2021) 49-65. DOI: https://doi.org/10.5604/01.3001.0015.5805

[20] S.H. Bakhy, M. Al-Waily, M.A. Al-Shammari, Analytical and numerical investigation of the free vibration of functionally graded materials sandwich beams, Archives of Materials Science and Engineering 110/2 (2021) 72-85. DOI: https://doi.org/10.5604/01.3001.0015.4314

[21] F. Alijani, M. Amabili, Theory and experiments for non-linear vibrations of imperfect rectangular plates with free edges, Journal of Sound and Vibration 332/14 (2013) 3564-3588. DOI: https://doi.org/10.1016/j.jsv.2013.02.015

[22] K.V. Singh, F. Khan, J. Veta, A.K. Singh, Influence of Printing Orientation on the Dynamic Characteristics and Vibration Behavior of 3D Printed Structures, Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 1: 37th Computers and Information in Engineering Conference, Cleveland, Ohio, USA, 2017, V001T02A032. DOI: https://doi.org/10.1115/DETC2017-68289

[23] S. Farah, D.G. Anderson, R. Langer, Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review, Advanced Drug Delivery Reviews 107 (2016) 367-392. DOI: https://doi.org/10.1016/j.addr.2016.06.012

[24] S. Jiang, M. Zhan, M. Sun, W. Dai, C. Zhao, Experimental and Theoretical Analysis on the Dynamic Characteristics of Fused Filament Fabrication Plates, Shock and Vibration 2019 (2019) 1219435. DOI: https://doi.org/10.1155/2019/1219435

[25] A. Majid, E. Abdeddine, K. Zarbane, Z. Beidouri, Geometrically non-linear forced transverse vibrations of C-S-C-S rectangular plate: Numerical and experimental investigations, Journal of Applied Nonlinear Dynamics 10/4 (2021) 739-757. DOI: https://doi.org/10.5890/JAND.2021.12.012

[26] A. Majid, E. Abdeddine, K. Zarbane, Z. Beidouri, Geometrically non-linear free and forced vibration of C-F-C-F rectangular plate at large transverse amplitudes, Proceedings of the XI International Conference on Structural Dynamics "EURODYN 2020", Athens, Greece, 2020, 225-238. DOI: https://doi.org/10.47964/1120.9018.19213

[27] E. Abdeddine, A. Majid, Z. Beidouri, K. Zarbane, Non-linear longitudinal free vibration of uniform rods and rods with sections varying exponentially, Proceedings of the XI International Conference on Structural Dynamics "EURODYN 2020", Athens, Greece, 2020, 239-251. DOI: https://doi.org/10.47964/1120.9019.19214