A REVIEW ON INFLUENCE OF PARAMETERS ON EVALUATION OF MECHANICAL AND DYNAMIC PROPERTIES OF 3D PRINTED COMPOSITE STRUCTURES

Abstract

The growing need for easy production of complicated shapes has made a gateway for 3D printing process to manufacturing realm. This process has made the complex geometries of the structures to be printed in a more flexible and easier way, which involves creation of geometric model, print material with a suitable printer. Composites through their high specific strength, lightweight, tailarobility have attracted major industries like aerospace, automotive, marine, sports, recreation to use them. Recently there has been an increase in use of 3D printing in printing of composites in industries. Though the process appears to be easy to produce any complicated structure, in real sense it is not so because of many influencing parameters on the behaviour of the structure. This review focuses on available literatures where composites have been 3D printed and the properties like mechanical and dynamic are characterized.

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I. INTRODUCTION

3D printing, also referred to as additive manufacturing(AM), rapid prototyping (RP), or solid-freeform (SFF), is a technology where a component is created by adding layers of material one above the other. The components have good geometric accuracy as compared to conventional subtractive manufacturing, where material is removed. The printing process begins with a meshed 3D computer model that can be created by acquired image data or structures built in computer-aided design (CAD) software. A STL(Surface Tessellation Language) file is commonly created. The mesh data will be further sliced into a build file of 2D layers and sent to a 3D printing machine (figure 1). Albeit 3D printing has emerged as an attractive manufacturing technique, because of availability of variety of printing process options such as Fused Deposition Modelling(FDM),Powder bed and inkjet head 3D printing(3DP), Stereolithography(SLA), Selective Laser Sintering(SLS), 3D Plotting/ direct-write and also latest techniques such as Digital Light Processing (DLP), Liquid Deposition Modelling and Fibre Encapsulation Additive manufacturing(FEAM)[1], with their own strengths and short comings, has opened up large opportunities in printing and characterizing composites. The next challenge in printing would be in choosing a suitable print material. Commercially, a wide variety of printable materials like Polylactic Acid(PLA), Acrylonitrile Butadiene Styrene (ABS), Nylon, Poly carbonate (PC) [1-13] available has further exasperated the challenge of printing. The use of these polymers as functional components is limited by their low mechanical strengths. A combination of polymers reinforced with different fibres forming a composite has recently drawn attention of many researchers with their superior properties as compared to neat polymers. Investigations have been carried out in recent past on additive manufacturing of fibre reinforced composites highlighting the functional performance. These are highly influenced by (1) slicing parameters (2) build orientation (3) temperature requirements [9].

Many research works have been carried out to evaluate mechanical properties such as tensile strength, toughness, fatigue resistance, hardness, creep behaviour of 3D printed parts with various standards as suggested by ASTM [2-13]. Available literatures on characterization of 3D printed specimens suggest that though, there is a considerable improvement in mechanical properties of 3D printed composites, there are still challenges that need to be addressed such as improving interlaminar and intralaminar strengths, reducing void content, lack of concrete guidelines on optimizing process parameters and print parameters, material selection, standard tests to evaluate material characteristics [11].

In addition to the strength properties of a material, the response of a material to vibration is an important aspect as it may pose significant problems in machine systems. Literatures focusing on the vibrational behaviour of 3D printed composites are in limited numbers and most of them concentrated on experimental evaluation of composites response [6, 9, 13].

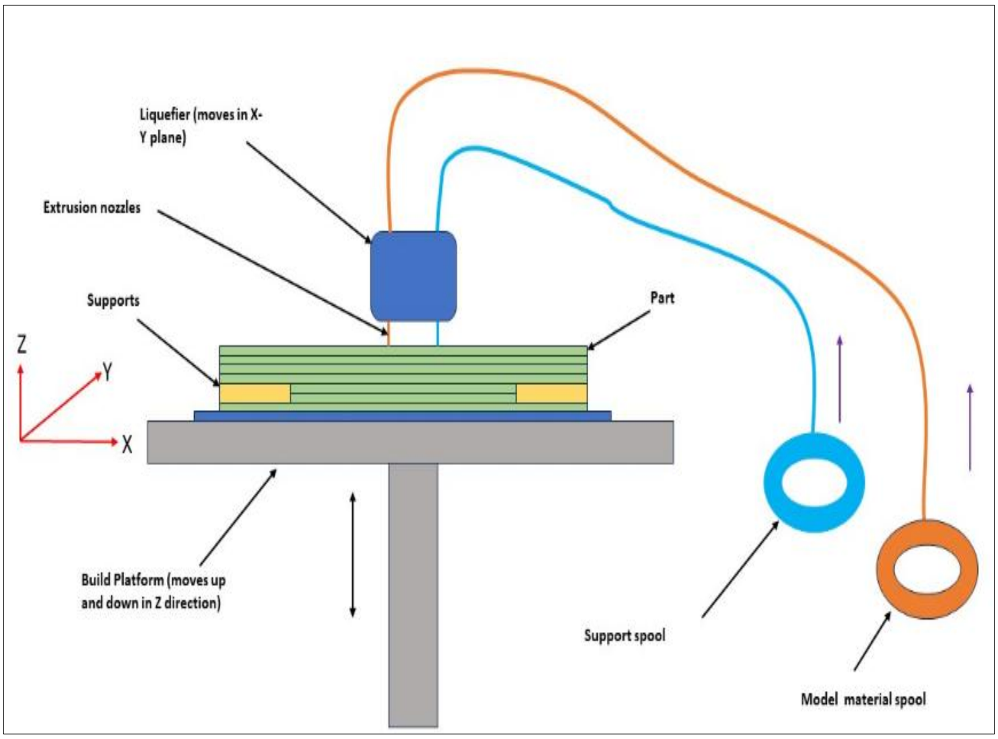

Figure1: Schematic of a Typical Fused Deposition Modelling (FDM) AM Process

The focus here is to review the available literature on printing of polymers and fibre reinforced polymer matrix composites, with various materials, reinforcements, printing processes, influence of printing parameters on the mechanical and dynamic behaviour of the structures in terms of strengths, vibration response parameters.

Xin wang et al. [1], conducted a review on 3D printing of Polymer matrix composites processed via Fused Deposition Modelling (FDM), Powder bed and inkjet head 3D printing (3DP), Stereolithography (SLA), Selective Laser Sintering (SLS), 3D Plotting/ direct-write approach and latest techniques such as Digital Light Processing (DLP), Liquid Deposition Modelling and Fibre Encapsulation Additive manufacturing (FEAM). From the review, the short comings of polymer printed parts for functional applications such as low mechanical strength are noticeable. To address these short comings, literature related to studies involving various types of reinforcements such as particles of TiO_2, carbon nanofibres, $BaTiO_3$, Al_2O_3 nanocomposites of different types were reviewed and their effects on the mechanical characteristics like tensile strength, impact resistance, flexural strength, thermal stability were also listed. However, variation in mechanical properties with fibre reinforcement was largely due to fibre distribution condition and interfacial bonding strength. Finally, they emphasized the need of further research on using diverse materials with special properties depending on industry needs, reducing voids formation, printing with high resolution and production of large parts for industry usage.

M. Mohammadizadeh et al. [2], conducted a study to understand the effect of fibre orientation on the mechanical properties of 3D print specimens. The process involved printing of Nylon polymer reinforced with Carbon fibre (CF), fibre Glass (FG), and Kevlar with respective volume fractions of 58%, 28%, and 43%, for tensile, fatigue and creep test using ASTM standards. Specimens were Fused Deposition Modelling (FDM) printed with two headed Markforged Mark Two printers. The nylon layers with fill density of 50 % at + 45^0/ -45^0 with specimen axial direction in rectangular pattern consisting fibres at 0^0 orientation with axial direction were printed. Infill patterns studied were concentric, isotropic and their combination.

The specimens with concentric fibre laying pattern generally showed lower resistance to failure compared to (isotropic + concentric) laying of fibres indicating the influence of fibre orientation. This behaviour was attributed to low fibre volume with concentric layup. Particularly the CF reinforced specimens showed higher strength among others but lacked ductility while FG reinforced specimens performed better in this regard. Fatigue tests carried out on specimens with load ranging from 3.33 kN – 17.4 kN, revealed that isotropic specimen's overall performance was good compared to concentric ones. When the load was highest, nylon- FG and nylon-Kevlar specimens failed completing justa cycle, however showing good performance at lower loads. Overall nylon-CF showed good results in fatigue tests. Creep tests conducted on the specimens showed that pure nylon had higher strain rate compared to reinforced specimens. Also, CF reinforced specimens possessed lower strain rates in comparison with others. The microstructure analysis at failed section using SEM was conducted for all the failed specimens under three tests. The SEM analysis of tensile test samples unveiled that the main mechanisms of failure were fibre breakage, fibre pull out and debonding. The nylon-CF specimens had higher fibre pull out damage, nylon -FG had fibre pullout and fibre breakage, nylon- Kevlar had fibre pullout and debonding. Fatigue failed specimens revealed that fibre pullout again appeared as a major failure mechanism. The creep failed specimens showed large voids and delamination in nylon-CF composites. For nylon-FG composites, fibre pullout and fibre breakage appeared to be dominant while for nylon-Kelvar it was fibre pullout.

G.D. Goh et al.[3], studied the mechanical properties of pre-impregnated continuous carbon fibre (CF) and glass fibre (FG) filaments coated with nylon polymer for free-form fabrication (FFF) of specimens using Markforged 3D printers. Specimens were printed according to ASTM standards with 100%fill density and 0.1 mm layer thickness. The fibres orientation was kept at 0^0 (unidirectional). Experimental methods included micro–Computerized Tomography scans, tensile, flexural, and quasi-static indentation tests, optical stereo microscope for interlayer and interfacial properties. Laser scanning confocal microscope and SEM were also utilized. The tensile tests showed a linear stress – strain relation before breakage with CF reinforced samples exhibiting maximum tensile strength of 600 MPaand young's modulus of 12.99 GPa while FG reinforced samples had maximum tensile strength of 450 MPa and young's modulus of 7.20 GPa. Higher strain bearing capacity for FG reinforcement vis-à-vis CF reinforcement was observed via this test. Failure mechanisms of both composites included tensile, shear rupture, and delaminations. Through flexure test they observed that the CF reinforced specimens behaved differently than that of GF reinforced specimens. Maximum flexural strength of CF reinforced specimens was 430 MPa with flexural modulus of 38.1 GPa but with a sudden failure after 1.5% strain. GF specimen possessed flexural strength of 149 MPa and flexural modulus of 14.7 GPa showing gradual reduction in strength before failing at 2.5% strain. During the test, it was noticed that Shear kinks formed on the compression side of the specimens. The indentation test revealed that the maximum indentation force for CF composite was 1078 N with indentation energy of 6530 J at 10.62 mm while the maximum indentation force for GF composite was 1406 N with indentation energy of 7046 J at 12.12 mm. During the tests fibre breakage and delamination were observed at the centre of the specimen.

J.M. Chaćon et al.[4], printed PLA specimens using Fused Deposition Modelling(FDM) with alow-cost Wit Box printer. Their study focused on evaluating the influence of printing parameters on mechanical performance of printed specimens. The printing parameters considered included build orientation, layer thickness and feed rate. ASTM standard coupon specimens were printed with flat, on edge and upright build orientations with layer thicknesses of 0.06, 0.12, 0.18,0.24 mm and feed rates 20, 50, 80 mm/s. Raster angle was kept at 0^0 with solid fill and zero air gap. There were 360 specimens printed with five specimens under each group of process parameters. Mechanical properties were evaluated in terms of average tensile strength and modulus, average bending strength and modulus. Response surface methodology for tensile and bending strength was developed to relate mechanical performance and process parameters. ANOVA was performed to understand the statistical significance level of different parameters. From the test plots it was observed that build orientation had a significant effect on the mechanical properties suggesting that flat and on edge build orientation were preferable, with higher values of tensile, flexural strength and modulus as against upright orientation. A similar behaviour was also noted with respect to elastic modulus. Higher layer thickness promoted higher strengths in upright direction while its influence on edge and flat specimens was meagre except for very low layer thickness. Feed rate played a significant role for on edge and flat specimens displaying higher strengths compared to upright specimens where they reduced. The SEM morphologies of fractured interface revealed that the failure modes transited from brittle failure to ductile failure with build orientation. In case of on edge specimens the trans-layer tensile failure resulted in ductile behaviour whereas upright orientation experienced a more brittle behaviour. The flat orientation specimens casted an intermediate brittle - ductile behaviour. In addition to these results a functional component was also printed and tested which confirmed the specimen behaviour like the above coupon tests. A functional structure which was printed with a particular combination of parameters also showed a similar behaviour in line with the standard specimen.

Mansour et al.[5], made a comparative study by evaluating mechanical and dynamic properties of graphene platelets reinforced PLA composite and neat PLA printed specimen using Fused Deposition Modelling (FDM) process with a preset printing parameters. Alternate layers printed had [0^0 / 90^0] raster orientations. The specimens printed were of cylindrical shape. The morphological study using Scanning Electron Microscope (SEM) showed a typical local thickening, as the layers had 90^0orientations alternatively. Graphene reinforced specimens surface cut showed a visible roughness and thus brittle cracks formation. Under the uniaxial compression tests, the stress-strain curve of reinforced specimen had a higher modulus of 3767MPa compared to 2684 MPa for neat PLA specimen with same failure strains. The nanoindentation showed the presence of creep phenomenon at peak load of 14mN in both the types of specimens and without any cracks. Through the test there was a clear indication of increase in elastic recovery of graphene inserted specimens with indentation modulus of 4522.25 MPa in comparison with neat PLA specimen having3715 MPa. The indentation test gave out a higher hardness for reinforced specimen, 255.6 MPa, as against neat PLA specimen, 142.7 MPa. The cyclic compression test on the specimens resulted in hysteresis loops which revealing increased damping with graphene reinforcement accompanied with a loss factor of 18% vis-à-vis neat PLA with loss factor of12.2%. The Frequency Response Function (FRF) from modal test of the specimens, showed a shift in the fundamental resonant frequency from 110 Hz for neat PLA specimen to 130 Hz for reinforced specimen, which in turn, is attributed to increased stiffness of graphene added specimens.

Sridharan Kannan et al.[6], employed Fused Deposition Modelling (FDM) process to print specimens of Polyethylene terephthalateglycol (PETG) reinforced with short carbon fibre to understand the influence of these short fibres on mechanical properties and vibrational response of composite specimens and compared the results with neat PETG. The specimens had [+ 45 / - 45] raster angle, 100 % infill density and 0.15 mm layer thickness. 25% by volume fraction of short carbon fibres was added to PETG and the specimens were had Flatbed orientation. Two geometries i.e., dumbbell and beam shaped specimens were prepared as per ASTM standards for tensile and vibrational testing respectively. The load bearing capacity of (PETG + CF) specimens increased due to more uniform distribution of fibres and hence higher strength. From the tensile stress-strain curve it was clear that adding short carbon fibre improved the failure strain from 3% for PETG specimens to 4-5% for reinforced specimens with ultimate tensile strength of 34.8 MPa as against 30.3 MPa for neat PETG specimens. Young's modulus for PETG + CF was reported as 2340 MPa vis-à-vis 1660 MPa for neat PETG. However, the Poisson's ratio for reinforced specimen decreased to 0.385 as against 0.419 of the counterparts. The morphology at the failure surface of the specimens using Field Emission Scanning Electron Microscope (FESEM) revealed the presence of fibre pullouts in reinforced parts due to poor bonding between the constituents. The ductile nature of PETG specimens showed visible flow lines under tensile test. The impact hammer test conducted on beam specimens to evaluate first five bending modes for clamped-clamped and clamp-free boundary conditions, showed that, the reinforcement improved the natural frequencies of the specimens in comparison to PETG specimens. These results of vibrational analysis were compared with ANSYS results and the both were in good agreement.

M. Iragi et al.[7], Fused Filament Fabrication (FFF) to print and mechanically characterize Poly Amide/Continuous Carbon Fibre (PA/CCF) composite material. Markforged Two printer was used to fabricate the specimens with 31.4 % fibre volume fraction. Rectangular fill pattern with 100 % fill density and 125 µm layer thickness was adopted in printing. The printed specimens met ASTM recommendations. The behaviour with tensile test on $[0]_{16}$ specimen was mostly linear with a brittle failure at 1.27 % of strain. The reported tensile modulus and tensile strength was 69.4 GPa and 905.3 MPa respectively. The failed specimens had longitudinal separations between the material beads and between layers. SEM images showed the presence of fibre pullouts, fibre breakage, and matrix fracture. Residues of matrix on pulled out fibres indicating proper fibre/matrix interfacial bonding was also observed. The compressive test on $[0]_{16}$ specimen also showed a linear curve with 0.69% failure strain. The reported compressive modulus and compressive strength was 63.9 GPa and 426 MPa respectively. The macroscopic images showed fibre kinking mechanism near the tab due to micro buckling of composite layers. Transverse tensile test gave 3.5GPa and 17.9 MPa respectively as modulus and strengths. The observed failure strain was around 0.6 % with brittle fracture. The fracture surface appeared along the fibre direction and showed localized matrix failure zones, fibre breakages, debonding and voids. Compressive tests gave 3.7GPa and 66MPa as modulus and strength respectively with over 5% failure strain. This is attributed to elasto-plastic behaviour of PA matrix. The failure during this test was mainly by micro buckling, layer delamination. In-plane shear test on $[\pm 45]_{4s}$ laminates showed the ductile nature of PA matrix with large strains. The reported strength was 61.5 MPa and shear modulus was 1.9 GPa. The fractured surface contained fibre breakage and pull out, shearing of beads, inter-layer delamination.

During SBS test small delaminations occurred between the load and support points in the area of maximum interlaminar shear stress. The averaged value noted was 37.9 MPa.DCB specimen used to evaluate mode I fracture toughness displayed linear load- deflection curve, with a slight deviation before fracture propagation. The obtained fracture toughness was 2 kJ/m^2. Debonded and fractured fibres were observed in these specimens. The ENF specimens' load-deflection curve was slightly non-linear. The reported fracture toughness was 1.59 kJ/m^2. Like mode I failure, debonded and fractured fibres, fibre imprints and matrix deformation and micro cracking were observed.

Hussein Alzyod et al.[8], employed a numerical solution to find correlation between printing parameters such as print orientation, raster angle, infill pattern on the residual stress of samples made of Acrylonitrile Butadiene Styrene (ABS) using Fused Deposition Modelling (FDM) process. The specimens were printed in horizontal, side and vertical directions, with raster angles 0^0, 45^0, 90^0 with infill consisting 0^0, 90^0 and zig-zag patterns. ANOVA, means and Signal to Noise (S/N) ratio graphs were used to calculate optimum values of the printing parameters. A L27 orthogonal array was utilised to identify significance level of various parameters. For S/N ratio, the response variable was residual stress with a minimum value. Finite Element Analysis was performed using Digi Mat -AM software. ANOVA based on 95% confidence level showed that printing orientation was the most significant factor with 66.7 % contribution for residual stress, followed by rater angle with 25% influence and infill pattern being the least significant factor with 0.13% contribution.

Kannan S. et al. [9], made a theoretical and experimental verification of frequency and deflection responses of 3D printed Carbon Fibre (CF) reinforced Polylactic Acid Composites (PLA) using Fused Deposition Modelling (FDM). The carbon fibreof 100 µm average length was the reinforcement. The specimens of PLA and PLA /CF were prepared, meeting ASTM standards. The specimens were horizontally printed with [+ 45^0, - 45^0] raster orientations, rectilinear fill pattern and 100 % fill density. The tensile test showed the modulus of 2880 MPa and a higher modulus of 3610 MPa for PLA/CF specimen. However, ultimate tensile strength of PLA/CF was 34.6 MPa while that of PLA was 42 MPa. Through morphology of the specimens using Field Emission Scanning Electron Microscope (FESEM), reinforcing CF increased voids. The frequency response analysis of the printed specimens was carried out to extract first three natural frequencies under Clamped-Free and Clamped-Clamped boundary conditions. The experiments brought out higher natural frequencies for reinforced specimens than neat PLA specimens due to increased stiffness of PLA/CF specimens. A parametric analysis using First Order Shear Deformation Theory (FSDT) based Finite Element method, under central concentrated load and uniformly distributed load with different end conditions, was also a part of the study, to evaluate the bending and vibration characteristics of the specimens. From the analysis, the results were in good agreement with the documented values in the reference paper. From this study it was also evident that the end conditions had no significant influence on vibration response of PLA/CF and neat PLA specimens. Increasing aspect ratio of specimens reduced the stiffness of specimens.

Hieu Tri Nguyen et al. [10], conducted experimental work performing modal analysis, vibration response analysis and characterization of Fused Deposition Modelling (FDM) additively manufactured Acrylonitrile Butadiene Styrene (ABS) parts. Specimens with layer thicknesses of 0.18 mm and 0.38 mm, skirt and raft adhesion types, and printing directions of 45^0 and 90^0 were printed. Tensile test was carried out on ASTM standard specimen to find mechanical properties including young's modulus, ultimate tensile test, yield strength and maximum strain. Modal analysis and frequency domain analysis were conducted in order to extract modal parameters including resonant frequency, dynamic modulus, damping coefficient. Inaddition, Scanning Electron Microscope (SEM) analysis was carried out to investigate microscopic structures. The stress-strain curve showed that skirt adhesion gave specimen higher ultimate tensile stress, yield strength and young's modulus as compared to raft adhesion. This was due to flattening of layers with skirt adhesion and thus allowing enhanced heat transfer, improved physical bonding of interlayer interface. Also, the skirt adhesion improved energy dissipation between the layers, higher damping coefficient and improved overall damping properties.

Behzad Rankouhi et al.[11], in their study considered layer thickness influence on mechanical characterization and failure analysis of 3D printed Acrylonitrile Butadiene Styrene (ABS) specimens printed using FDM. Nominal values of layer thickness considered for the study were 0.2 mm and 0.4 mm. The specimens were printed with raster orientations of 0^0, 45^0 and 90^0 and 100 % infill density. The graphs of ultimate tensile strength and elastic modulus showed 0^0 raster orientation putout highest values of these for both thicknesses, followed by 90^0 and 45^0. In particular, 0.2 mm layer thickness specimen displayed higher values of ultimate tensile strength(UTS) and young's modulus as compared to 0.4 mm specimens. This was due to lower air gap to material ratio. Regression models were built and ANOVA was used to analyse the effects of layer thickness and raster orientation on mechanical properties. ANOVA revealed that the layer thickness was the only parameter influencing the elastic modulus. For UTS, layer thickness and orientation along with their combinations were found to have influence. The microscopic inspection of the failed specimen displayed two main failure modes viz., inter raster fusion bond failure and trans-raster failure. These failure modes were independent of layer thickness and changed with raster orientation.

Fuda Ning et al. [12], made a comparative study on the effect of reinforcing chopped carbon fibre (CF) and graphite (GR) particles into Acrylonitrile Butadiene Styrene (ABS) matrix on porosity and tensile properties. The specimens were printed in horizontal direction with [0^0/90^0] and [+ 45^0/ - 45^0] raster angles by Fused Deposition Modelling (FDM) process. The fracture interface was observed using Field Emission Scanning Electron Microscope. Porosity was measured with Differential Scanning Calorimetry. From the porosity plot, it was found that reinforcing graphite reduces porosity compared to carbon fibre. The CF/ABS parts with [0^0/90^0] raster angle possessed higher tensile strength, young's modulus, and yield strength than [+ 45^0/ - 45^0] orientation because of a wider interaction region resulting in higher bonding strength.GR/ABS specimens had no influence of raster angle on tensile properties.

Vinyas Mahesh [13], experimentally investigated the dynamic response of additively manufactured glycol-modified polyethylene terephthalate (PETG) beams reinforced with organically modified montmorillonite (OMMT) nano clay (NC) and carbon fibre (CF) with different percentage combinations by weight of the reinforcements. The dynamic behaviour of PETG based composite beam with fixed ends and cantilever configuration was assessed by measuring natural frequencies, mode shapes and damping factors using Frequency Response Functions (FRF's). The first three natural frequencies namely bending, twisting and secondary bending with the two boundary conditions were evaluated. The frequency plots demonstrated that with 5% weight of NC addition to PETG increased the natural frequency as compared to 1% and 3% weight due to increased interface bonding with more void filling and higher layer adhesion. Compared to fixed end condition, the natural frequencies were less for cantilever beam. The damping factor increased with the addition of NC till 3% by weight, after which, it decreased. Also, the damping factor was larger in cantilever condition as against fixed end conditions. With the addition of CF to PETG increased fundamental natural frequency as compared to neat PETG. However, the damping factor decreases with 5% weight of CF as against neat PETG. But the damping ratio increased for 10% and 15% weight of CF. From the frequency plots, the addition of 3% OMMT to PETG + 5% CF increased fundamental natural frequency as compared to PETG + 5% CF. Further addition of NC and CF lead to increased natural frequencies.

II. CONCLUSION

In this review, the most commonly used 3D printing process of FDM to print polymers and fibre reinforced polymer composites has been reviewed to understand the current state of research in mechanical characterization and dynamic characterization of these. Though there are considerable number of studies focusing on evaluating mechanical properties are available, still the challenges posed by voids, distribution of fibres, understanding of failure mechanisms, influence of process parameters, optimization of parameters could serve as a beacon for future research. In particular, process parameters influence on dynamic behaviour of 3D printed composites is under explored. This further could draw attention of researchers to carryout inspections in this regard.

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