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A Non-Destructive Experimental-cum-Numerical Methodology for the Characterization of 3D-Printed Materials – Polycarbonate-Acrylonitrile Butadiene Styrene (PC-ABS)

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Abstract

With increasing prevalence of the use of 3D-printing, the structural integrity of these 3D-printed parts becomes a concern, especially if bulk properties are assumed in the design phase since 3D-printing usually results in material properties inferior to that of bulk properties. In this paper, we present an experimental-cum-numerical methodology for the characterization of 3D-printed polycarbonate-acrylonitrile butadiene styrene (PC-ABS). This paper investigates the effects of raster angle and orientations on the elastic properties of the Fused Deposition Modelling (FDM) printed PC-ABS material. The orthotropic elastic properties of PC-ABS material were determined by conducting ultrasonic testing, which is a non-destructive test method that allows us to deduce all the anisotropic elastic constants from the bulk density and the velocities of shear and longitudinal ultrasound wave propagating along different directions. Several tensile tests were also carried out to validate the ultrasonic tests, and these were generally in good agreement, with an average of 11% deviations. Next numerical verification was by comparing numerical finite element simulation results (using properties from ultrasonic testing) with experimental four-point bending test and impact hammer test, where excellent correspondence between the experimental and numerical data was observed. Further, scanning electron microscopes were utilized to analyze the fracture surface to understand the effects of the raster angles and orientations on the fracture behaviour and the microstructure of the FDM printed PC-ABS.

Keywords: Ultrasonic Testing; 3D-Printed PC-ABS; Orthotropic Properties; Numerical Finite Element Simulation; Additive Manufacturing.

1. Introduction

Additive Manufacturing (AM) is a new and emerging technological advancement in the field of engineering due to its highly adaptable manufacturing capabilities and ease of use. Often synonymous with AM, 3D printing reduces production costs and shortens manufacture times for complex prototype designs that would otherwise require expensive moulds and long fabrication periods (Baumers et al., 2016; Vashishtha et al., 2011). In order to adopt this technology in manufacturing structural components, the material properties which are highly dependent on the process parameter, need to be properly understood and characterized. However, there is limited report on the orthotropic properties of 3D printed materials, rendering them insufficient for designing structural components using numerical simulations.

Belonging to the material extrusion family in AM, Fused Deposition Modelling (FDM) involves the melting of the filament material and extruding it out at specific intervals and predetermined locations where it cools and solidifies. As the process of material deposition by the nozzle and extrusion head repeats itself on a layer by layer basis, this successive build-up of each layer eventually shapes the material into a final 3D object (Klippstein et al., 2017). Due to the additive nature of the FDM process whereby layers of material are built upon each other, the intrinsic material properties of a 3D printed object will be different from that of the material bulk properties. Within each layer, however, the fusion between the individual lines of extruded material (known as raster) is vastly different from that between layers and affects the material properties. As shown in Figure 1, the key FDM printing parameters include raster width, raster angle, layer thickness and air gap. Raster width refers to the width of the extruded material while raster angle is the angle of the raster with respect to the X-axis. Layer thickness, also known as slice height, is the height of each printed layer. Air gap is the amount of distance between two adjacent rasters. The air gap can be adjusted to zero air gap, positive air gap and negative air gap, this parameter would affect the inter-raster adhesion strength and the amount of porosity within the printed part, which in turn determining the strength of the printed part. Contour is the outline of a part; the number of contours and the contour width can be adjusted accordingly.

Part orientation plays a significant role in the mechanical properties_ (Odell et al., 2002; Onwubolu and Rayegani, 2014; Sood et al., 2012) (~~!!! INVALID CITATION !!! (Odell, Wright et al. 2002, Sood, Ohdar et al. 2012, Onwubolu and Rayegani 2014))~~, dimensional accuracy (Singh, 2014) and surface finish (Thrimurthulu et al., 2004). In addition, other building parameters in FDM, such as raster angle (Cantrell et al., 2017; Onwubolu and Rayegani, 2014; Sood et al., 2012; Wu et al., 2015), raster width (Onwubolu and Rayegani, 2014; Sood et al., 2012), layer thickness (Onwubolu and Rayegani, 2014; Sood et al., 2012; Wu et al., 2015) and air gap (Knoop et al., 2017; Onwubolu and Rayegani, 2014; Sood et al., 2012), also contribute to the anisotropy in material properties. Research on the anisotropic elastic properties has been carried out on many FDM-printed materials including acrylonitrile butadiene styrene (ABS) (Dawoud et al., 2016; Sood et al., 2010), polylactic acid (PLA) (Chacón et al., 2017; Odell et al., 2002) and polycarbonate (PC) (Cantrell et al., 2017; Domingo-Espin et al., 2015). However, there is limited research on polycarbonate-acrylonitrile butadiene styrene (PC-ABS), which is a commonly used industrial thermoplastic for automotive and electronics applications.

Figure 1. FDM printing parameters.

The elastic properties of orthotropic 3D printed materials are commonly determined by mechanical testing, namely the tensile and shear testing, of materials built in different orientations (Cantrell et al., 2017; Domingo-Espin et al., 2015). Non-destructive ultrasonic testing is another technique to characterize the anisotropic elastic constants of materials that do not have a fixed shape or have constraints in the size of specimens. Typically used for characterizing bones, rocks and other composites, this well-established technique can deduce all the anisotropic elastic constants from the bulk density and the velocities of shear and longitudinal ultrasound wave propagating along different directions through a single specimen (Cheeke, 2012; Peralta et al., 2017; Qiao et al., 2011; Van Buskirk et al., 1981; Yann et al., 2006).

This paper aims to characterize the elastic properties of the 3D printed PC-ABS material using the non-destructive ultrasonic testing. Mechanical testing was also carried out to corroborate some of the ultrasonic testing results and to understand the material properties beyond the yield point of the PC-ABS material. In addition, fractography analysis was performed to understand the relationship between the fracture mechanism and the orientation or raster. Lastly, numerical verification was performed with the four-point bending test and the impact hammer test. Using the orthotropic elastic properties obtained from ultrasonic test, there was excellent agreement between experimental and finite element simulation results.

2. Theoretical Basis

2.1 Orthotropic Constitutive Model

The elastic properties of a material can be described by the generalized Hooke's Law, relating stresses to strains by

$$\sigma_i = c_{ij}\epsilon_j \quad (1)$$

For an orthotropic material, the stiffness matrix, c_{ij} , has nine independent elastic constants

$$[c_{ij}] = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{bmatrix} \quad (2)$$

The strain-stress relationships of an orthotropic material can be written in terms of a compliance matrix s_{ij} such that $\epsilon_i = s_{ij}\sigma_j$

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} & 0 & 0 & 0 \\ s_{12} & s_{22} & s_{23} & 0 & 0 & 0 \\ s_{13} & s_{23} & s_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \quad (3)$$

$$[S_{ij}] = \begin{bmatrix} \frac{1}{E_1} & \frac{-v_{21}}{E_2} & \frac{-v_{31}}{E_3} & 0 & 0 & 0 \\ \frac{-v_{12}}{E_1} & \frac{1}{E_2} & \frac{-v_{32}}{E_3} & 0 & 0 & 0 \\ \frac{-v_{13}}{E_1} & \frac{-v_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (4)$$

From symmetry of the compliance matrix

$$\frac{v_{12}}{E_1} = \frac{v_{21}}{E_2}; \quad \frac{v_{13}}{E_1} = \frac{v_{31}}{E_3}; \quad \frac{v_{23}}{E_2} = \frac{v_{32}}{E_3} \quad (5)$$

2.2 Ultrasonic Wave Velocity and Elastic Constants

The components in the stiffness matrix given in Equation (2) can be shown to be directly related to wave velocities passing through the material. The following equations, derived by Mason (1956) and subsequently used by Van Buskirk et al. (1981), show the relationships for the various components

$$c_{11} = \rho v_1^2 \quad (6)$$

$$c_{22} = \rho v_2^2 \quad (7)$$

$$c_{33} = \rho v_3^2 \quad (8)$$

$$c_{44} = \rho v_{23}^2 = \rho v_{32}^2 \quad (9)$$

$$c_{55} = \rho v_{13}^2 = \rho v_{31}^2 \quad (10)$$

$$c_{66} = \rho v_{12}^2 = \rho v_{21}^2 \quad (11)$$

$$c_{12} = \sqrt{(c_{11} + c_{66} - 2\rho v_{12/12}^2)(c_{22} + c_{66} - 2\rho v_{12/12}^2)} - c_{66} \quad (12)$$

$$c_{13} = \sqrt{(c_{11} + c_{55} - 2\rho v_{13/13}^2)(c_{33} + c_{55} - 2\rho v_{13/13}^2)} - c_{55} \quad (13)$$

$$c_{23} = \sqrt{(c_{22} + c_{44} - 2\rho v_{23/23}^2)(c_{33} + c_{44} - 2\rho v_{23/23}^2)} - c_{44} \quad (14)$$

$$c_{55} + c_{66} = 2\rho v_{23/1}^2 \quad (15)$$

$$c_{44} + c_{55} = 2\rho v_{13/2}^2 \quad (16)$$

$$c_{44} + c_{55} = 2\rho v_{12/3}^2 \quad (17)$$

where v_i denotes the velocity of a longitudinal wave in direction i ; v_{ij} the velocity of transverse wave travelling in direction i , with particle displacements in direction j ; $v_{ij/k}$ the velocity of a transverse wave travelling in direction $(i+j)/2$ with particle displacements in direction k ; and $v_{ij/ij}$ the velocity a transverse or longitudinal wave travelling in direction $(i+j)/2$ with particle displacements in the i - j plane. Velocities are quasi-longitudinal or quasi-transverse, and ρ represents the density of the material.

It is to be noted that Equations (15) to (17) are not used directly in the derivation of the constants, but rather serve as checks for the assumption of orthotropy.

3. Experimental Testing Procedures

3.1 Raster Configurations

The specimens were printed using Stratasys Fortus 450mc fitted with T12 model and support tips, which could produce slice height of 0.1778 mm. Other build parameters are listed in Table 1.

Table 1. Build Parameter of PC-ABS.

Raster width (mm)	Contour width (mm)	Slice height (mm)	Air gap (mm)
0.3556	0.3556	0.1778	0

Two types of raster, namely the 0° raster and the alternating layers of $0^\circ/90^\circ$ were investigated in this paper, the raster layouts are illustrated in Figure 2. These two types of raster were chosen because the 0° raster represents the narrow and thin-walled components whereby they must be printed with only several contours that are unidirectional as shown in Figure 2(a) while alternating layers of $0^\circ/90^\circ$ as shown in Figure 2(b), was used to characterize the orthotropic properties of the default alternating $+45^\circ/-45^\circ$ raster setting for printing any components.

For ultrasonic testing specimens as shown in Figure 3, the specimen follows the coordinate system of X_1 , X_2 and X_3 , which correspond to the typical 3D printing coordinate system of X, Y and Z. The 0° raster is set to be parallel to the X_1 axis.

The tensile specimens were built in 3 orientations, where the longitudinal direction of the tensile specimen is aligned to the 3D printer's X-, Y- and Z-axes. The alternating $0^\circ/90^\circ$ raster in X- and Y-orientations are assumed to be transversely isotropic because the 0° raster and 90° raster are identical with 90° rotation. Hence, $E_1 = E_2$. Therefore, only 2 orientations, X and Z, are needed to be tested to calculate for the elastic constants for this configuration.

It is to be noted that while X- and Y-axes are considered to be indifferent for a FDM printer, the raster direction, in this case, determines the orientation of our specimens. Specimen with 0° raster parallel to the longitudinal direction of the tensile specimen is denoted as X- 0° . On the other hand, specimen with 0° raster orthogonal to the longitudinal direction of the tensile specimen is identified as Y- 0° .

Figure 2. Raster configuration: (a) 0° and (b) $0^\circ/90^\circ$ with alternating layer of 0° and 90° raster.

3.2 Ultrasonic Testing

3.2.1 Ultrasonic Testing Procedures

The elastic characterization of orthotropic material can be achieved through measuring the wave velocities in different direction of the orthotropic materials. Typically, the ultrasonic samples have to be cut in various directions to allow access to all constants. In this paper, instead of creating one specimen containing all symmetrical faces as shown in Figure 3(a) (Van Buskirk et al., 1981), two types of specimens, cubic and oblique specimens, as shown in Figure 3 (b)- (d), were designed to allow the wave propagation in various directions. These specimens not only ensure that the distances across any two planes are constant, the specimen can also be printed more efficiently with lower material consumption. Based on the chosen transducers and the wave attenuation, both specimens were designed with a constant thickness of 10 mm, and surface area that is able to fit the transducer. The cubic specimen in Figure 3(b) was used to measure v_i and v_{ij} while the oblique specimen in Figure 3(c) and 3(d) has faces with unit normal $n_1 = \pm(e_1 + e_2)/\sqrt{2}$, $n_2 = \pm(e_1 + e_3)/\sqrt{2}$ and $n_3 = \pm(e_2 + e_3)/\sqrt{2}$, was used to measure $v_{ij/k}$ and $v_{ij/ij}$.

Two specimens of cubic and oblique specimens were built for each raster. The thickness of each specimen was measured using a vernier calliper before carrying out the ultrasonic test. Mass of the PC-ABS specimens was measured using an electronic weight balance and the density was obtained by dividing the mass by the volume of specimen. The average density of PC-ABS was found to be 1.024 g/cm³.

Figure 3 (a) Ultrasonic testing specimen adapted from (Van Buskirk et al., 1981), (b) the actual cubic specimen used for measuring v_i and v_{ij} , (c) the actual oblique specimen used for measuring $v_{ij/k}$ and $v_{ij/ij}$, (d) the oblique specimen showing three faces with unit normal $n_1 = \pm(e_1 + e_2)/\sqrt{2}$, $n_2 = \pm(e_1 + e_3)/\sqrt{2}$ and $n_3 = \pm(e_2 + e_3)/\sqrt{2}$.

The pulsed transmission technique was used to measure the ultrasonic wave velocities. MultiX-LF low-frequency parallel system with 16 channels and Multi2000 software were used in this study. Following the pioneering works of Lang (1970) and Van Buskirk et al. (1981), a 5MHz single element longitudinal wave transducer capable of generating and receiving the longitudinal waves were used together with GE ultrasonic testing couplant ZG-F. The wave velocity can be obtained from the time-of-flight of the first back wall echo and the specimen thickness. On the other hand, a pair of 2.25MHz shear wave transducers was used to transmit and receive the transverse waves directly into the test specimen. The ultrasonic velocity can be calculated from the time delay of the propagation between the transmitted and received waves, and the specimen thickness.

3.2.2 Ultrasonic Testing Results of PC-ABS

The wave velocities measured are presented in Table 2. Using Equations (6-14), the stiffness coefficients can be derived using the wave velocities measured. The elastic constants were then calculated using Equation (4), using the inverse of the stiffness matrix. Elastic properties of PC-ABS in raster 0° and $0^\circ/90^\circ$ are shown in Table 3. From the ultrasonic results in Table 3, $E_1 \approx E_2$, $G_{13} \approx G_{23}$, and $\nu_{13} \approx \nu_{23}$, it is confirmed that $0^\circ/90^\circ$ configurations are transversely isotropic as expected.

A trend can be concluded for all waveforms is that when the ultrasonic wave is propagating along the direction of a raster, the waveform is smooth and clear. On the other hand, when the ultrasonic wave is propagating across the rasters, there were small peaks before and after the back wall echo due to the presence of air gaps.

Table 2. Measured wave velocities for 0° and $0^\circ/90^\circ$ raster configurations (unit in m/s).

Raster	V ₁	V ₂	V ₃	V ₂₃	V ₁₃	V ₁₂	V _{12/12}	V _{13/13}	V _{23/23}
0°	1914	1667	1667	749	778	772	1800	1800	1667
$0^\circ/90^\circ$	1794	1786	1747	766	769	775	1790	1771	1767

Table 3. Mean elastic constants for raster 0° and $0^\circ/90^\circ$.

Elastic Constant	0°	$0^\circ/90^\circ$
E_1 (GPa)	1.94	1.71
E_2 (GPa)	1.53	1.69
E_3 (GPa)	1.55	1.65
G_{23} (GPa)	0.58	0.60
G_{13} (GPa)	0.62	0.61
G_{12} (GPa)	0.61	0.62
ν_{12}	0.455	0.385
ν_{21}	0.361	0.381
ν_{31}	0.351	0.377
ν_{13}	0.438	0.392
ν_{23}	0.34	0.393
ν_{32}	0.344	0.382

In determining the elastic properties through ultrasonic testing, one concern that may arise is the directionality of density used in the calculations. Due to the printing orientation, the different faces of the ultrasonic testing specimens may possess different densities, which may lead to varying results. Therefore, in addition to the cubic specimens, small rectangular plates (Figure 4) of different printing orientations, representing the different faces of the cubic specimens, were printed separately to determine the significance of density variation with printing orientation.

The densities of each small rectangular plate were measured and are summarized in Table 4. Between the 0° and $0^\circ/90^\circ$ rasters, the average densities vary by less than 0.4. Within each raster, the densities of individual plates show very small variations in density of 0.7% to 1.3% standard deviation from the respective average densities. The differences seen here are within experimental error and hence do not have significant effects on the orthotropic properties.

It is to be noted that due to the terms in the stiffness matrix being coupled after matrix inversion of the compliance matrix, it is not possible to apply different density values for each of the density terms from Equations (6) to (17).

Figure 4. Small rectangular plates with different print orientations.

Table 4. Densities for specimens printed in various orientations, given in g/cm^3 .

Specimen orientation	0°	0°/90°
1	1.013	1.012
2	0.990	1.011
3	1.023	1.027
12	1.019	1.022
23	1.000	1.009
13	1.018	1.010
Average (std. dev.)	1.011 (1.3%)	1.015 (0.7%)

Comparing with the average density value of 1.024 g/cm³ reported in Section 3.2.1 and used in calculation of values, the average density of the small rectangular plates are about 1% lower. The difference is due to the differences of raster and contour present in the cubic specimens and the rectangular plate specimens, which results in different amounts of air gap present and hence the densities. However, this difference in density is insignificant in the calculation of the orthotropic properties, as shown in Table 5.

Table 5. Orthotropic elastic constants with different values of density used.

	0°			0°/90°		
	$\rho = 1.024$	$\rho = 1.011$	Deviation	$\rho = 1.024$	$\rho = 1.015$	Deviation
	g/cm ³	g/cm ³	(%)	g/cm ³	g/cm ³	(%)
E ₁ (GPa)	1.94	1.91	1.3	1.71	1.70	0.4
E ₂ (GPa)	1.53	1.51	1.1	1.69	1.68	0.4
E ₃ (GPa)	1.55	1.53	1.2	1.65	1.62	1.9
G ₂₃ (GPa)	0.58	0.57	2.2	0.60	0.60	0.7
G ₁₃ (GPa)	0.62	0.61	1.3	0.61	0.60	1.5
G ₁₂ (GPa)	0.61	0.60	1.2	0.62	0.61	1.6
ν_{12}	0.455	0.455	0.0	0.385	0.389	-1.0
ν_{21}	0.361	0.36	0.3	0.381	0.385	-1.0
ν_{31}	0.351	0.351	0.0	0.377	0.371	1.6
ν_{13}	0.438	0.438	0.0	0.392	0.391	0.3
ν_{23}	0.34	0.341	-0.3	0.393	0.392	0.3
ν_{32}	0.344	0.345	-0.3	0.382	0.377	1.3

3.3 Supplementary Mechanical Testing

3.3.1 Mechanical Testing Procedures

To corroborate some of the ultrasonic testing results, we carried out some mechanical testing for the Young's Modulus, where 5 specimens for each orientation and each raster were designed, built and tested according to the ASTM D638 Standard Test Method for Tensile Properties of Plastics, where the specimen geometry follows the Type I specifications, as shown in Figure 5(a). The tensile tests were performed using Shimadzu AGS-10kNX universal testing machine with a crosshead displacement rate of 1 mm/min. Axial displacement was measured using Shimadzu TRview x55s, a non-contact video extensometer.

In addition, rectangular bars with dimensions of 165 mm × 20 mm × 3.2 mm as shown in Figure 5(b) were printed for determining the Poisson's ratio using the strain gauge GFCA-3-350-70. The TDS-303 portable data logger was used to measure the axial and transverse strain during the elastic tensile loading. For every orientation and every raster, 5 specimens were printed and strain measurements were repeated 3 times for every specimen. Instead of finding all the six Poisson's ratios, only ν_{12} , ν_{31} and ν_{23} are required for the 0° raster because of the symmetry of the compliance matrix as shown in Equation 5. For 0°/90° raster, only two Poisson's ratios, ν_{12} and ν_{31} , are needed.

Figure 5. Dimensions of specimen: (a) ASTM D638 Type I tensile specimen, (b) strain gauge specimen.

3.3.2 Tensile Testing Results of PC-ABS

The mean and standard deviation of the Young's Modulus, yield strength, elongation at yield, ultimate tensile strength and maximum elongation are presented in Table 6. The stress-strain curves of these configurations are also shown in Figure 6.

As expected, the X-orientation exhibited the highest tensile properties. For the X-0°/90° configuration, the tensile load is split equally between the bonding within the raster itself and the adhesion between the individual rasters. Thus, a lower Young's modulus and yield strength are expected from the X-0°/90°. When subjected to a tensile load, the adhesion between adjacent raster within a layer in the Y-0° configuration bears most of the load unlike in the X-orientation, where either all or some of the load is borne by the material itself. Hence Y-0° configuration has lower tensile properties than the X-orientation because of its weaker raster-to-raster bonding. SEM images of the fractured surfaces of the specimens, as shown in Figure 7, show how the rasters are bonded to adjacent rasters and their arrangement across layers (Z-direction). Despite having porosity within the X-0° configuration, the axial loads applied onto the X-0° specimens were transferred through the raster by having a clean fracture. By examining the fracture surfaces of the 0° fibres in the X-0°/90° specimens as shown in Figure 7(c), the 0° fibres had a different failure mode as compared to X-0°.

Z-orientation was found to possess the weakest mechanical properties, and this is likely due to the weak inter-layer bonds bearing the tensile load. As opposed to the inter-raster adhesion acting as the main loading mechanism in the Y orientation, the inter-layer adhesion in the Z-orientation is weaker. The layers are only fused together after the entire layer has been printed and cooled down in the Z-orientation, whereas the inter-raster bonds are formed immediately after the material is extruded from the nozzle for the Y-orientation. Hence, the tensile properties for the Z-orientation specimens are expected to be the lowest among all orientations. Micrographs of the Z-orientation specimens as shown in Figure 8(a) have reflected that the interlayer bonding is relatively weak since the fracture surfaces are smooth and had no significant features to show significant plastic deformation. Between the Z-0° and Z-0°/90° configurations, the latter demonstrated better mechanical properties overall, with a larger Young's Modulus and a higher maximum yield strength. This behaviour may be ascribed to the difference in the inter-layer bonding present in both specimens. An initial look at the 0°/90°

raster pattern in the Z direction revealed that there is a more effective overlap between the layers compared to the Z-0° configuration, as shown in Figure 8(b). As observed in Figure 8(b), the criss-cross overlap arising from the 0°/90° raster pattern results in a stronger inter-layer bond adhesion compared to a simple build-up of layers in one direction. Hence, the Z-0°/90° configuration will exhibit a higher tensile strength than the Z-0° configuration as the loading interface (inter-layer adhesion) is stronger.

Figure 6. Average stress-strain curves for specimens with different orientations and raster configurations.

Table 6. Means and standard deviations of Young's modulus, yield strength, elongation at yield, ultimate tensile strength and maximum elongation for each orientation and raster.

Orientation- Raster	Young's Modulus (GPa)	Yield Strength (MPa)	Elongation at yield (%)	Ultimate Tensile Strength (MPa)	Maximum elongation (%)
X-0°	2.20 ± 0.07	38.9 ± 0.8	1.98 ± 0.09	44.7 ± 0.6	2.78 ± 0.03
X-0°/90°	1.88 ± 0.04	25.3 ± 0.7	1.58 ± 0.06	28.0 ± 0.4	1.88 ± 0.03
Y-0°	1.79 ± 0.05	20 ± 1	1.23 ± 0.09	20 ± 1	1.23 ± 0.09
Z-0°	1.24 ± 0.08	12 ± 1	1.08 ± 0.04	11 ± 1	1.0 ± 0.1
Z-0°/90°	1.54 ± 0.07	15 ± 1	1.08 ± 0.09	15 ± 1	1.08 ± 0.09

(a)

(b)

Figure 7. SEM images showing the fractured surfaces of specimens with raster configurations of (a) X-0°, (b) Y-0° and (c) X-0°/90°.

Figure 8. SEM images showing the fractured surfaces of specimens with raster configurations of (a) Z-0° and (b) Z-0°/90°.

The elastic constants extracted from the tensile test are shown in Table 7. For 0°/90° configuration, only 4 elastic constants were needed because of the raster symmetry.

Table 7. Mean elastic constants and standard deviations for raster 0° and 0°/90° from by tensile testing.

Elastic Constant	0°	0°/90°
E_1 (GPa)	2.20 ± 0.07	1.88 ± 0.04
E_2 (GPa)	1.79 ± 0.05	-
E_3 (GPa)	1.24 ± 0.08	1.54 ± 0.07
ν_{12}	0.384 ± 0.007	0.34 ± 0.01
ν_{31}	0.32 ± 0.04	0.36 ± 0.02
ν_{23}	0.391 ± 0.002	-

3.4 Correspondence of Elastic Constants from Ultrasonic Testing with Tensile Testing

Figure 9 shows the comparison of the elastic constants obtained from tensile test and ultrasonic test. As shown in Figure 9(a) and 9(c), elastic moduli, E_1 and E_2 , obtained from tensile tests are consistently higher than that obtained from ultrasonic tests, while E_3 has an opposite correlation from E_1 and E_2 . This could be due to the difference in the density of the specimen when printed in varying orientations. As seen from Figure 6 and Figure 7, the amount of porosity varies due to the raster angle and the printing orientations. However, the value of density used was calculated from the average density of cubic and oblique specimens. Hence this results in the discrepancy in the trend of Young's moduli and Poisson's ratios for different orientations. In addition, the 5.3% – 20% difference between the ultrasonic and mechanical elastic constants could also be associated with the viscoelastic behaviour of the PC-ABS material. This discrepancy could be due to the very slow strain rate used in the tensile test (0.0017 s^{-1}) as compared to the dynamic strain rate used in the ultrasound wave propagation.

Figure 98. Comparison of the elastic constants obtained from tensile test and ultrasonic test: (a) Elastic moduli for 0° raster; (b) Poisson's ratio for 0° raster; (c) Elastic moduli for $0^\circ/90^\circ$ raster; (d) Poisson's ratio for $0^\circ/90^\circ$ raster.

4. Numerical verification through finite element simulation

In addition to comparison with properties obtained from tensile tests, numerical verification was carried out using the four-point bending test and the impact hammer test. Test specimens were printed in $45^\circ/-45^\circ$ raster for both tests. Thereafter, using the orthotropic linear elastic properties obtained for the $0^\circ/90^\circ$, coordinate transformation was performed using an in-house code (Joshi and Toh, 2011) to obtain equivalent linear elastic properties for a $45^\circ/-45^\circ$ raster as the material property of the specimen.

4.1. Four-point bending test

Figure 10 shows the experimental set-up and the dimensions of the four-point bending test specimen.

Figure 10. Experimental set up of four-point bending test and dimensions of test specimens.

The experimental procedure was performed until failure of the specimen, which exhibited a large amount of plastic deformation prior to failure at about 40 mm displacement. In the simulation, the specimen was loaded till 10 mm displacement to simulate the response within the linear elastic region. Figure 11(a) and Figure 11(b) show the deformed shapes of the specimen as observed in the experiment and predicted by finite element model while Figure 11(c) shows the deformed specimen when it was loaded to 30 mm during the experiment.

Figure 11. (a) Deflection of the specimen at 10 mm in the experiment, (b) deflection of the model at 10 mm in simulation, (c) deflection of the specimen at 30 mm in the experiment.

Figure 12 shows a comparison of the experimental and numerical response of the specimen under the four-point bending test, illustrating excellent correlation between both sets of results. This shows that the properties used in the simulation, which were obtained from the ultrasonic tests, were in good agreement with reality.

Figure 12. Comparison of experimental and finite element results of the four-point bending test.

4.2. Impact hammer test

In addition to the four-point bending test, a separate $45^\circ/-45^\circ$ raster beam specimen with 30 cm length was used for the modal analysis for comparison with finite element results. Figure 13 shows the two orientations of the beams tested for mode shapes in different orientations. The accelerometer was placed in the middle of the beam during both tests.

Figure 13. Impact hammer test of beam specimen in (a) normal orientation, and (b) lateral direction.

Figure 14 shows the FRF for the $45^\circ/-45^\circ$ beam specimens, obtained in two orientations. The peaks illustrated in Figure 14(a), correspond to bending mode shapes in the normal orientation and the peaks in Figure 14(b) corresponding to bending mode shapes in the lateral orientation.

(a)

(b)

(c)

Figure 14. FRF for 45° - 45° raster beam for all three mode shapes detected. (a) and (c) depict the FRF from the normal orientation for the first and third modes, while (b) shows the FRF from the impact hammer test from the lateral orientation for the second mode.

It is seen from Figure 14 that there are a total of three mode shapes present in the beam specimen for the frequency range of 0 Hz to 500 Hz, corresponding to three unique natural frequencies. These natural frequencies, which are highly sensitive to changes in mass and stiffness, were then compared with modal analysis results using finite element simulation. Table 8 consolidates and compares the natural frequencies of the beams obtained experimentally and through finite element, which show excellent agreement.

Table 8. Comparison of natural frequencies obtained experimentally (as seen in Figure 14) and numerically.

Mode	Type	Expt	FE
1	Normal bending	31.02	30.16
2	Lateral bending	88.13	89.289
3	Normal bending	191.96	190.71

Figure Figure 15 shows the first four mode shapes obtained from the modal analysis, showing that Modes 1 and 3 are normal bending modes, Modes 2 is a lateral bending mode and Mode 4 corresponds to a torsional mode shape. These results are in tandem with the FRF, where normal bending modes and lateral bending modes are captured separately in the two FRFs, whereas torsional mode is not captured in either. It is to be noted, however, that the torsional mode shape obtained through finite element was not obtainable through the impact hammer test.

Figure 15. First four mode shapes of beam specimen obtained from FE modal analysis for $45^\circ/-45^\circ$ raster beam.

Both the four-point bending test and the impact hammer test have shown excellent agreement between experimental and numerical results, which gives us confidence that the material properties obtained through the characterization were close to reality.

5. Conclusion

A non-destructive experimental-cum-numerical methodology for the characterization of 3D-printed materials has been successfully demonstrated on FDM printed PC-ABS. This dual-pronged strategy of coupling ultrasonic testing with numerical finite element simulation ensures reliable accuracy in determining the material properties, which are inferior to bulk properties, and thus have to be accurately determined. The effects of raster angle and orientations on the elastic properties of the 3D-printed PC-ABS material were investigated through both experimental ultrasonic testing and numerical finite element simulation. It was found out that raster and orientations have significant influence on the mechanical properties of the FDM printed PC-ABS. When the specimen is printed in the X-orientation and 0° raster, the elastic modulus and yield strength are the highest among the 3 orientations and 2 raster configurations. On the contrary, PC-ABS has weak interlayer bonding as the mechanical properties for the Z-orientation specimen are the lowest. Comparing the elastic constants from ultrasonic testing and tensile testing, the disparity in the results are not too significant and both follow similar trends in their elastic moduli and Poisson's ratios. More importantly, the properties obtained through ultrasonic testing were also verified by comparison with finite element simulation, where specimens of $45^\circ/-45^\circ$ raster

were subjected to the four-point bending test and impact hammer test. This work has demonstrated the effectiveness of using non-destructive ultrasonic testing to obtain the elastic properties of 3D printed materials.

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