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The influence of layer height in the orthotropic elastic properties of PLA material obtained by additive processes

Luís Gonçalves[a], Gonçalo Couto[a], Armando Ramalho[a,b,*]

[a] *Polytechnic Institute of Castelo Branco, 6000-767, Castelo Branco, Portugal*
[b] *CEMMPRE, University of Coimbra, 3030-790, Coimbra, Portugal*

Abstract

Polylactic acid (PLA) is a biodegradable thermoplastic polyester used extensively in 3D printing, that can be obtained from renewable resources with low production costs and low carbon emissions. The extrusion temperature of PLA is lower, and its tensile strength and elastic modulus are higher than that of other common polymeric thermoplastic materials.
To assess the structural integrity of parts obtained by additive manufacturing, especially in more complex geometries, the finite element method is extensively used, being necessary, for this purpose, to characterize the constitutive model of the material. From the printer manufacturing parameters, one of the most affecting the elastic and strength properties is the layer height.
The layer-by-layer slicing sequence of additive manufacturing processes can introduce anisotropy into the materials, whereby, in most applications, materials obtained by these processes are considered orthotropic. The mechanical characterization of anisotropic materials through classical tests is not always the most suitable for this purpose, given the economic aspects, the time required, precision requirements and, sometimes, the technological difficulties of the tests. The ASTM E1876-21 standard presents a method for determining the dynamic elastic properties of materials by impulse excitation of vibration, at room temperature.
In this article, the influence of the layer height in the dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio obtained by impulse excitation of vibration (ASTM E1876-21 standard), of Tough PLA is analyzed.

Keywords: Additive manufacturing; Dynamic elastic properties; Anisotropy; Layer height

* Corresponding author. Tel.: +351-272-339-600.
E-mail address: aramalho@ipcb.pt

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1. Introduction

The use of additive processes in the manufacture of prototypes and structural components, or machine parts, had a great growth in the last decade. The availability of low-cost 3D printers, the use of materials optimized for this type of manufacturing, from renewable sources and with low environmental impact, the readiness in moving from design to production associated with direct digital manufacturing, have contributed to the rapid expansion of this manufacturing method, especially when unique or customizable models or small series are desired, Cojocaru et al. (2022).

Polylactic acid (PLA) is a biodegradable thermoplastic polyester used extensively in 3D printing, that can be obtained from renewable resources with low production costs and low carbon emissions. The extrusion temperature of PLA is lower, and its tensile strength and elastic modulus are higher than that of other common polymeric thermoplastic materials, Cojocaru et al. (2022).

The use of such resistant and rigid thermoplastics, including their reinforcement with short fibres, allowed the expansion of the 3D printed components in areas with more important structural requirements. To assess the structural integrity of parts obtained by additive manufacturing, especially in more complex geometries, the finite element method is extensively used, being necessary, for this purpose, to characterize the constitutive model of the material, Ramalho et al. (2023).

Nyiranzeyimana et al. (2022), Wang et al. (2020), Doshi et al. (2022), have studied the effect of printing parameters on the mechanical properties of materials in components obtained by fused filament fabrication (FFF). Of the printer's parameters, one that has profound influence on the mechanical properties of the deposited materials is the layer height.

The layer-by-layer slicing sequence of additive manufacturing processes can introduce anisotropy into the materials, whereby, in most applications, materials obtained by these processes are considered orthotropic, Song et al. (2017).

In most studies, the characterization of materials obtained by FFF is done using classic tensile and shear tests, ASTM D638 and ASTM D5379/D5379M/D3518. In the layer plane the material is considered elastic orthotropic and in the packing direction it is considered transversely isotropic elastic, Song et al. (2017).

The mechanical characterization of anisotropic materials through classic tests is not always the most suitable for this purpose, given the economic aspects, the time required, precision requirements and, sometimes, the technological difficulties of the tests. The ASTM E1876-21 standard presents a method for determining the dynamic elastic properties of materials by impulse excitation of vibration, at room temperature.

In the literature, there are some studies that apply the impulse excitation technique to characterize the elastic properties of isotropic materials, Barboni et al. (2018), although the ASTM E1876-21 standard also applies it in anisotropic materials.

In this article is presented the influence of the layer height in the dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio obtained by impulse excitation technique, of Tough PLA components obtained by FFF.

2. Methodology

2.1. Materials and specimens

To obtain the dynamic elastic properties of orthotropic materials of parts manufactured by additive processes, right rectangular prism specimens were 3D printed.

The material used was the Tough PLA from Ultimaker.

The specimens were manufactured with the Ultimaker S5 printer with the following manufacturing parameters: the samples were printed in the XY plane, using a 0.4 mm AA print core, 100% infill without wall line neither top/bottom layers, a 215°C nozzle temperature, a glass build plate heated at 85°C and a print speed of 30.0 mm/s. Three layer heights were used: 0.10, 0.15 and 0.20 mm.

Following the procedure used by Casavola et al. (2016), Song et al. (2017), Chacón et al. (2017) and Reverte et al. (2020) in the mechanical characterization of 3D-printed PLA using classic tensile and shear tests, to characterize the orthotropic properties of Tough PLA, four type of specimens were constructed, for each layer thickness, with the orientation and raster angles indicated in Fig.1.

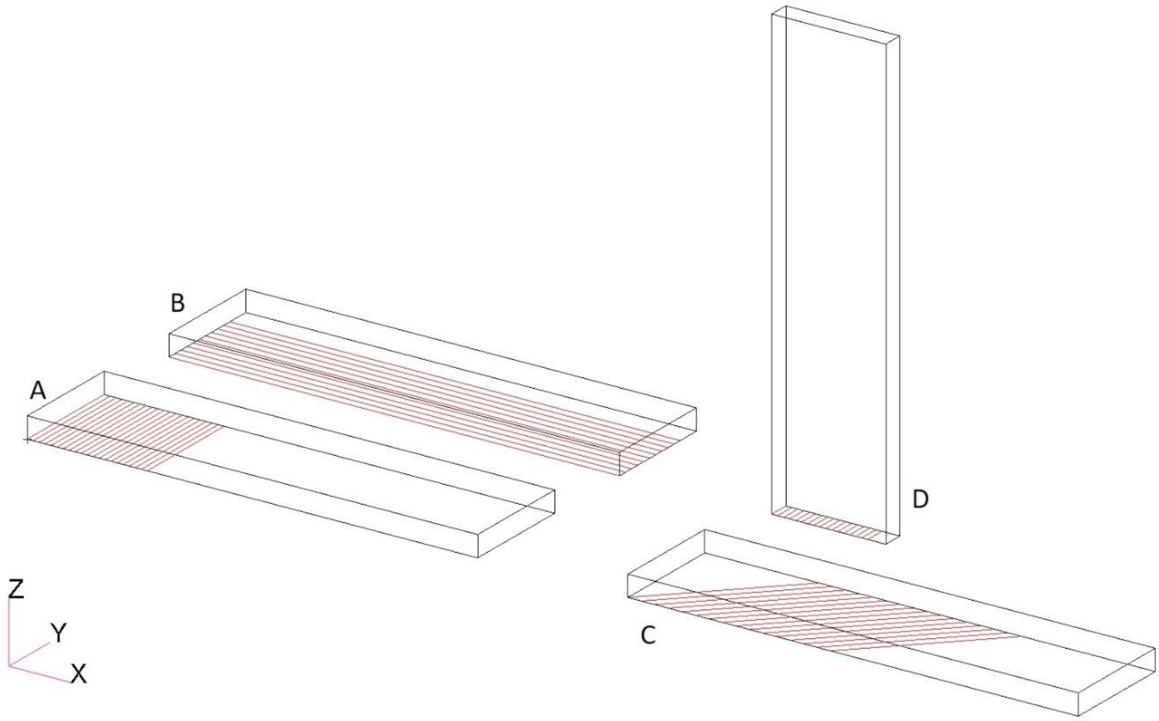

Fig. 1. Orientation and raster angles of the four types of manufactured specimens.

As specified by Lord and Morrell (2006), in impulse excitation method an accurate control of test-piece dimensions, geometry and form should be assured. Machining of the faces of the test-pieces should be carried out carefully to ensure flatness and parallelism to better than 0.3%. Surface roughness should be as high a quality as practically possible, since this can affect the accuracy in the measured test-piece dimensions and the subsequent calculation of modulus. A smooth surface is desirable, and a standard engineering finish should be considered as the minimum specification.

Attending these requirements, in this study all the ends of the specimens were removed by grinding with sandpaper, to ensure the desired surface finish and to remove the effect of variation in the printing direction. The length, L, and width, w, of each specimen were obtained by the mean of three measures taken at the extremes and middle sections with a micrometer. The thickness, t, was obtained by the mean of nine measures taken at the extremes and middle sections with a micrometer, and in each section three measurements are also taken at its ends and middle. All measurements were obtained in compliance with the variance and precision requirements imposed by the ASTM E1876-21 standard.

2.2. Characterization of the material elastic properties by impulse excitation method

The impulse excitation method is well established and widely used for the determination of the dynamic elastic properties of a large diversity of materials (metals, ceramics, and plastics). This method is supported in ASTM standards, ASTM E1876-21 and ASTM C1259-98. The method consists of promoting a vibration by impact and obtaining the natural frequencies of the excited mode of vibration.

Knowing the vibrational mode’s frequency, dimensions, and mass of the specimens, it is possible to compute the elastic modulus of the materials.

For a prismatic specimen, there are three vibration modes of interest: Out-of-plane flexural; Torsional; Longitudinal.

The main vibrational modes used to characterize the elastic properties of small and thin specimens are the out-of-plane flexural and the torsional. In these tests, the specimens are placed on supports located at the nodes corresponding to the respective fundamental vibrations, a signal transducer is placed, preferably close to the antinode points, to collect data on the vibratory movement, and the impact is made in the center of the specimen for the flexural test and in the quadrant opposite the transducer for the torsion test, as represented in Fig. 2a and 2b respectively. The impact on the specimen should be done lightly and elastically. To strike the specimen a flexible polymer rod with a glued steel ball was used.

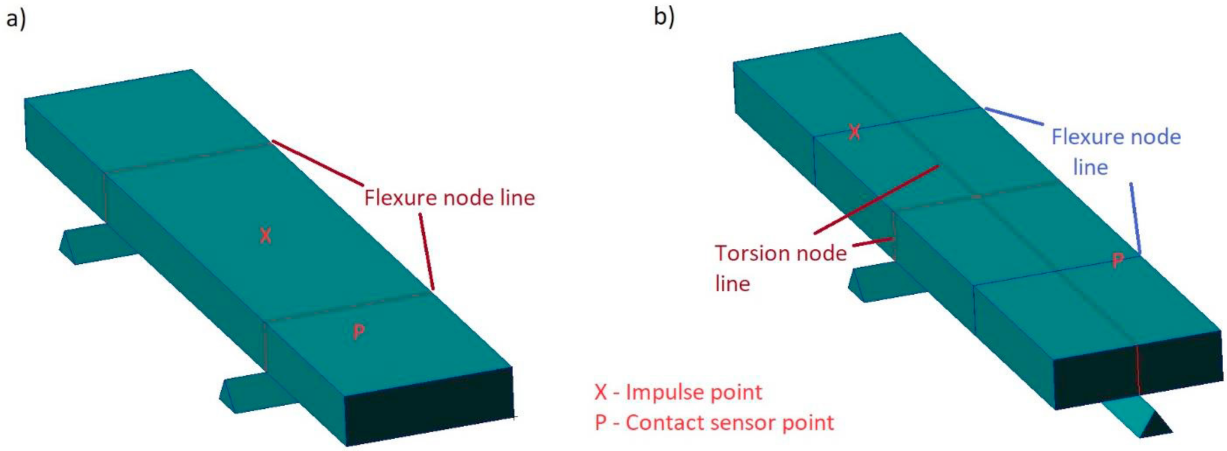

Fig. 2. Schematic representation of the test specimens (a) out-of-plane flexural vibration mode; (b) torsional vibration mode.

For the flexural mode, the Young’s modulus is calculated by the equation (1).

$$E = 0.9465\left(\frac{m\,f_f^2}{w}\right)\left(\frac{L^3}{t^3}\right)T \qquad (1)$$

where *m, L, t*, and *w* are respectively the mass, length, thickness, and width of the prismatic specimen, f_f is the first frequency in bending, and *T* is a correction factor depending on the Poisson’s ratio and the dimensions of the specimen.

Attending to the used specimen's dimensions, when $L/t > 20$, the *T* parameter can be simplified by the equation (2).

$$T = 1.000 + 6.585\left(\frac{t}{L}\right)^2 \qquad (2)$$

In the torsion mode, the Shear modulus is calculated by the equation (3).

$$G = \frac{4Lmf_t^2}{wt}\left[{}^{B}\!/_{(1+A)}\right] \qquad (3)$$

where f_t is the first frequency in torsion, and *A* and *B* are factors depending on the dimensions of the specimen, calculated by equations (4).

$$A = \frac{\left[0.5062 - 0.8776\left(^{w}/_{t}\right) + 0.3504\left(^{w}/_{t}\right)^{2} - 0.0078\left(^{w}/_{t}\right)^{3}\right]}{\left[12.03\left(^{w}/_{t}\right) + 9.892\left(^{w}/_{t}\right)^{2}\right]}$$

$$B = \left[\frac{\left(^{w}/_{t}\right) + \left(^{t}/_{w}\right)}{4\left(^{t}/_{w}\right) - 2.52\left(^{t}/_{w}\right)^{2} + 0.21\left(^{t}/_{w}\right)^{6}}\right] \quad (4)$$

2.3. Experimental set-up and tests

The specimens were placed on suitable supports for torsion and out-of-plane flexural tests, as shown in Fig. 3. The vibration movement in time was collected through a thin piezoelectric disc contact transductor, that works by bimorph effect. The generated electric signal (the voltage) was collected on the PicoScope 3204A. The collected signal was processed by Fourier transform algorithm to obtain the values of the natural frequencies of vibration.

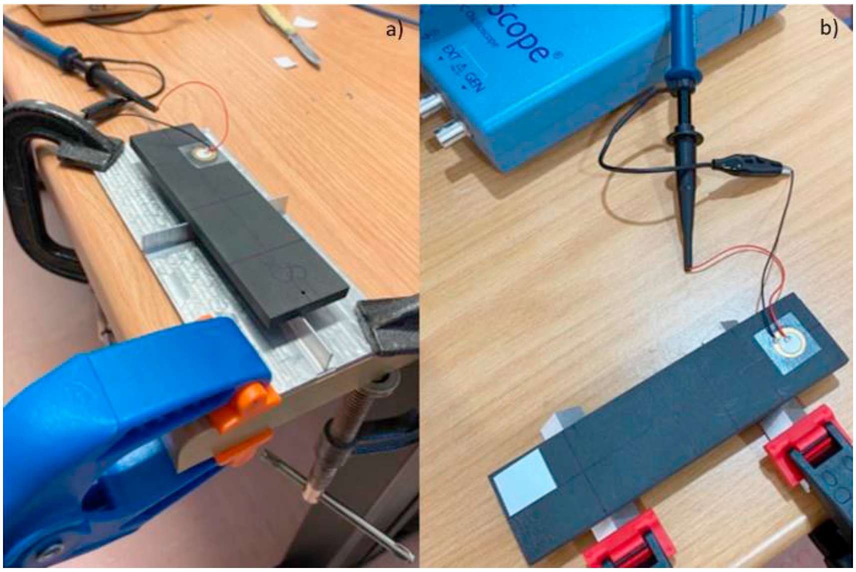

Fig. 3. Experimental set-up (a) torsional vibration mode; (b) out-of-plane flexural vibration mode.

As for the mechanical characterization of anisotropic materials through classic tests, Casavola et al. (2016), Song et al. (2017), from the impulse excitation technique applied in the out-of-plane flexural mode on specimens A and B (Fig. 1) were obtained the Young's moduli on the deposition layer in the extrusion direction, the 1st (E_{11}), on its perpendicular, the 2nd (E_{22}) respectively. Using the same excitation mode on specimen D (Fig. 1) it was obtained the Young's modulus in the staking direction, the 3rd (E_{33}).

From the impulse excitation technique, applied in the out-of-plane flexural mode on specimen C (Fig. 1), the Young's modulus on the deposition layer in the longitudinal direction (E_{45}) was obtained. Applying this technique in the torsional mode on the same specimen, the Shear modulus in the 1-2 plane (G_{12}) was obtained.

The impulse excitation technique applied in the torsional mode on the specimen D was used to obtain the Shear modulus in the 2-3 plane (G_{23}) and the corresponding Poisson's ratio (ν_{23}) in transverse isotropic conditions, Song et al. (2017).

The elastic moduli obtained in the 1-2 plane was used in equation (5), Hennessey et al. (1965), to obtain the corresponding Poisson's ratio (ν_{12}).

$$\nu_{12} = \frac{E_{11}}{2}\left(\frac{1}{G_{12}} - \frac{4}{E_{45}} + \frac{1}{E_{22}} + \frac{1}{E_{11}}\right) \quad (5)$$

3. Results and discussion

In Tables 1, 2 and 3 are presented the dimensions and masses of the specimens, with the layer heights of 0.1, 0.15 and 0.20 mm, respectively. In these tables are also presented the obtained fundamental resonant frequencies of the specimens, obtained for the out-of-plane flexural and the torsional modes. The specimens are identified by their manufacturing orientation (Fig. 1), followed by the layer height.

Table 1. Characteristics of specimens tested for the 0.10 mm layer height.

Specimen	Raster angle	L [mm]	b [mm]	t [mm]	m [gr]	f_f [Hz]	f_t [Hz]
A-0.10	[90]	165.30	36.76	6.43	41.30	319.87	879.64
C-0.10	[45]	165.40	36.80	6.03	40.97	339.86	899.64
B-0.10	[0]	164.98	37.35	5.33	39.36	339.86	919.63
D-0.10	[90]	168.10	33.53	6.14	40.41	339.86	919.63

Table 2. Characteristics of specimens tested for the 0.15 mm layer height.

Specimen	Raster angle	L [mm]	b [mm]	t [mm]	m [gr]	f_f [Hz]	f_t [Hz]
A-0.15	[90]	133.22	33.43	5.94	35.09	560.00	1059.80
C-0.15	[45]	133.44	37.21	6.01	35.19	558.00	1119.90
B-0.15	[0]	134.37	36.41	5.92	33.83	520.00	1099.80
D-0.15	[90]	168.10	33.53	6.14	40.41	339.86	919.63

Table 3. Characteristics of specimens tested for the 0.20 mm layer height.

Specimen	Raster angle	L [mm]	b [mm]	t [mm]	m [gr]	f_f [Hz]	f_t [Hz]
A-0.20	[90]	166.80	37.01	5.80	39.86	299.86	749.67
C-0.20	[45]	166.30	37.33	5.86	41.05	299.86	849.62
B-0.20	[0]	166.19	37.80	5.73	40.58	349.84	749.67
D-0.20	[90]	168.52	36.03	5.99	41.23	349.84	949.62

Using the characteristics of the specimens presented in Tables 1, 2 and 3, through the equations (1) to (5) the dynamic orthotropic elastic properties of the Tough PLA material obtained by extrusion based additive manufacturing were computed. These elastic properties are presented in Table 4.

Table 4. Dynamic orthotropic elastic properties for the Tough PLA material.

Layer height	E_{11} [GPa]	E_{22} [GPa]	ν_{12}	ν_{23}	G_{12} [GPa]	G_{23} [GPa]	E_{33} [GPa]
0.20	2.180	3.034	0.270	0.242	0.821	1.189	2.952
0.15	2.785	3.512	0.323	0.279	1.032	1.151	2.945
0.10	1.852	3.418	0.320	0.407	1.166	0.958	2.697

When the dynamic Young's moduli at the deposition plane were compared, it is verified that the value of E_{11} (in the deposition direction) is significantly lower than the value of E_{22} (in the transverse direction of deposition). This result is in agreement with those obtained by Song et al. (2017), but their absolute values are not comparable, because this author uses PLA and a higher deposition speed, Khosravani and Reinicke (2020). Therefore, to validate the results obtained for the dynamic elastic properties of the Tough PLA, classic tensile tests are currently underway using specimens machined from those used in impulse excitation tests.

In Fig. 4a, the variation with the layer height of the longitudinal elastic moduli, E_{11}, E_{22}, and E_{33} is represented, and the Shear moduli, G_{12} and G_{23}. In Fig. 4b, the variation of Poisson's ratios (ν_{12} and ν_{23}) with the layer height is represented.

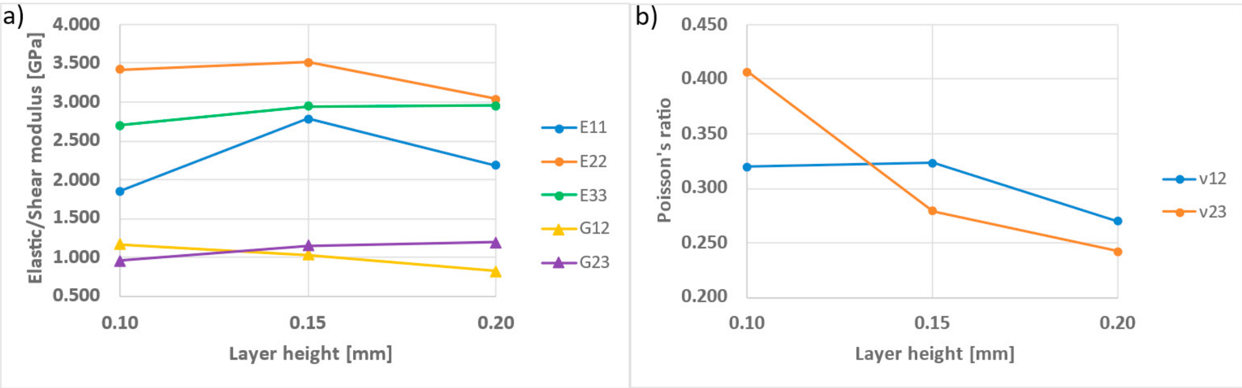

Fig. 4. (a) Elastic moduli as a function of layer height; (b) Poisson's ratios as a function of layer height.

From the analysis of the results presented in the graphs in Fig. 4, a well-defined trend in the variation of the dynamic orthotropic elastic properties of the Tough PLA with layer height is not observed. Thus, it appears that the Poisson's ratios and the Shear moduli at the deposition plane show a decreasing trend as the layer thickness increases. For the Young's modulus and the Shear modulus in the staking direction (axis 3), the opposite trend is observed. Regarding Young's modulus in the deposition plane, it is observed an increase followed by a decrease as the layer height grows up.

The dynamic elastic properties vary with the density of materials and the layer height have profound influence on the porosity of the 3D printed PLA, Song et al. (2017). Consequently, the obtained results may have been influenced by the variation in porosity. Microtomography analysis is currently being conducted to investigate this hypothesis.

4. Conclusions

The impulse excitation technique is a simple and effective method to identify the elastic properties of orthotropic Tough PLA obtained by extrusion based additive manufacturing.

The Young's moduli at the material deposition plane in the deposition direction and in their transverse direction, as well as in-plane Shear modulus, were obtained applying this method.

The Young's and elastic shear modulus in the staking direction were obtained too.

The proposed methodology allows to directly obtain the Poisson's ratios of orthotropic materials.

The advantage of this method is the minimal preparation of the experimental set-up, short measurement time and the utilization of inexpensive equipment.

From the analysis of the results obtained for the elastic properties of orthotropic Tough PLA, a well-defined trend in the variation of the dynamic orthotropic elastic properties of the Tough PLA with layer height is not observed.

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