

13th
ICKEM
2023

Istanbul, Türkiye | March 24-26, 2023

2023 The 13th International Conference on
Key Engineering Materials

**Measuring the dynamic elastic
properties of anisotropic materials to
characterize the mechanical
behaviour of products manufactured
by additive processes**

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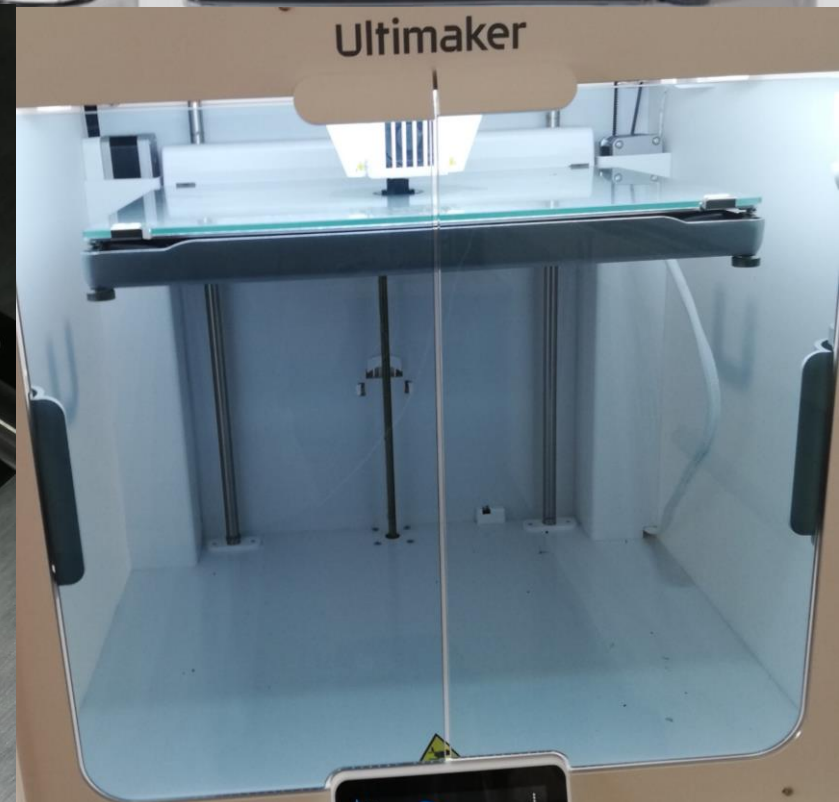
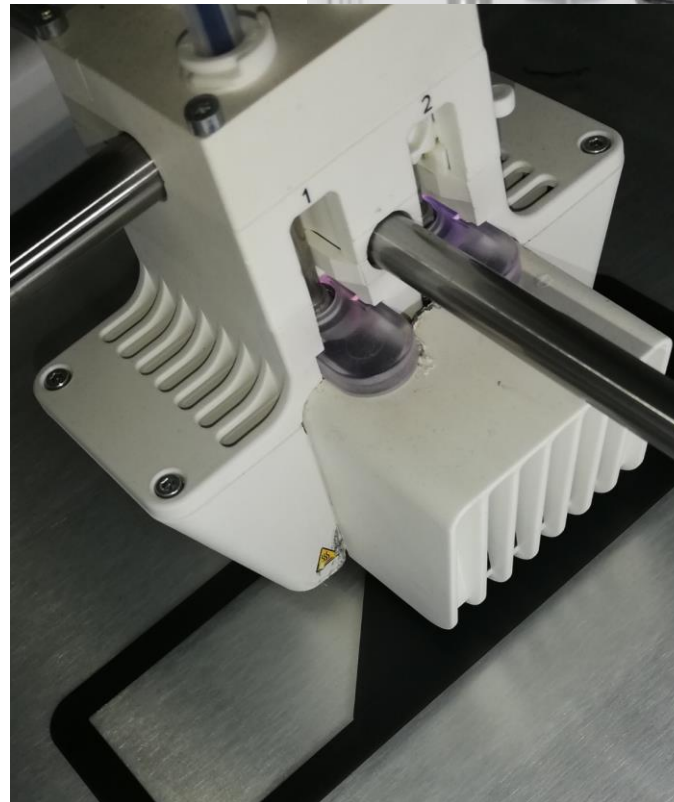
Summary

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- Anisotropy in 3D printing processes
- Characterization of the elastic properties of isotropic materials by impulse excitation method
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- Simulation of the mechanical behaviour of 3D printed parts
- Conclusions



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 layer-by-layer slicing sequence of 3D printing processes is prone to introducing anisotropy into the materials;
- The mechanical characterization of anisotropic materials through classical tests is not always the most suitable for this purpose;
- The ASTM E1876 standard [1] presents a method for determining the dynamic elastic properties of materials by impulse excitation method;
- This communication will present the adaptation of the methodology of the ASTM E1876 to obtain the dynamic Young's Modulus, Shear Modulus and Poisson's Ratio by impulse excitation of orthotropic materials obtained by 3D printing.

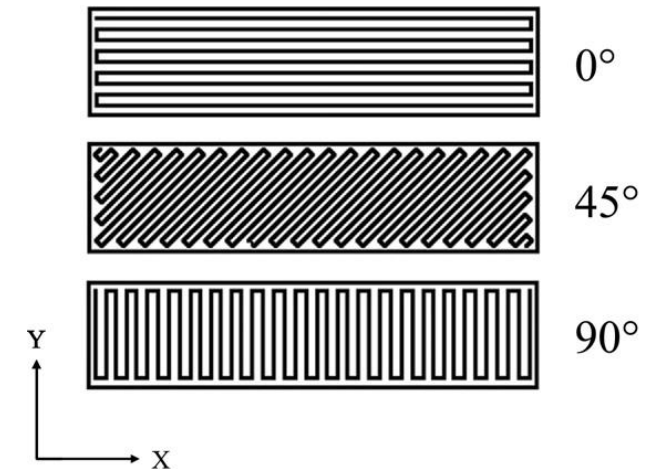
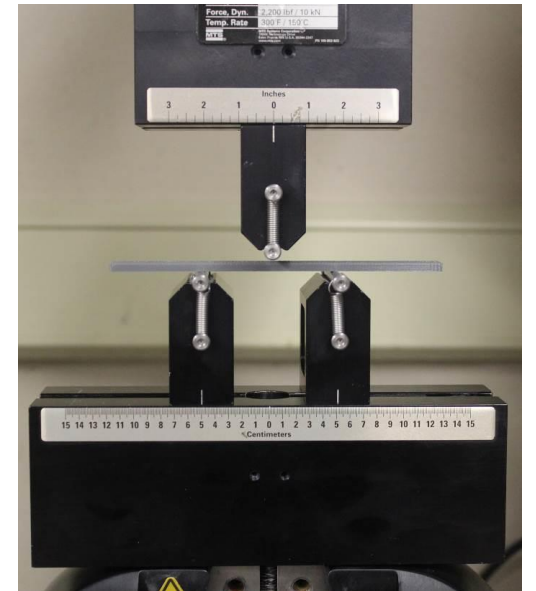
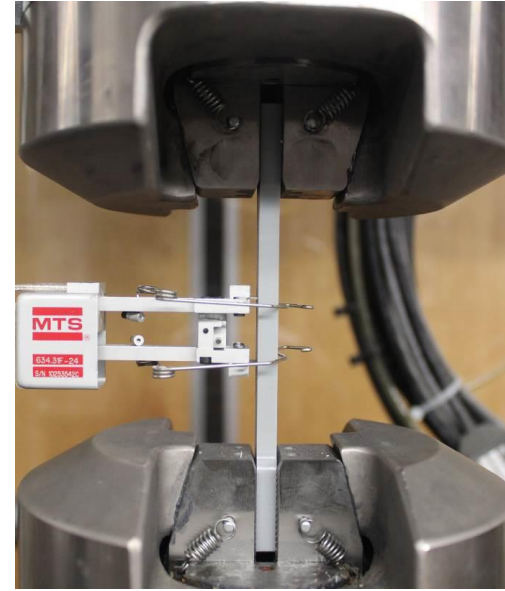


Anisotropy in 3D printing processes

There are some works in the literature that address the anisotropy of components manufactured by additive processes. In the field of 3D printing stands out the following works, in which classical methods are applied, using tensile and three-point bending tests of selected specimens:

- Y. Song, Y. Li, W. Song, K. Yee, K.-Y. Lee, V.L. Tagarielli, Measurements of the mechanical response of unidirectional 3D-printed PLA [2];
- T. Letcher and M. Waytashek, Material Property Testing of 3D Printed Specimen in PLA on an Entry Level 3D Printer [3];
- S.-H. Ahn, M. Montero, D. Odell, S. Roundy, P. K. Wright, Anisotropic material properties of fused deposition modeling ABS [4].

In these works, specimens with three raster orientation directions – 0°, 45° and 90° – were tested.



Characterization of the elastic properties of isotropic materials by impulse excitation method

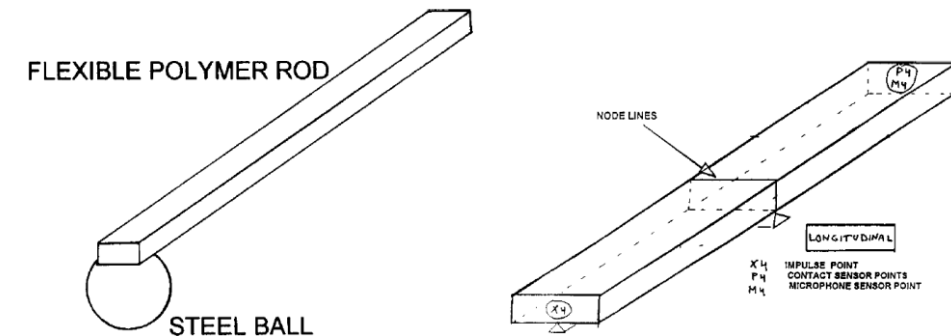
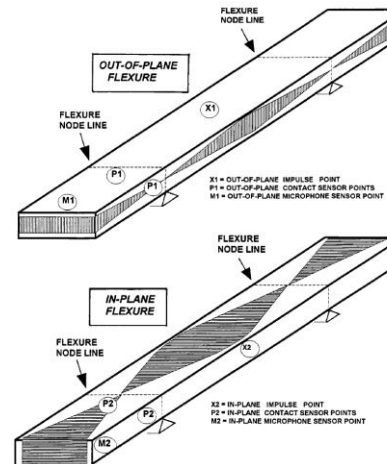
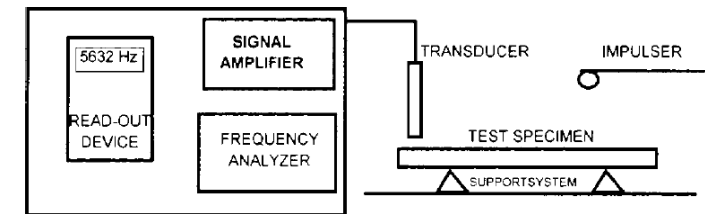
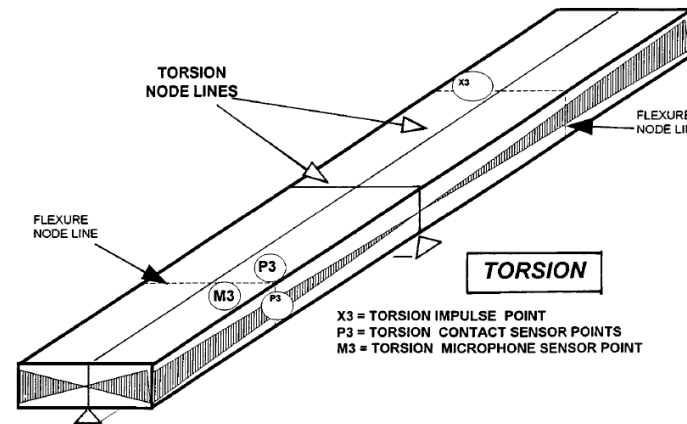
The impulse excitation method is well established and widely used for the determination of the dynamic elastic properties of a large diversity of materials (metals, ceramics and plastics). This method is supported in ASTM standards, ASTM E1876 [1] and ASTM C1259 [5]. The method consist of promoting a vibration by impact, and in obtaining the natural frequencies of the excited mode of vibration.

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

For a prismatic specimen, there are basically four vibration modes of interest:

- Out-of-plane flexural
- In-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.



Characterization of the elastic properties of isotropic materials by impulse excitation method

For the flexural mode, the Young's modulus is calculated by the following equation:

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

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.

The T parameter is computed by the following expression:

$$T = 1 + 6.585 (1 + 0.0752 \mu + 0.8109 \mu^2) (t/L)^2 - 0.868 (t/L)^4 - \left[\frac{8.340 (1 + 0.2023 \mu + 2.173 \mu^2) (t/L)^4}{1.000 + 6.338 (1 + 0.1408 \mu + 1.536 \mu^2) (t/L)^2} \right]$$

where μ is the Poisson's ratio. When $L/t \geq 20$, T can be simplified by:

$$T = 1.000 + 6.585 (t/L)^2$$

Characterization of the elastic properties of isotropic materials by impulse excitation method

In the torsional mode, the Shear modulus, G , for a prismatic bar, is calculated by the following equation:

$$G = \frac{4 L m f_t^2}{b t} [B / (1 + A)]$$

where m , L , t and b are respectively the mass, length, thickness and width of the prismatic specimen, f_t is the first frequency in torsion and B and A are factors depending on the dimensions of the specimen.

The factor B is calculated by the following equation:

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

The empirical correction factor A is calculated by the following equation:

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

Characterization of the elastic properties of isotropic materials by impulse excitation method

Generally the accuracy in modulus data from the dynamic test is of the order of 1%, but it is affected by a number of factors. To obtain high quality data there are a number of recommendations to consider, including:

- Accurate control of test-piece dimensions, geometry and form. The thickness of the beam, which enters into the equations as the third power, is probably the most important factor affecting the accuracy and reliability of the results.
- 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 practical as 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.

Characterization of the elastic properties of anisotropic materials by impulse excitation method

There are few works in the literature that address the use of the impulse excitation method to characterize the elastic properties of orthotropic materials. We only identified two articles that present works in which Young's modulus and shear modulus of composite materials are obtained:

- P. Y. Akishin, E.N. Barkanov, M. Wesolowski, E.M. Kolosova, Static and dynamic techniques for non-destructive elastic material properties characterization [6];
- Y. Ivanova, T. Partalin and I Georgiev, Comparison of NDT Techniques for Elastic Modulus Determination of Laminated Composites [7].

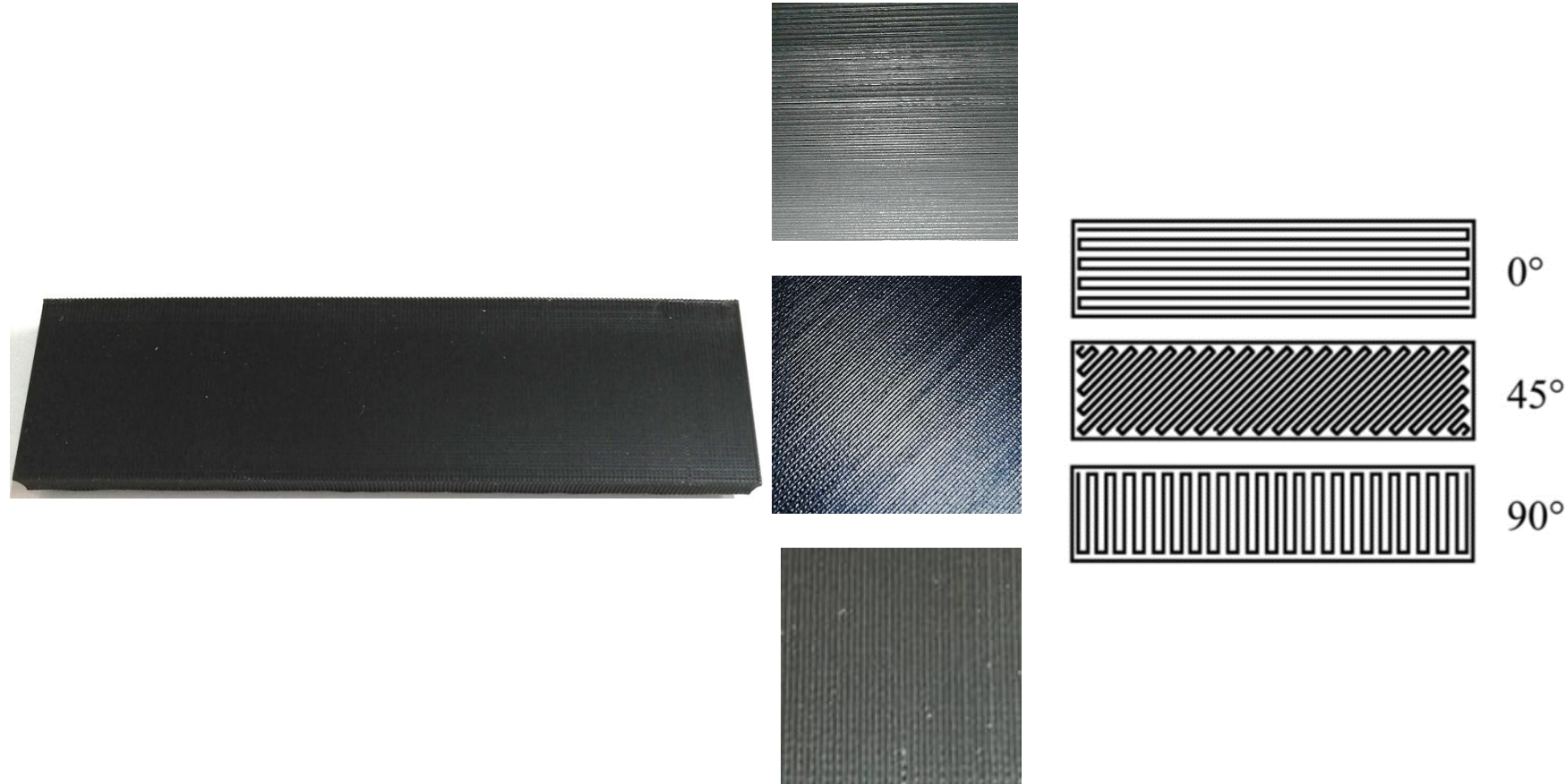
In these works, the Poisson's ratios are not obtained by the impulse excitation method.

In this speech we propose a methodology to obtain the dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by impulse excitation method, of materials obtained by 3D printing. The characterization of the elastic properties of orthotropic materials using tensile tests, presented in [2] and shear test in [8] is adapted to the impulse excitation method.

Characterization of the elastic properties of anisotropic materials by impulse excitation method

Materials and specimens

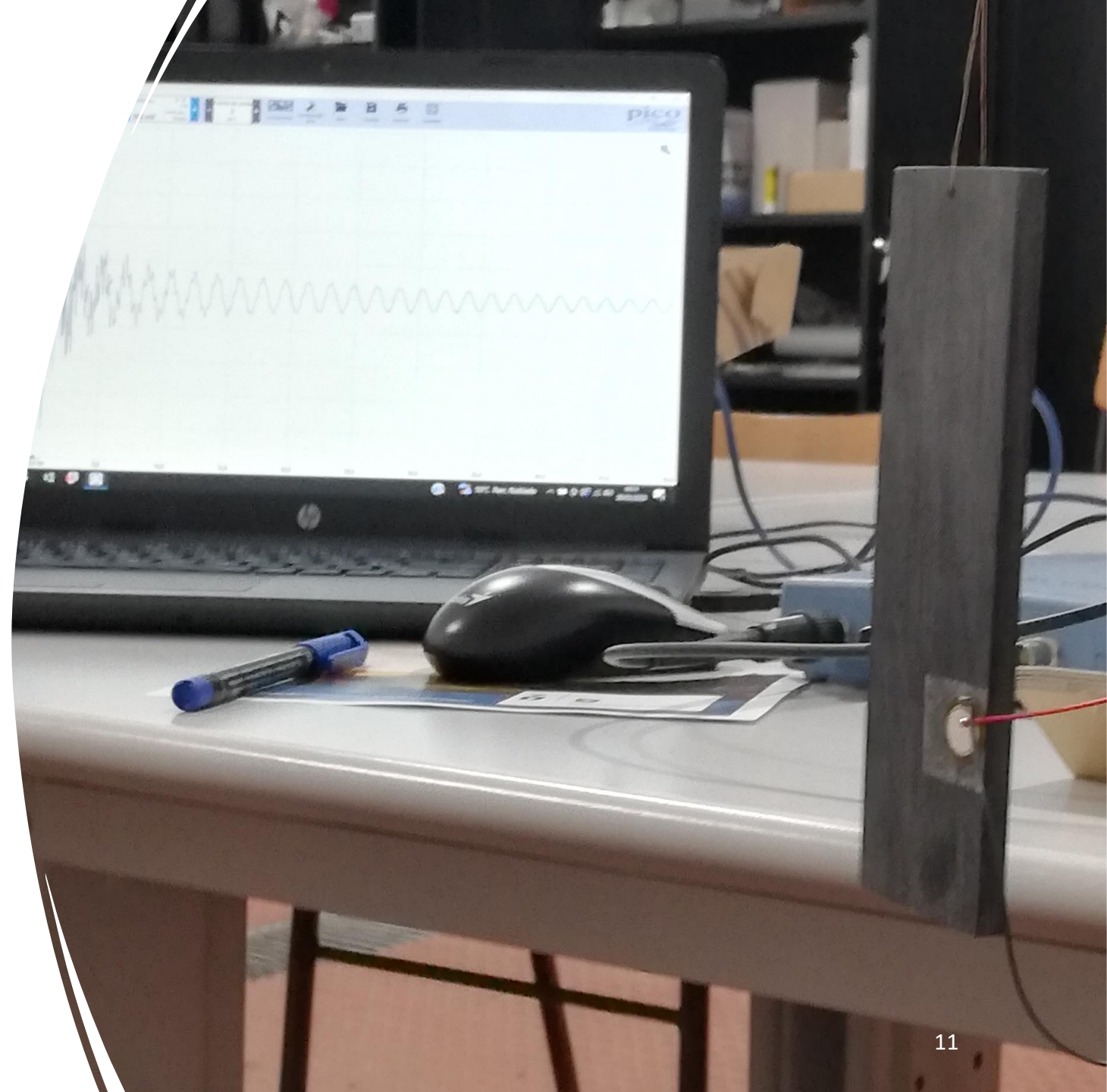
- To obtain the dynamic elastic properties of orthotropic materials of parts manufactured by additive processes, right rectangular prism specimens were 3D printed.
- The used material was the **Tough PLA** from Ultimaker.
- Were used the **Ultimaker S5 printer** with the following manufacturing parameters: the samples were printed in the XY plane, using the standard quality profile, a 0.4 mm AA print core, 100% infill, 0.15 mm layer height, without wall line neither top/bottom layers, a 215 °C nozzle temperature, a build plate temperature of 85°C, a print speed of 30.0 mm/s, a line infill pattern with tree raster angles of 0°, 90° and 45°/-45° corresponding to the tree types of manufactured specimens.
- All the ends of the specimens were removed by grinding with sandpaper, to ensure the desired surface finish and remove the effect of variation in the printing direction.



Characterization of the elastic properties of anisotropic materials by impulse excitation method

Experimental set-up

- The specimens were suspended by a thin flexible wire and allowed to vibrate freely.
- It was used a thin piezoelectric disc contact transducer, that works by bimorph effect.
- The electric signal was collected on the PicoScope 3204A.
- The collected signal was processed by Fourier transform algorithm in order to obtain the values of the natural frequencies of vibration.

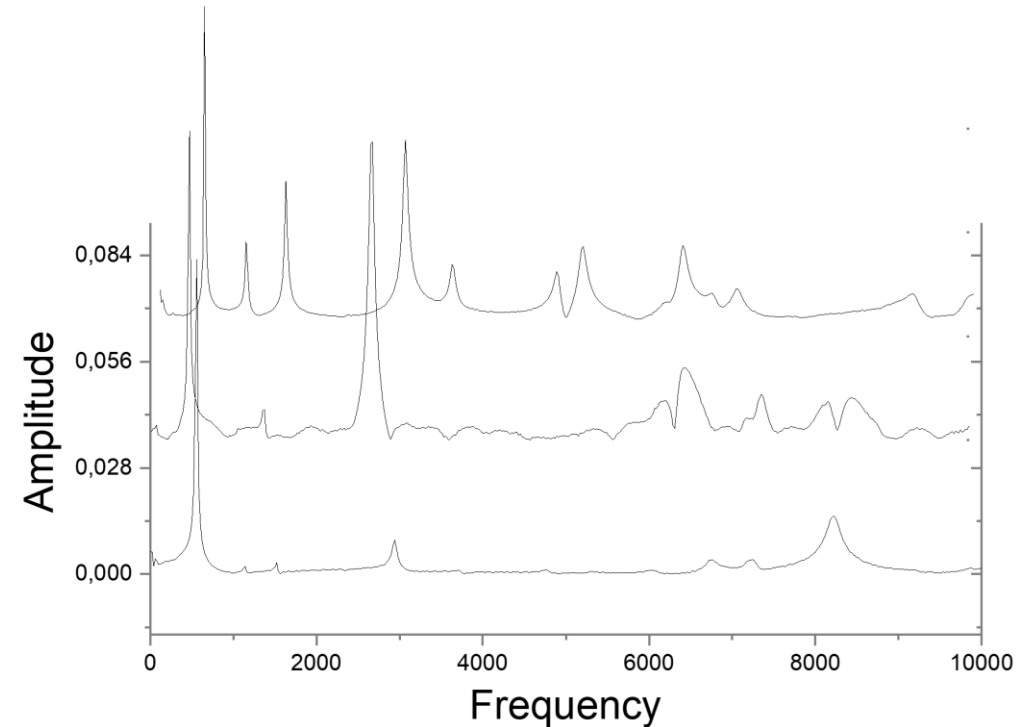


Characterization of the elastic properties of anisotropic materials by impulse excitation method

Experimental tests

- As in literature [6, 7], from the impulse excitation mode applied in the out-of-plane flexural mode on the specimens with 0° and 90° raster angles where obtained the Young's moduli in the extrusion direction, the 1 (E_{11}) and on its perpendicular, the 2 (E_{22}) respectively.
- From the impulse excitation mode applied in the out-of-plane flexural mode on the specimen with 45°/-45° raster angles were obtained the Young's modulus in the longitudinal direction (E_{45}).
- From the impulse excitation mode applied in the torsional mode on the specimen with 45°/-45° raster angles were obtained the Shear's modulus in the 1-2 plane (G_{12}).
- Given that the axis of orthotropy is the 3 axis, the impulse excitation mode applied in the torsional mode on the specimens with 90° raster angle was used to obtain the Shear's modulus in the 2-3 plane (G_{23}) and the corresponding Poisson's ratio (μ_{23}) in isotropic conditions [2].
- The elastic moduli obtained in the 1-2 plane was used in the following equation [8], to obtain the corresponding Poisson's ratio (μ_{12}):

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



Characterization of the elastic properties of anisotropic materials by impulse excitation method

Results

In the tables, the characteristic of the tested specimens and the dynamic elastic properties obtained for the extruded tough PLA from the Ultimaker are presented.

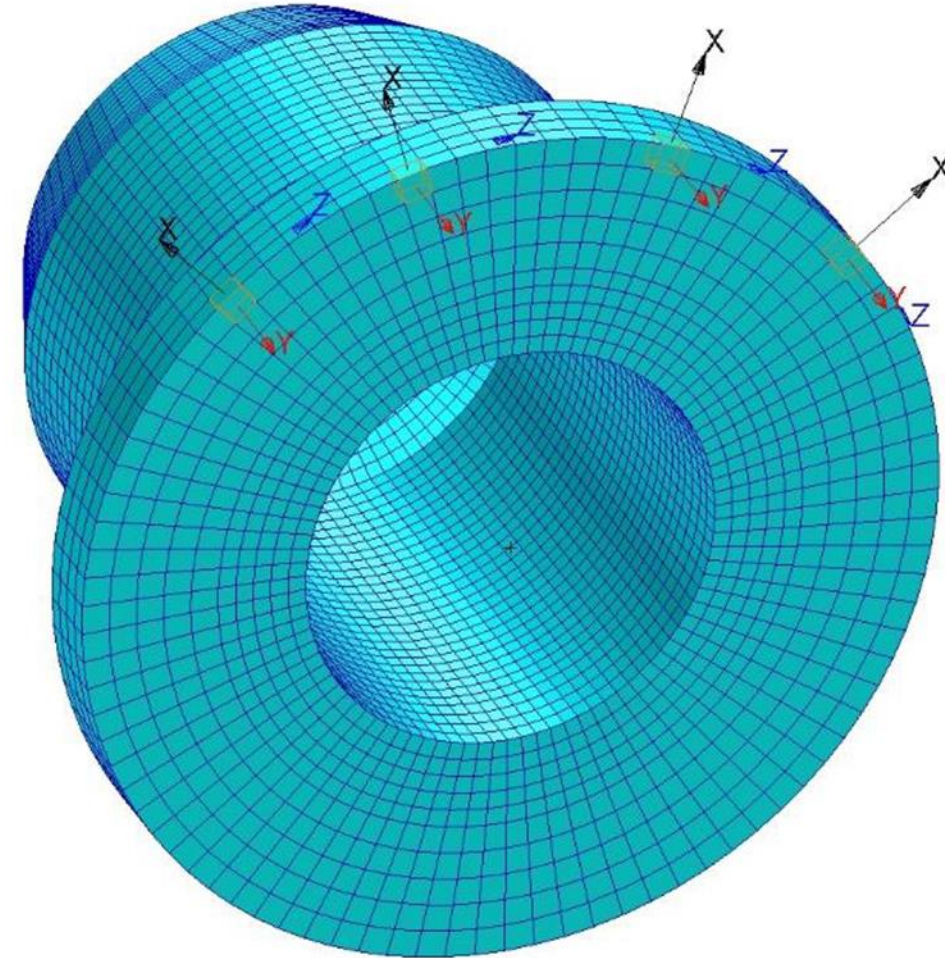
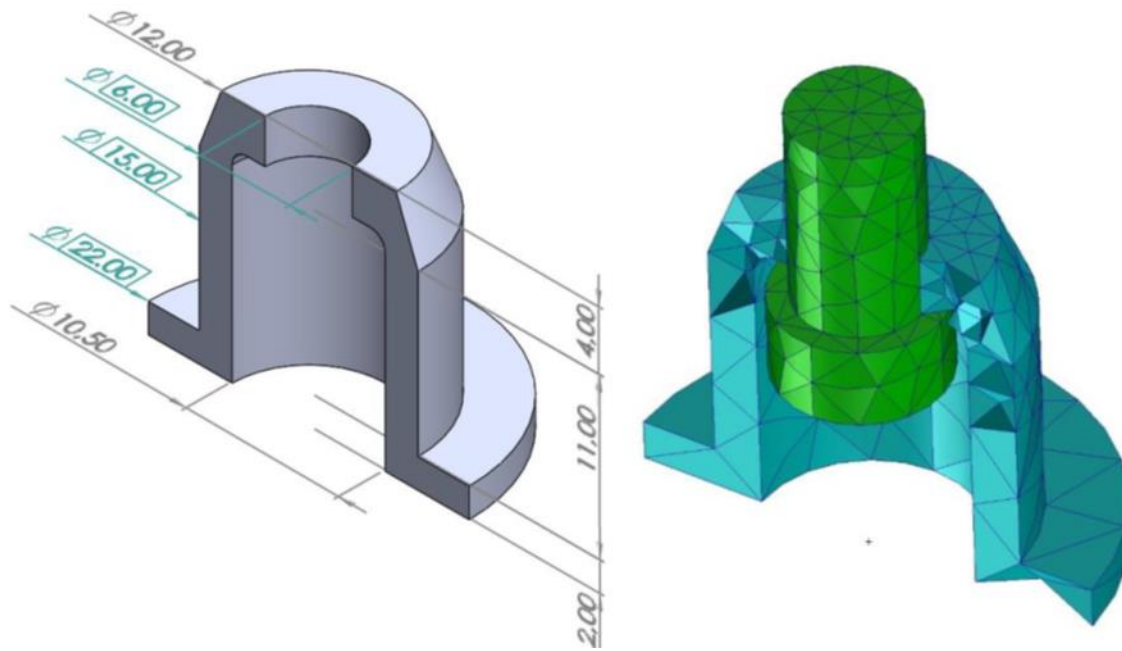
| Specimen characterization | | | | | | | |
|---------------------------|--------------|----------------|-------------------|----------------|----------------|--------------------|--------------------|
| Specimen | Raster angle | L <i>mm</i> | w, b <i>mm</i> | t <i>mm</i> | m <i>gr</i> | f_f <i>Hz</i> | f_t <i>Hz</i> |
| Beam 1 | [0] | 133.22 | 33.43 | 5.94 | 35.09 | 560 | 1059.5 |
| Beam 2 | [45/-45] | 133.44 | 37.21 | 6.01 | 35.19 | 558 | 1119.9 |
| Beam 3 | [90] | 134.37 | 36.41 | 5.92 | 33.83 | 519 | 1099.5 |

| Dynamic elastic properties (1 is the extrusion direction) | | | | | |
|---|-------------------|------------|------------|-------------------|-------------------|
| E_{11} [GPa] | E_{22} [GPa] | μ_{12} | μ_{23} | G_{12} [GPa] | G_{23} [GPa] |
| 3.51 | 2.78 | 0.35 | 0.33 | 1.15 | 1.10 |

Simulation of the mechanical behaviour of 3D printed parts

Reverse-engineering project

These results were applied in a reverse-engineering project where the in-service behaviour of a bushing is simulated before it's manufacturing using tough PLA material through 3D printing.



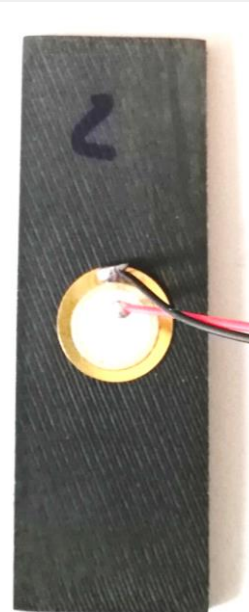
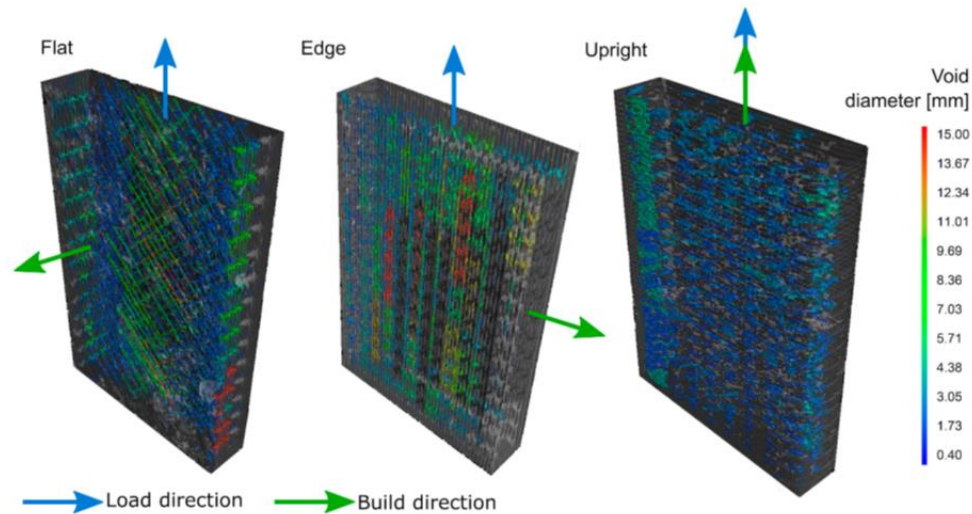
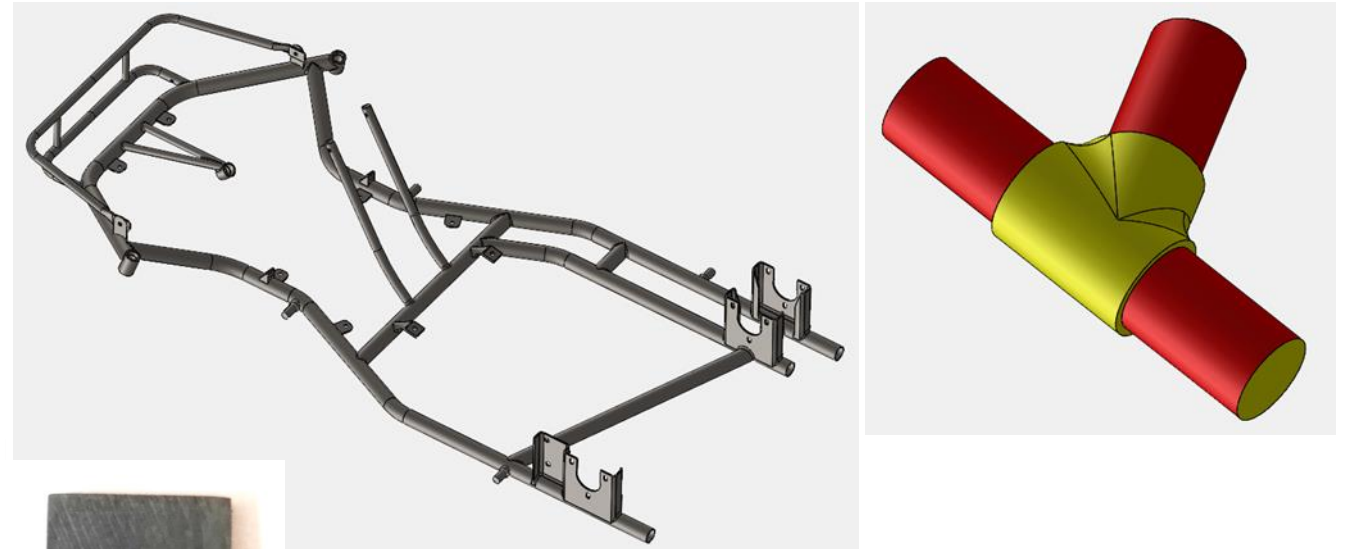
Simulation of the mechanical behaviour of 3D printed parts

Simulation of the dynamic behaviour of a kart chassis

This technique is being applied in an investigation of the behaviour of a kart chassis made of composite materials.

This chassis is made of epoxy resin tubes reinforced with carbon fibres, joined together through joints made of polyamide reinforced with carbon short fibres.

The influence of voids and porosities in the elastic properties of the joints manufactured by 3D printing will be studied.



Conclusions

The impulse excitation technique is a simple and effective method for identification the elastic properties of orthotropic materials.

The Young's moduli in the material principal directions, as well as in-plane shear modulus, were estimated applying this method.

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

The advantage of the method is the little preparation of experimental set-up and short measurement time.

Thank You!

- **Main References**

- [1] ASTM E1876: Standard test method for dynamic Young's modulus, shear modulus and Poisson's ratio by impulse excitation of vibration;
- [2] Y. Song, Y. Li, W. Song, K. Yee, K.-Y. Lee, V.L. Tagarielli, Measurements of the mechanical response of unidirectional 3D-printed PLA, *Materials and Design* 123 (2017) 154–164;
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- [4] S.-H. Ahn, M. Montero, D. Odell, S. Roundy, P. K. Wright, Anisotropic material properties of fused deposition modeling ABS, *Rapid Prototyping* Volume 8, Number 4 (2002) 248–257 R.J. Dexter and J.M. Ocel. *Manual for Repair and Retrofit of Fatigue Cracks in Steel Bridges*. Tech. rep. No. FHWA-IF-13- 020, United States. Federal Highway Administration (2013);
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- [8] J.M. Hennessey, J.M. Whitney, M.B. Riley, *Experimental Methods for Determining Shear Modulus of Fiber Reinforced Composite Materials*, Technical Rept. for Jul–Dec, 64, 1965.