

A numerical and experimental study of the compression uniaxial properties of PLA manufactured with FDM technology based on product specifications

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Abstract

This paper presents a numerical and experimental study of the compression uniaxial properties of PLA material manufactured with FDM based on product specifications. A first experimental test in accordance with the requirements and conditions established in the ISO 604 standard characterizes the mechanical and elastic properties of PLA manufactured with FDM technology and product requirements in a uniaxial compression stress field by testing six specimens. A second experimental test allows analyzing the structural behavior of the industrial case, evaluating the compression stiffness, the compression yield stress, the field of displacements and stress along its elastic area until reaching the compression yield stress and the ultimate yield stress data. To improve the structural analysis of the case study, a numerical validation was carried out using two analytical models. The first analytical model applies an interpolation procedure to the experimental results of the tested specimens in order to characterize the uniaxial tension-compression curve versus the nominal deformations by means of an 8-degree polynomial function. The second model defines the plastic material as elastic and isotropic with Young's compression modulus constant and according to the guidelines established in ISO standard 604. The comparison between experimental tests and numerical simulation results for the study case verify that the new model that uses the proposed polynomial function is closer to the experimental solution with only an 0.36% error, in comparison with the model with Young's compression modulus constant that reaches an error of 4.27%. The results of the structural analysis of the mechanical element indicate that the elastic region of the plastic material PLA manufactured with FDM can be modeled numerically as an isotropic material, using the elastic properties from the experimental results of the specimens tested according to ISO standard 604. In this way it is possible to characterize the PLA FDM material as isotropic, obtaining as an advantage its easy definition in the numerical simulation software as it does not require the modification of the constitutive equations in the material database. SEM micrographs have indicated that the fracture of the failed test specimens is of the brittle type, mainly caused by the separation between the central plastic filament layers of the specimens. The results presented suggest that the use of FDM technology with PLA material is promising for the manufacture of low volume industrial components that are subject to compression efforts or for the manufacture of components by the user.

Keywords: Additive manufacturing, FDM, Numerical simulation, Experimental tests, Plastic part design, CAD.

1. Introduction

Additive manufacturing (AM) is a manufacturing process that enables the production of functional parts with complex geometries and different materials, as well as individualized mass production enabling companies to produce first and effective design for not only prototypes but also successful and efficient end-products. Additive manufacturing is widely used nowadays in industrial product development [1]. The main advantage of the additive fabrication concept compared to other traditional manufacturing processes like injection molding is the ability to create almost any possible shape [2-5]. This capability is governed by the building-up layer-by layer process. The additive manufacturing technologies are playing an increasingly important role in production scenarios [6]. In particular, one of the main strong points is the production of small series components with innovative geometries not feasible using traditional technologies [7]. Additive manufacture involves the progressive addition of material to generate component geometry; this differs fundamentally from traditional, subtractive manufacture, whereby material is progressively removed from an initial geometry as required [8]. There are several available technologies based on this additive machining concept [9]: stereolithography, selective laser sintering, 3D printing, fused deposition

modeling, etc. Of these, FDM, also known as fused-filament fabrication (FFF), is among the most popular. In the FDM process a feedstock filament of the raw material on a spool is fed into the extrusion head with the aid of a tractor wheel arrangement through generating extrusion pressure. The movement of the extruder by a numerical control-based code coupled with the extrusion of a semi-molten filament above the material's glass transition temperature enable the production of the desired geometry [10].

Traditionally, FDM 3D printers have been able to build parts in thermoplastic materials such as polylactic acid (PLA) and acrylonitrile-butadiene-styrene (ABS). PLA offers better thermomechanical characteristics than ABS, having greater mechanical resistance and a lower coefficient of thermal expansion. The latter characteristic improves the printability of PLA because it reduces the effects of warping during the printing phase. Moreover, it generates fewer health risks than ABS when printing in small and improperly ventilated spaces [11]. PLA is a bio-based plastic made up of a repeating chain of lactic acid. It is recyclable using conventional methods. In addition, PLA can be composted like other organic matter [12].

In recent years, FDM has evolved from a rapid prototyping technique towards a rapid manufacturing method, changing its main purpose to producing finished components ready for use [13,14]. Indeed, this technique is particularly promising for the fabrication of a single part or in general low volume products, increasing their useful life through technical approaches such as repair or self-fabrication of parts.

The manufacturing of plastic parts is a complex process because detailed knowledge in several scientific fields is required. The advantages of plastic materials are related to the large range of material properties. Unfortunately, this is also a limiting factor because the industrial use of a specific polymer is preceded by a lot of tests. This usually requires very time-consuming and cost-intensive experimental activities. For this reason, it is necessary to implement advanced simulation approaches able to manage and reduce this complexity. The design of plastic parts and their optimization is still a very complicated engineering challenge

Addressing the design of a new product with greater security involves validating its mechanical behavior with numerical FEM simulations prior to its manufacture. These simulations require an accurate knowledge of the mechanical characteristics of the material, these being influenced by the manufacturing process as well as the mechanical efforts to which the design will be subject in an operation state. In the case of end parts manufactured with FDM technology, the material properties differ enormously from those of a homogeneous material whose data are easily found in the manufacturer's sheets. On the other hand, the material characterization under specific manufacture requirements and efforts could be unavailable for all the materials and mechanical requirements [15]

Product design requirements are established by the final customer, conditioning the concept design and the manufacturing parameters. Specifically, in the FDM manufacturing process dimensional tolerances have an influence on layer height, component topology determines its specific positioning in the printing machine, product quality affects the layer height as well as the deposition speed, etc. Target cost affects the manufacturing specifications in the same way, for example by minimizing printer dimensions, reducing manufacturing supports etc.

An accurate simulation of components manufactured with FDM implies knowing in advance what the behavior of the material will be according to the manufacturing specifications and the requirements of the final product. Since this information is not easily accessible in all cases, it is necessary to perform a set of experimental tests prior to the simulation using a set of test specimens manufactured under the same conditions as the final part. This usually requires very time-consuming and cost-intensive experimental activities. Additionally, and to complete the validation process once the experimental information has been obtained, it is necessary to know what the best way will be to treat the experimental information in the FEM software in order to obtain simulation results that match perfectly the experimental behavior of the material. All these reasons mean that the design and optimization of industrial plastic parts manufactured with FDM is still a complicated engineering challenge.

Many researchers have focused their efforts on determining the effect of process parameters on the mechanical properties of FDM manufactured parts [16-28]. Several papers deal with the anisotropic characteristics of FDM parts, analyzing the properties of the material in a state of tension, flexion and compression. More specifically Rodriguez et al. [19] introduce a strategy for optimizing the design of Fused-Deposition Manufacture of ABS P400 components, analyzing stiffness and strength under a given set of loading conditions. In this research a mathematical model of the structural system is linked to an approximate minimization algorithm to find the settings of manufacturing parameters which optimize the mechanical performance of the component. Ahn et al. [20] characterize the properties of ABS parts fabricated by FDM using a Design of Experiment (DOE) approach, analyzing the process parameters like raster orientation, air gap, bead width, color, and model temperature, obtaining tensile strengths and compressive strengths and comparing these with the analysis of injection molded specimens. Some researchers have used the Taguchi

method to study the optimal process parameters for a fused deposition modeling (FDM) rapid prototyping machine. Anitha et al. [21] assess the influence of the process parameters on the quality characteristics of the prototypes manufactured with FDM technology. Lee et al. [22] analyzed a set of FDM parameters like layer thickness, raster angle and air gap, studying their influence on the elastic performance of an ABS prototype. Croccolo et al. [23] studied the effects of the Fused Deposition Modelling production parameters on the tensile strength and on the stiffness of the components made of ABS-M30, tackling the question from both the experimental and the analytical points of view. Domingo- Espín et al. [24] proposed a model to simulate FDM parts, correlating a finite element analysis (FEA) simulation with physical testing.

Casavola et al. [25] described the mechanical behavior of FDM parts through the classical laminate theory (CLT) and in a later study [26] analyzed the residual stress of FDM parts made of ABS by employing the hole-drilling measure method. Li et al. [27] performed a quantitative investigation of distortion of polylactic acid (PLA) part in FDM from the point of interface residual stress. Tymrak et al. [14] quantify the basic tensile strength and elastic modulus of printed components using realistic environmental conditions for standard users of a selection of open-source 3-D printers. Tanikella et al. [28] investigated the mechanical properties of 3D printed parts using a commercial open-source 3D printer for a wide range of materials, testing the samples for tensile strength. Kuznetsov et al. [29] studied the influence of geometrical parameters of fused deposition modeling (FDM) on printed part strength for open source desktop 3D printers and PLA material. Wittbrodt et al. [30] determined the effect of color and processing temperature on PLA material properties in various colors. More recently Chacón et al. [31] characterized the effect of build orientation, layer thickness and feed rate on the mechanical performance of PLA samples manufactured with a low cost 3D printer. Puigoriol-Forcada et al. [10] presented an experimental investigation of the influence of part build orientation on the flexural fatigue behaviors of fused-deposition modelling (FDM) processed polycarbonate (PC) parts. Torres et al. [32] presented the influences of key processing parameters on the resulting material properties of fused-deposition-modeled (FDM) polylactic acid (PLA) components tested in torsion. To broaden the understanding of torsional properties, Balderrama-Armendariz et al. [33] studied the impact on the shear strength of test specimens manufactured with FDM.

Plastic polymers are characterized by their good performance in comparison with high compressive strengths, this mechanical feature being a great advantage when designing mechanical assemblies manufactured with FDM technology. Uddin et al. [34] presented a comprehensive experimental study exploring the influence of key printing parameters on mechanical properties and failure mechanisms of acrylonitrile butadiene styrene (ABS) material. Upadhyay et al. [35] focused on the effect of build direction on the mechanical properties of acrylonitrile butadiene styrene ABS P400 part specimens analyzing tensile and compressive strength, Izod impact and hardness. Sood et al. [36] focused on extensive study to understand the effect of five important parameters such as layer thickness, part build orientation, raster angle, raster width and air gap on the compressive stress of test specimens. Lee et al. [37] investigated the measurement of the anisotropic compressive strength of rapid prototyping parts.

For the specific case of PLA material subject to uniaxial compression tests, there are no specific scientific or industrial data that allow characterizing the material in the FDM process for specific manufacturing requirements obtained from the technical specifications of the product [15]. These data are necessary to correctly develop the industrial component subject to these efforts. All industrial designs require of a set of conceptual validation simulations before obtaining the final design. In this way it is assured that the product will meet all the requirements of the product in terms of cost, development deadlines and final quality. Without having this information, it would be necessary to carry out a large number of experimental tests, using physical parts, for each design modification, thus increasing costs and causing possible delays in the product development.

At research level most of the studies that have been carried out so far analyze the dependence between FDM process parameters and the mechanical behavior only for test specimens. In this line there is only one research paper [22] that analyzes the behavior of a real part manufactured with FDM [15]. For industrial uses it is necessary to know with security if the information about the mechanical properties obtained from experimental tests using 3D printed specimens could be used for predicting the mechanical behavior of FDM end-parts. According to [15] there are very few research studies on this subject, this area being considered a new line of research.

This paper presents a numerical and experimental study of the uniaxial compression properties of PLA manufactured with FDM based on real industrial product specifications. The new product [38] consists of an innovative mechanical device for the displacement of heavy loads in olive harvesting manufactured completely in PLA using FDM technology. The new device has been designed so that most of its components work under uniaxial compression stresses, a favorable operation state of PLA material. The case of study consists of a hollow bar of slender geometry subject to uniaxial compression stresses and to the technical specifications required for manufacturing and product

commercialization. The paper presents an application case where the characterization of the material has been validated using a real industrial part. This fact allows obtaining research results of which there are very few publications since most of the presented research presents only general results on test specimens [15]. In addition, the results presented show a coincidence between the material behavior of the part and for specimens in the elastic zone, validating in this way the behavior of the industrial product in concrete manufacturing specifications. The research presented allows us to safely address the manufacture of the product, which has as additional advantages its biodegradability, low cost and self-repair by the farmer in case of breakage of any component.

The research presented has allowed validating the rest of the components of the design that were subject to the same requirements, without the need to physically manufacture the components thus avoiding costly experimental tests. In the same way it has allowed us to validate those components whose dimensions exceeded the limits of the test device. The results obtained have made it possible to simulate the design in the conceptual phase. This fact has allowed us to reduce the cost of the product and the development periods, making the validation of the modifications in the design more efficient.

2. Geometrical and functional description of the FDM mechanical case study

In this section, the geometry of the FDM mechanical case study is presented and described. Additionally, factors that intervene in the selection of material for 3D printing using FDM techniques, the boundary conditions and load scenario to which this mechanical element is subject are presented. As shown in Fig.1, this mechanical element is part of a mechanism for the optimization of agricultural processes [38].

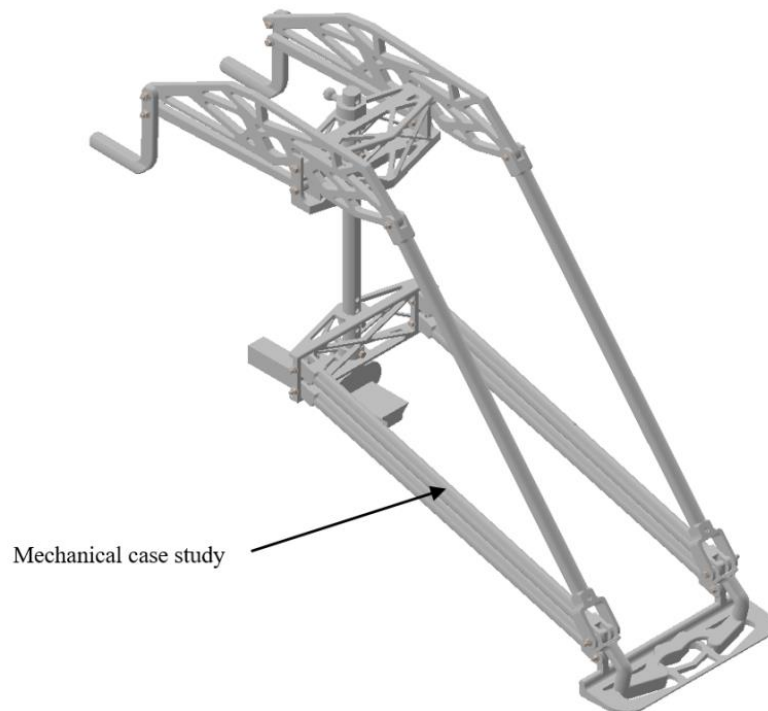


Fig. 1.- Geometry of the mechanical assembly manufactured with FDM for the optimization of agricultural processes.

This mechanical element is a bar with a constant circular ring section throughout its domain. The bar has at its ends some anchors that allow the correct assembly of the bars with the rest of the mechanical assembly. The material used for the manufacture of the mechanical assembly with FDM 3D printing is a polylactic acid type plastic (PLA). This plastic being biodegradable allows the mechanical assembly to be sustainable. That is, it can be eliminated as organic waste and in the presence of microorganisms can serve as organic fertilizer, which can be interesting also for agricultural applications. Table 1 shows the physical, mechanical and manufacturing properties of the PLA commercial material yarn, manufactured by Smart Material 3D [39], used for printing the mechanical element presented.

PLA Properties	Value	Units
Density	1.24	g/cm ³
Tensile strength MD	110	MPa
Tensile strength TD	114	MPa
Tensile modulus MD	3309	MPa
Tensile modulus TD	3861	MPa
Elongation at break MD	160	%
Elongation at break TD	100	%
Heat deflection temperature	65	°C
Vicat softening temperature	85	°C
Print temperature	220±10	°C
Hot pad	0-60°C	°C

Table 1.- Physical, mechanical and printing properties for PLA material manufactured with FDM technology.

The mechanical element under study is subjected to a tensional state of pure uniaxial compression. That is to say, the load scenario to which the mechanical element under study is subjected means that the mechanical stresses it undergoes are pure uniaxial compression. In this way, the object of this study is the analysis of the structural behavior of the main geometry of the mechanical element for a tensional state of pure uniaxial compression. Fig.2 shows in detail the geometry of the mechanical element under study. As can be seen, the ends of the element have been modified to adapt the geometry to the measuring instruments and the uniaxial compression testing machine, while the geometry and tubular section of the study area of the mechanical element remain constant.

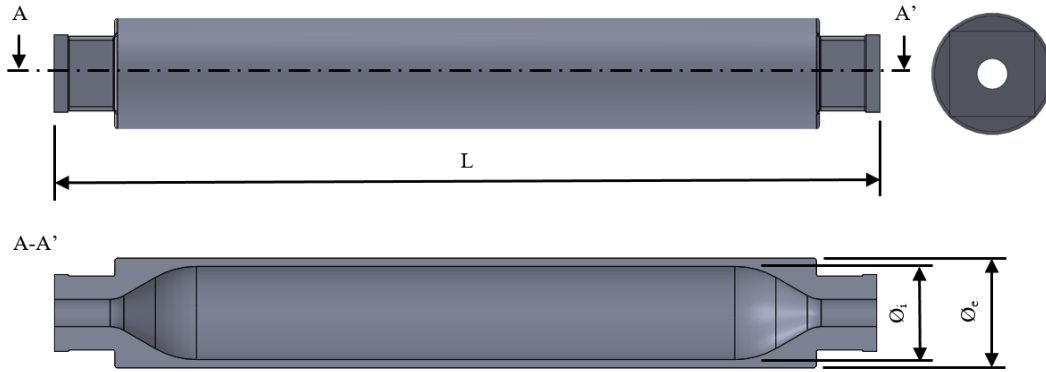


Fig. 2.- Geometry of the mechanical case study.

The dimensions of the mechanical element under study (see Fig.2) are presented in Table 2. The geometrical variables $\varnothing_i$ (inner diameter) and $\varnothing_e$ (outer diameter) which determine the cross section of the mechanical element have been dimensioned according to the mechanical properties of the PLA material (see Table 1). In this way, starting from the uniaxial compression force to which the mechanical element under study and the tensile yield stress of the plastic material are subjected, the magnitude of the cross-sectional area of the mechanical element is determined by a classical structural analysis (see Eq. 1)

$$\sigma_y \geq \frac{F_c \cdot \gamma_s}{A_{\text{cross}}} \quad (1)$$

Where σ_y [MPa] represents the tensile yield stress of the plastic material, F_c [N] represents the uniaxial compression force to which the mechanical element is subjected, A_{cross} [mm²] represents the area of the cross section of the mechanical element and γ_s represents a structural safety coefficient equal to 1.5.

Variable	Description	Units	Value
$\varnothing_e$	Outer diameter of the mechanical element	mm	40
$\varnothing_i$	Inner diameter of the mechanical element	mm	34
L	Length of the mechanical element	mm	300

Table 2.- Geometrical variables that define the mechanical element under study.

Fig.3 shows the load scenario and the boundary conditions to which the mechanical element under study is subjected. As can be seen, it is a pure uniaxial compressional tension state where the maximum uniaxial compressive force that the mechanical element bears during the nominal operation of the mechanism, to which it belongs, is equal to 900 N. The application of this uniaxial compression force is performed at the opposite end of the mechanical element where the boundary conditions are defined. The boundary condition established for the structural analysis of this mechanical element is either fixed or of the embedment type.



Fig. 3.- Boundary conditions and definition of the loads borne by the mechanical element.

Finally, the manufacture, using FDM 3D printing techniques, of the mechanical element under study has been carried out with a commercial 3D printer Ultimaker 2+ Extended [40]. The printing dimensions of this commercial 3D printer are: 223 mm on the X axis, 223 mm on the Y axis and 305 mm on the Z axis. Therefore, given the dimensions of the mechanical element the manufacturing is carried out along the longitudinal axis, ie the Z axis (MD direction) (see Fig. 4). Authors such as [35] conclude that the structural behavior and the compressive strength of the elements manufactured along the longitudinal direction (Z axis) improves with respect to those manufactured along the transversal direction (X or Y axis).

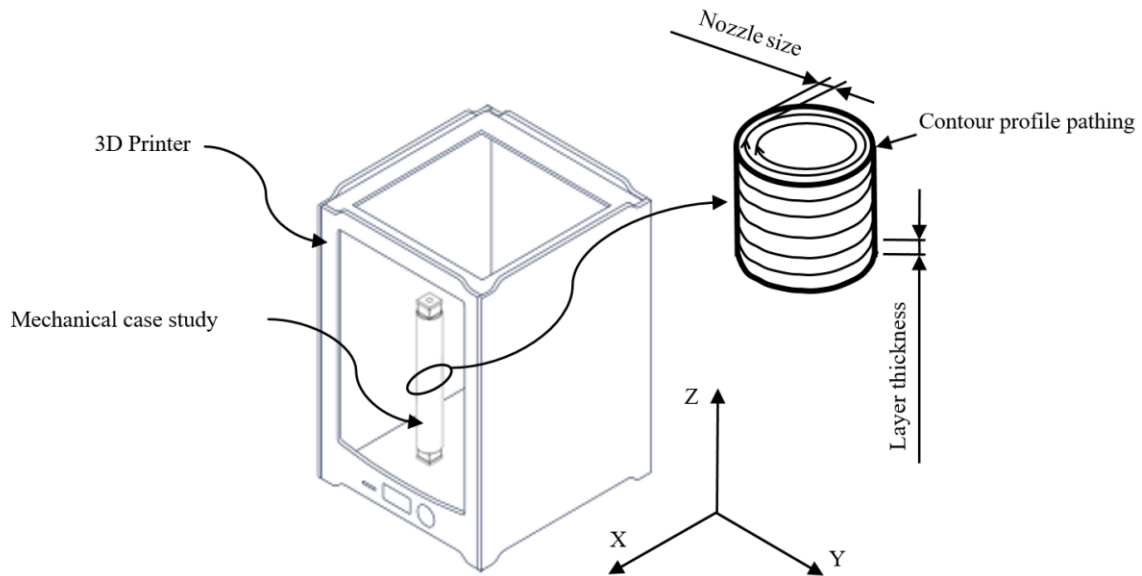


Fig. 4.- Configuration of the 3D printing process of the mechanical element under study.

As shown in Fig.4, the 3D printing strategy used to generate the different layers during the manufacturing process has been that of contour profile. Authors such as [34] conclude that for a manufacturing by deposition of layers along the Z direction, the orientation or printing strategy used for each layer has a negligible effect on compressive properties given the symmetry that occurs in the cross section of the mechanical element. Table 3 shows the magnitude of the parameters defined for the configuration of the manufacturing process. For the correct manufacture of the mechanical element under study and the optimization of the printing process the geometric design of this element is adapted to the criteria and requirements of additive manufacturing using the FDM technique. This allows the geometry to be printed completely without needing auxiliary supports, minimizing in this way the quantity of material used during the manufacturing process.

Manufacturing parameters	Value	Units
Layer height	0.2	mm
Nozzle size	0.4	mm
Infill density	100	%
Print speed	50	mm/s
Travel speed	120	mm/s

Table 3.- Parameters of manufacture used for the manufacture of the elements of the present study.

3. Experimental set-up and methodology

In this paper two types of experimental uniaxial compression tests are described for mechanical elements manufactured using additive manufacturing techniques of the FDM type. The first type of test focuses on the characterization of the mechanical and elastic properties of the 3D PLA plastic printing material, according to the conditions and requirements established in the ISO-604 standard (2003) [41]. On the other hand, in the second test the structural behavior of the mechanical element object of study is analyzed before a tensional state of uniaxial compression, evaluating the compressive stiffness of the mechanical element, its compression yield stress, the field of movements and strengths along its elastic behavior until reaching the compression yield stress and the ultimate yield stress. Subsequently, with the information of the mechanical and elastic properties of the PLA material, a set of numerical simulations with different elastic models has been carried out for the mechanical element under study. In this way, the results of the numerical simulations are validated by the results obtained in the second experimental test on the mechanical element under study.

According to the standard ISO-604, to carry out the characterization of the mechanical and elastic properties to uniaxial compression of the plastic material for 3D printing PLA, specimens with rectangular prism geometry should be tested experimentally (see Fig.5). Table 4 shows the dimensions of the specimens, both for the calculation of the compression elastic modulus and for the calculation of yield stress compression. The magnitude of the manufacturing parameters used for the manufacture of the specimens is shown in Table 3, and these are analogous to those used for the manufacture of the mechanical element under study in this paper.

Measurement parameter	Length, L_s	Weidth, W_s	Thickness, T_s	Unit
Compression Young's modulus	50 ± 2	10.0 ± 0.2	4.0 ± 0.2	mm
Compression yield stress	50 ± 2	10.0 ± 0.2	4.0 ± 0.2	mm

Table 4.- Dimensions of the specimens used for the characterization of PLA compression material.

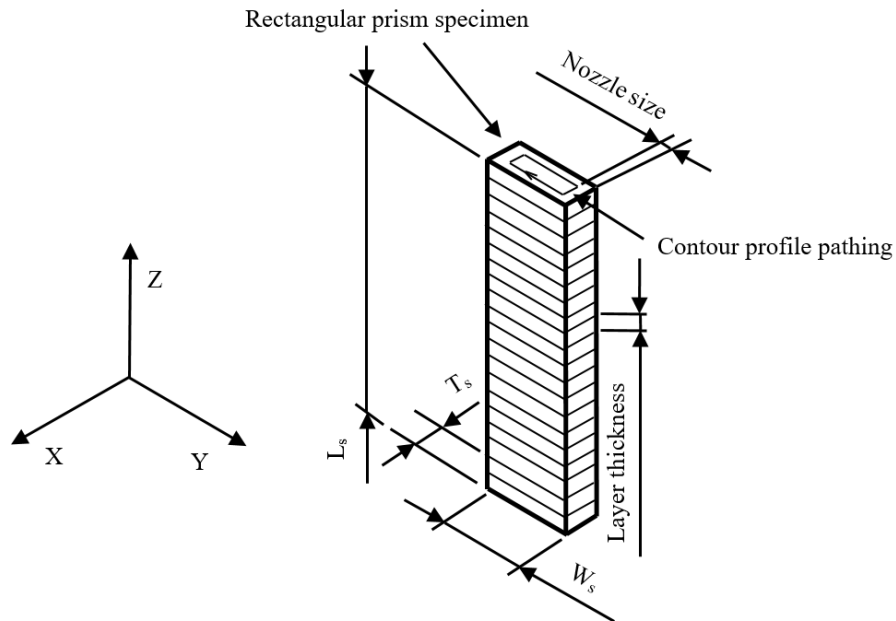


Fig. 5.- Configuration of the 3D printing process for the specimens analyzed in the experimental test.

The standard applied for this type of test, ISO-604, recommends testing at least 5 specimens for each main direction in which we wish to obtain the elastic and mechanical properties of the plastic material. Therefore, in order to validate the experimental tests according to this standard a total of 6 specimens with the same geometrical and manufacturing characteristics have been tested.

Fig.6 shows a specimen prepared for testing on the compression machine. As can be seen, the specimen is placed between the surfaces of the compression plates, ensuring that the specimen end surfaces are parallel to the compression plates surfaces. Then, before starting the test the test machine is adjusted so that the surfaces are not in contact. The compression speed used for the test of the different specimens has been 1 mm/min, according to the criteria established in standard ISO-604 (see Eq.2), and this speed has been constant from the start of the uniaxial compression test to the break instant of each specimens.

$$v = 0.02 \cdot L_s \quad (2)$$

Where v [mm/s] represents the compression speed of the test and L_s [mm] the length of the specimens tested.

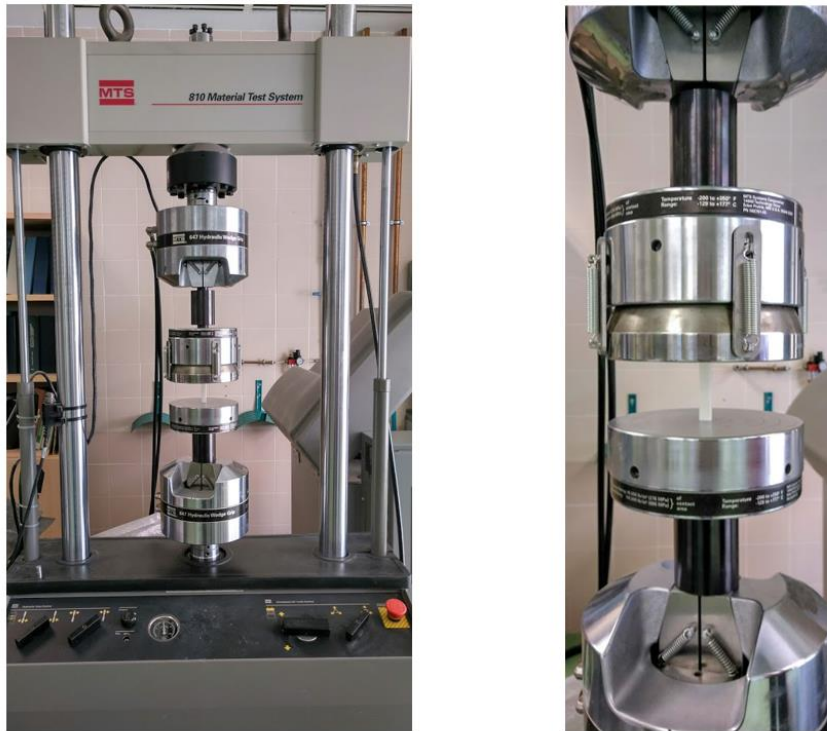


Fig. 6.- Uniaxial compression test of the specimens. A) Test machine, MTS-810. B) Compression plates and specimen.

The compression machine used for the execution of the experimental tests is MTS-810 (see Fig.6), which meets the ISO-5893 standard. This machine has two hardened steel compression plates with a flatness between both plates of 0.02 mm, and parallel to each other in a perpendicular plane to the axis of the compression load. The compression machine has a mechanism capable of displaying and recording the uniaxial compression load that each specimen supports during the tests. It also incorporates a mechanism capable of displaying and recording the distance between the surfaces of the compression plates, allowing us to define both the tensional state and the nominal deformation without inertial slowing of the test speed of 1 mm / min. of the specimens during the tests

Fig.7 shows the graph of uniaxial compression force versus the field of nominal compression displacements to which the specimens are subjected during the compression test. As shown, these parameters were recorded until the moment of breakage or structural failure of each specimen. From these parameters of compression forces and nominal displacements, the uniaxial compression stress and the nominal strain (see Fig.8) are determined according to Eq.3 and Eq.4, in accordance with standard ISO-604.

$$\sigma_c = \frac{F_c}{A_{\text{cross specimen}}}$$

(3)

$$\varepsilon_c = \frac{\Delta L}{L_s}$$

(4)

Where σ_c [MPa] represents the uniaxial compression stress, F_c [N] the uniaxial compression force, $A_{\text{cross specimen}}$ [mm²] represents the cross sectional area (assumed to be constant throughout the compression test), ε_c [mm / mm] represents the nominal deformation of compression, ΔL [mm] represents the nominal displacement of the specimen and L_s [mm] represents the initial length of the specimen.

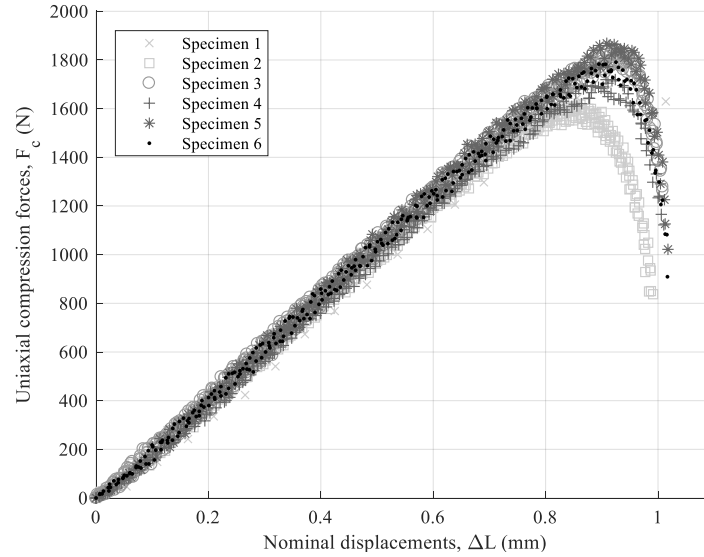


Fig. 7.- Uniaxial compression force versus nominal displacements for the specimens tested.

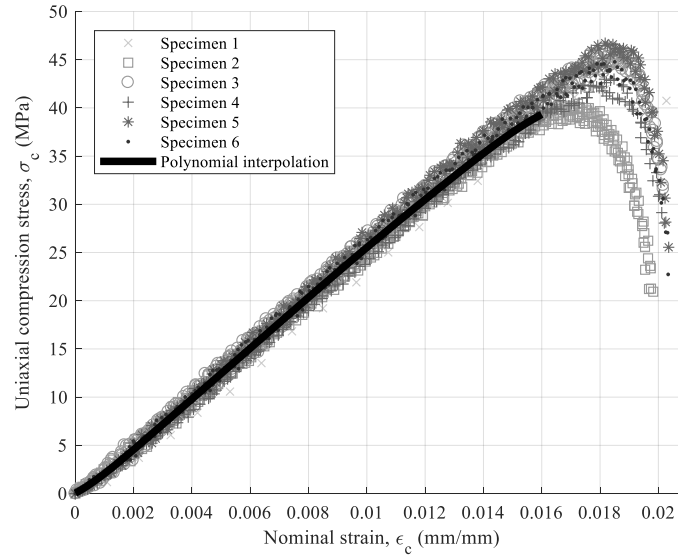


Fig. 8.- Uniaxial compression stress versus nominal strains for the specimens tested.

As shown in Fig.8, the stress-strain curve (σ_c - ε_c) presents a linear-elastic behavior until reaching the compression yield stress. From this value, the fracture process of the specimens begins and the curve descends until reaching the fracture yield stress. As shown in Figs.14, 15, 16 and 17, the fracture that occurs in the specimens is of a brittle type. That means the fracture is produced by the separation between the central plastic filament layers of the specimen. When the compression yield stress is exceeded, the central layers of plastic filament begin to separate until reaching the yield stress fracture, from which a complete separation between layers of material is produced and therefore the fracture of the specimen.

From the data of uniaxial compression stress and nominal deformations obtained for the 6 specimens tested, a polynomial interpolation is performed for the elastic regime of the curve presented in Fig.8. The interpolation is achieved by means of a polynomial of degree 8 (see Eq.5). Table 5 shows the results obtained in the interpolation of the uniaxial compression stress curve versus nominal deformations.

$$\sigma_c(\varepsilon_c) = P_1 \cdot \varepsilon_c^8 + P_2 \cdot \varepsilon_c^7 + P_3 \cdot \varepsilon_c^6 + P_4 \cdot \varepsilon_c^5 + P_5 \cdot \varepsilon_c^4 + P_6 \cdot \varepsilon_c^3 + P_7 \cdot \varepsilon_c^2 + P_8 \cdot \varepsilon_c + P_9 \quad (5)$$

Interpolation parameters	Value
Coefficients (95% confidence bounds):	
P1	-3.465·10 ¹⁷
P2	2.394·10 ¹⁶
P3	-6.613·10 ¹⁴
P4	9.253·10 ¹²
P5	-6.803·10 ¹⁰
P6	2.386·10 ⁸
P7	-2.266·10 ⁵
P8	2131
P9	-0.004
Goodness of fit:	
SSE	113.1
R-Square	0.999
Adjusted R-Square	0.999
RMSE	0.2741

Table 5.- Results of the polynomial interpolation of the uniaxial curve compression stress against nominal deformations

Thus, the elastic and mechanical properties of the PLA plastic material are determined by 3D printing manufacturing for each of the specimens tested. According to the ISO-604 standard, the compression Young's modulus is determined based on two pairs of uniaxial compression stress values corresponding to nominal deformations equal to 0.0025 and 0.0005 (see Eq.6).

$$E_c = \frac{\sigma_c(\varepsilon_c = 0.0025) - \sigma_c(\varepsilon_c = 0.0005)}{0.0025 - 0.0005} \quad (6)$$

From the Young's modulus compression of each tested specimen (see Table 6), the Young's modulus compression of PLA plastic material for 3D printing has been calculated as the arithmetical mean of the values obtained for the specimen. Table 6 shows the elastic and mechanical properties of PLA plastic material manufactured with 3D printing.

Compression properties	Units	S1	S2	S3	S4	S5	S6	Arithmetic average	Typical deviation
Young's modulus, E_c	MPa	2304.7	2363.3	2903.1	2319.0	2899.3	2381.3	2528.5	290.087
Yield stress, σ_y	MPa	44.09	40.59	46.08	42.99	46.72	44.77	44.2	2.223
Fracture stress, σ_f	MPa	40.76	20.94	31.58	28.05	25.54	22.73	28.3	7.196

Table 6.- Elastic and mechanical properties of PLA plastic material for each specimen.

In this way, the characterization of the elastic regime of PLA plastic material for 3D printing is carried out by means of two analytical models. The first by interpolation through a polynomial function of the uniaxial compression stress curve versus nominal deformations, and the second by obtaining the Young's modulus in compression according to the guidelines established in the ISO-604 standard. Both analytical models are compared and used for the definition of the numerical simulations of the mechanical element which is the object of study of the present paper.

As shown in Table 6, there is a notable dispersion in the results of the compression fracture stress parameter σ_f . This is because the specimen fracturing process is an unstable state that requires increasing the frequency of force and displacement data recording by the test machine to analyze in detail the exact moment of breakage or collapse of the specimen. Since the main objective of the present article is to evaluate the elastic behavior of the PLA plastic material, ie the compression elastic modulus, the recording frequency of force and displacement data of the MTS-810 test machine remains constant.

Finally, after conducting the experimental tests of the different specimens we proceeded to analyze experimentally the structural behavior of the mechanical element. Analogous to the tests carried out for the specimens, the uniaxial compression analysis of the mechanical element (see Fig.2) was performed on the MST-810 test machine (see Fig.9). The compression speed used was 6 mm / min, according to Eq.2, this speed being constant from the beginning of the uniaxial compression test until the moment of rupture of the mechanical element. Fig.10 shows the graph of uniaxial compression force versus the field of nominal displacements of compression to which the mechanical element was subjected during the compression test. As shown, these parameters were recorded until the moment of breakage or structural failure. From these parameters of compression forces and nominal displacements the uniaxial compression stress and the nominal strain (see Fig. 11) are determined according to Eq.3 and Eq.4. Table 7 shows the magnitude of the uniaxial compression force and the maximum nominal displacement reached at the breaking point of the mechanical element. As can be observed, the fracture of the mechanical element is brittle because the compressive yield stress is close to the fracture yield stress.



Fig. 9.- Uniaxial compression test of the mechanical element under study.

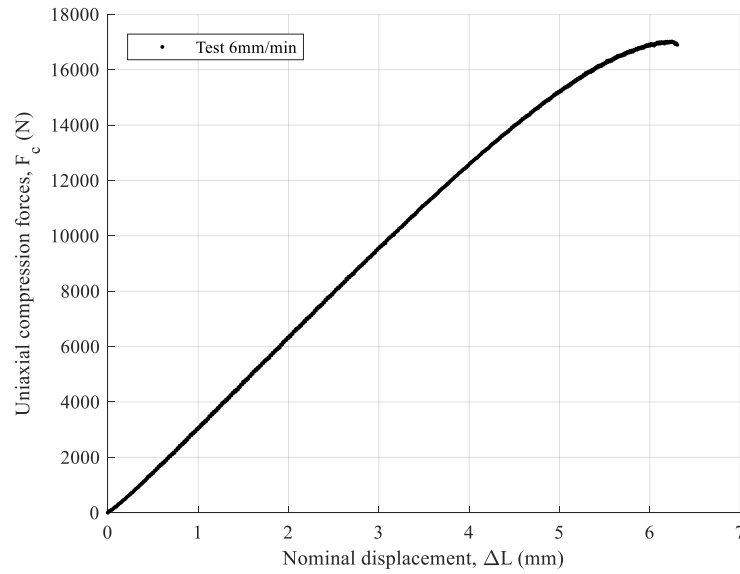


Fig. 10.- Uniaxial compression force versus nominal displacements for the mechanical element tested.

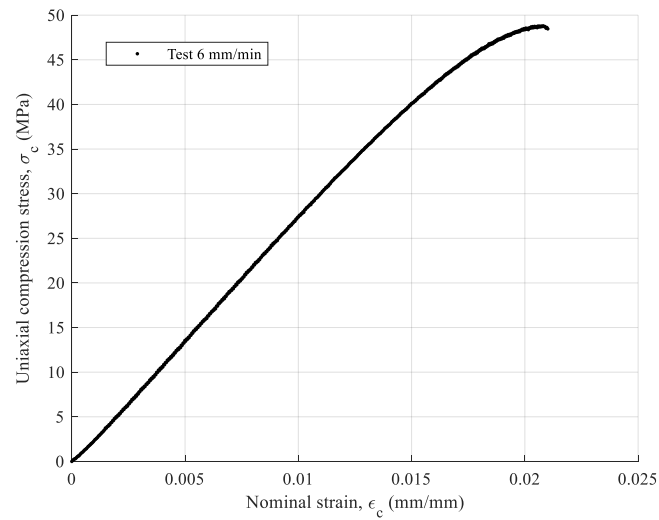


Fig. 11.- Uniaxial compression stress versus nominal deformations for the mechanical element tested.

Compression properties	Units	Value
Maximum uniaxial force	N	16091.0
Maximum nominal displacement	mm	6.304
Yield stress, σ_y	MPa	48.78
Fracture stress, σ_f	MPa	48.47

Table 7.- Mechanical properties of the study object obtained in the uniaxial compression test.

4. Fractography

Fig. 13 shows the scanning electron microscope of high resolution (FESEM) Carl Zeiss: Merlin, used to obtain the fractography images of the tested specimens. This electron microscope consists of EDX and WDX analytical capacity from Oxford, an electron beam gun by hot tip field emission, high resolution secondary electron detectors located in the sample chambers (SE-Everhart-Thornley and SE in lens), high resolution backscattered electron detectors located in the sample chamber (4-quadrant solid state AsB integrated in the lens of the GEMINI II and EsB in lens column) and cathodoluminescence (CL) detectors. This unit of microscopy allows a maximum resolution of the secondary electron image (SE) from 0.8 nm to 15 Kv, from 1.4 nm to 1 kv and 2.4 nm to 0.2 Kv, the range of acceleration potential is between 0.02 V and 30 kV and the beam current between 10 pA and 300nA

The chemical microanalysis system is based on an EDX X-ray detector (Oxford Inca Energy 350X-MAX 50) with linear resolution of 127eV in Mn K α from 1 to 100,000 cps. This is complemented, in turn, with a WDX spectrometer, Oxford Inca Wave 500, with Rowland circle of 210 mm and range 2 θ from 33° to 135°, includes four analyzer glasses with six interchangeable positions at any position. The system covers a wide range of analysis, including O and N. Furthermore, the detection and quantification of elements is made from the atomic number 4 (Beryllium). Finally, the electronic microscope (FESEM) has a load compensation system by nitrogen injection. This system allows the observation of uncoated insulating samples using high vacuum electron detectors (see Fig. 13).

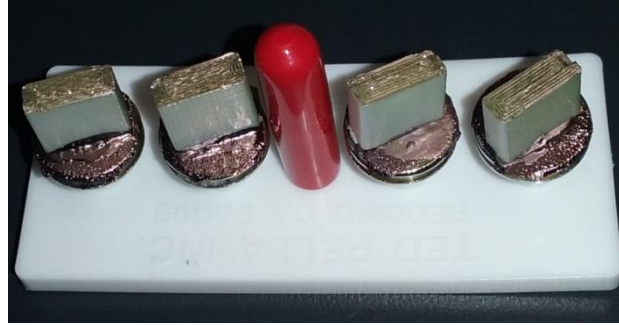


Fig. 12.- Specimens used to analyze brittle fracture using the FESEM electron microscope.

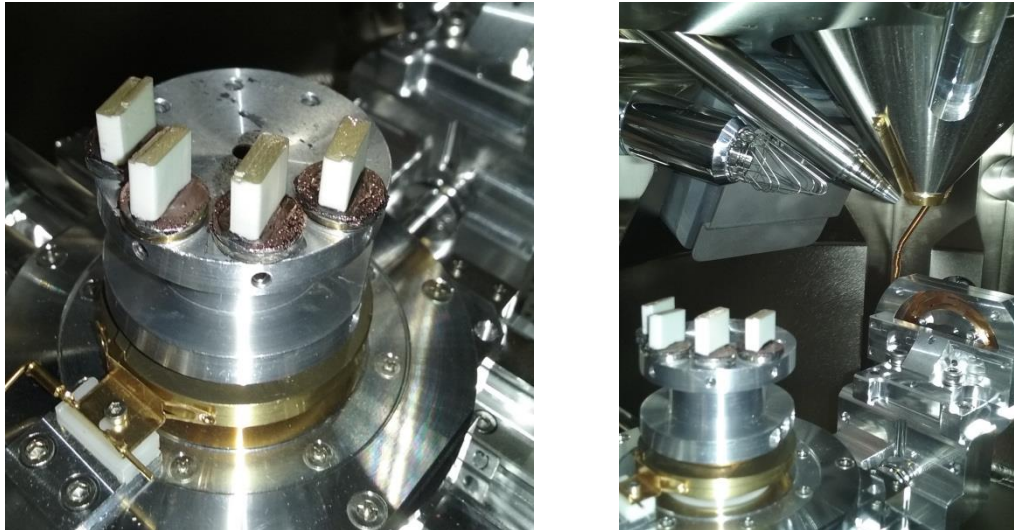


Fig. 13.- Scanning electron microscope of high resolution (FESEM), Carl Zeiss: Merlin.

In order to analyze the mechanics of the fracture produced in the tested specimens, two specimens have been selected in which the fracture, besides being brittle and caused by the complete delamination between plastic material layers, presents brittle breaks of the plastic filaments between layers. That is, the section produced in the specimens after the fracture retains plastic filaments belonging to adjacent layers (see Figs.14, 15, 16 and 17). As can be seen in Fig. 12 the plastic PLA material specimens have been coated with a thin layer of gold to give them conductive properties, and in this way to generate particles of backscattered (e1) and secondary (e2) electrons.

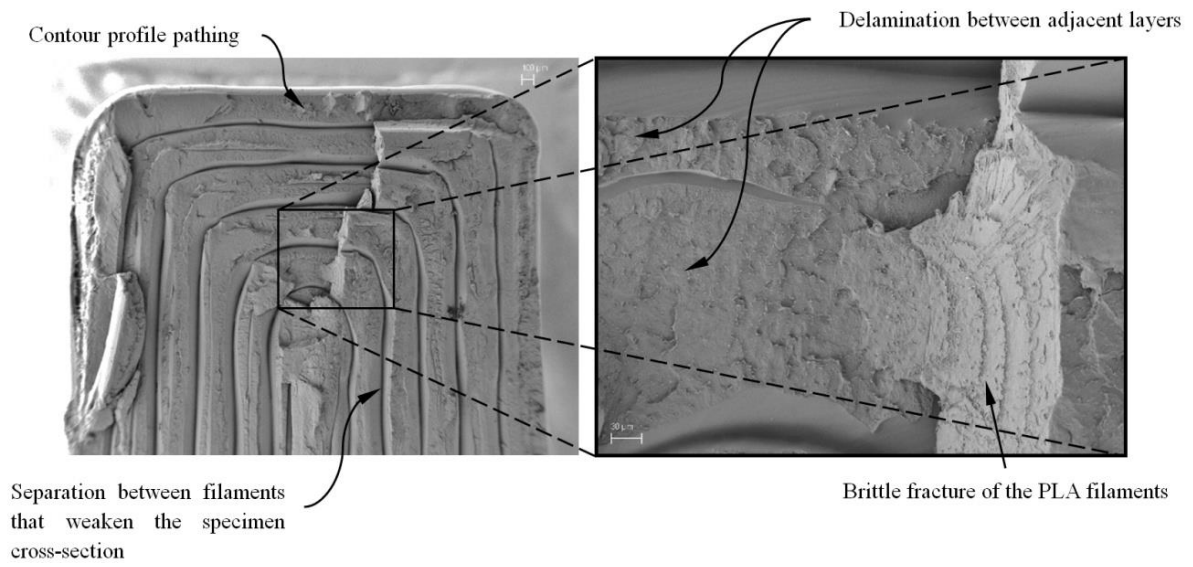


Fig. 14.- Failed tensile test specimens, specimen 1 – Part A.

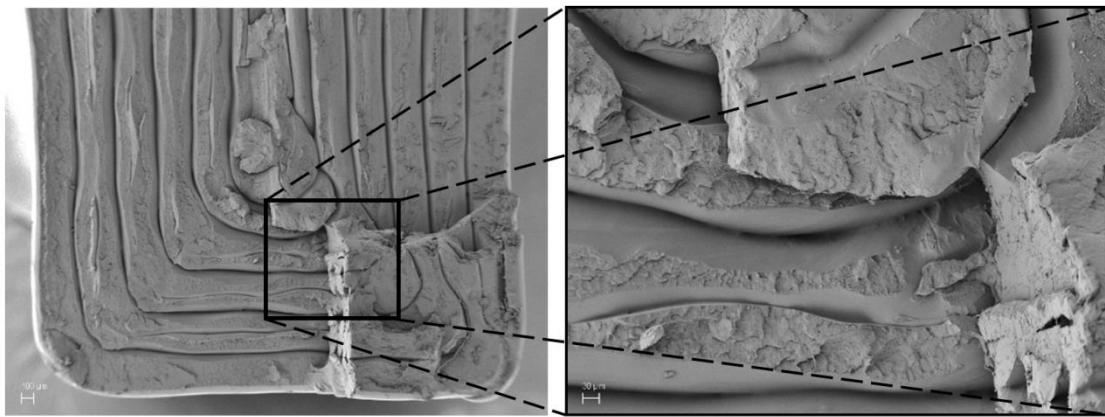


Fig. 15.- Failed tensile test specimens, specimen 1 – Part B.

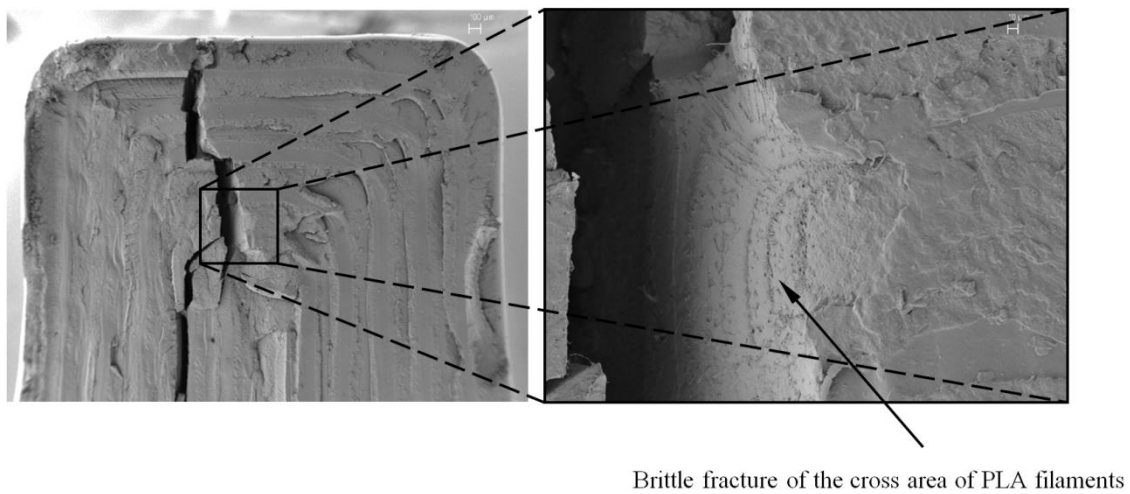
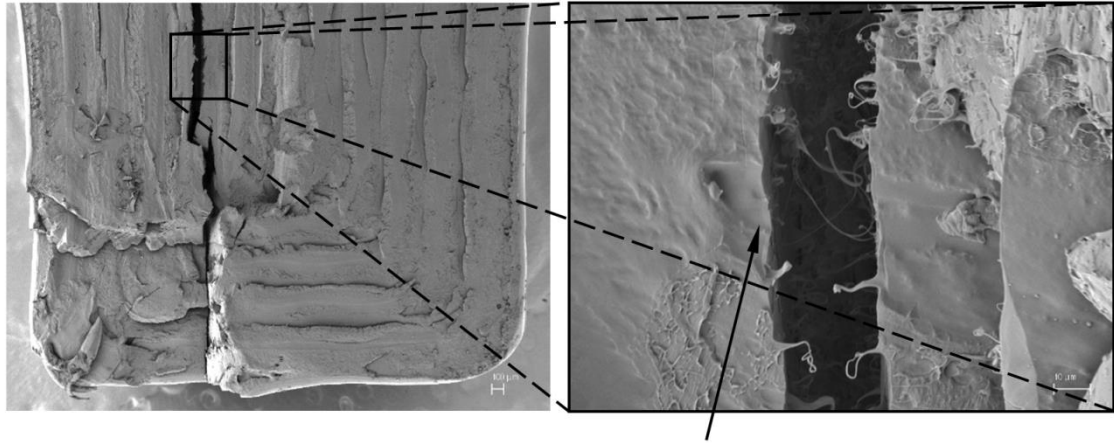


Fig. 16.- Failed tensile test specimens, specimen 2 – Part A.



Brittle fracture of the longitudinal area of PLA filaments

Fig. 17.- Failed tensile test specimens, specimen 2 – Part B.

Fig.14 (100 μ m-30 μ m), Fig.15 (100 μ m-30 μ m), Fig.16 (100 μ m-10 μ m) and Fig.17 (100 μ m-10 μ m), show the result of two brittle fracture pairs from the set of specimens analyzed. As can be seen in Figs.14, 15 16 and 17, the fracture mechanics of specimen 1 and 2 is brittle, smooth, free and is produced mainly by delamination of the adjacent layers of PLA filament, welded together during the 3D printing of the specimen. However, in certain regions of the transverse sections of the specimens a brittle fracture of the transversal and longitudinal area of the PLA filaments is produced, leaving layers of PLA filament divided and adhered to the different parts of the specimen generated after the fractures. This occurs during delamination between adjacent layers of the specimens. In this way the growth of the fracture weakens the cross section of the specimens, causing shear and bending stresses that affect the PLA filaments of the layers adjacent to the delamination process. Similarly, comparing Fig. 14 and Fig.17 it can be verified that the transverse fracture of the PLA filament is brittle, smooth and free, however the longitudinal fracture of the PLA filament generates some very thin and long polymers fibers over the fractured surfaces. These originate from a plastic fracture mechanism, allowing the material to yield and form long PLA fibrils. When the fibrils finally break they seem to buckle and adhere onto the fractured surfaces.

5. Numerical method

Ansys Mechanical [42] was the commercial software used to simulate numerically the structural behavior of the mechanical element under study under the scenario of loads and boundary conditions that are presented in Fig.3 and Fig.18. These are a fixed support on the bottom face of the mechanical element and a constant and static load of 900 N applied on the top face, with the same compression velocity that it is applied during the experimental test. In the mechanical simulations it is assumed that the established numerical models are linear and static. To define the plastic material of the numerical simulations, the isotropic and elastic properties have been established from the experimental results of the specimen tests (see Fig.8). On the one hand, in the first set of numerical simulations PLA plastic material is defined as an elastic isotropic material, where the value of the compression Young's modulus employed is constant and equal to 2528.5 MPa (see Table 6). This value is established according to the defined criteria in standard ISO-604 (see Eq.6). On the other hand, in the second set of numerical simulations the elastic properties of the plastic material are defined as uniaxial compression test data by importing a two columns array (uniaxial compression stress and nominal deformations) with the numerical values of the polynomial function used to interpolate the elastic area of uniaxial compression stress versus the nominal deformations obtained from the specimens' experimental tests. The coefficient of Poisson, for both numerical models, is equal to 0.38 (Parameter established by the manufacturer of the plastic material).

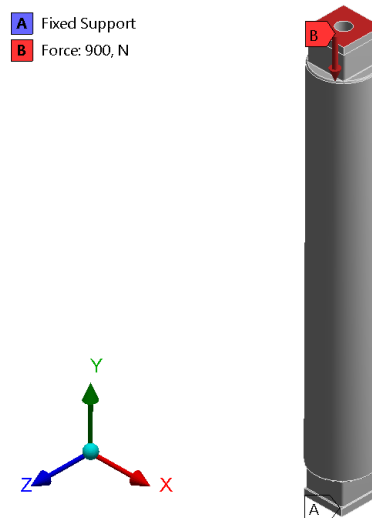


Fig. 18.- Load scenario and boundary conditions of the numerical simulations.

The mechanical element geometry is analyzed continuously throughout its domain, since the characterization of the plastic material includes implicitly the effects and modifications of the elastic and mechanical properties of the plastic material which are carried out during the additive manufacturing process. In order to discretize the geometry of the mechanical element under study solid structural tetrahedral elements of the type SOLID 92 were used. These elements have a quadratic displacement behavior, they are composed of 10 nodes (4 nodes in the vertices of the tetrahedron and 6 nodes in the midpoints of the same) and have three degrees of freedom in each node: translation in the Nodal X, Y and Z directions. To define the mesh a sizing operation is used that determines the approximate size of each element of the mesh, the section size being 2 mm. Fig. 19 shows the mesh used in the numerical simulations and Table 8 the statistics of the same. Finally, it should be noted that, given the modeling of the PLA plastic material used for both numerical simulations carried out the option of Large displacement in the Solver definition has been activated to ensure that the final solutions of both numerical models converge.

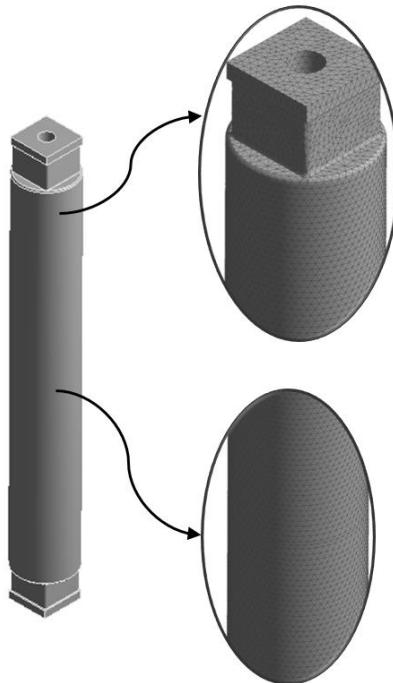


Fig. 19.- Mesh generated for mechanical simulation.

Number of elements	251,298
Number of nodes	159,494
Element quality (Average)	0.850

Table 8.-Statistics of the mesh generated for thermal modeling.

6. Results and discussion

The data of uniaxial compression force and nominal displacements (see Fig.10) for the experimental test of the mechanical element under study show that the structural behavior is not compromised for the load scenario and boundary conditions to which it is subjected. According to the agricultural application of the mechanical assembly in which the mechanical element under study is included, the element is subjected to a uniaxial compression force of 900 N applied at one end of its geometry, and supported by a fixed articulation to the mechanical assembly at the opposite end to the load application (see Fig.3). As shown in Fig.10 and Fig.11, for a uniaxial compression force of 900 N the mechanical element under study has a nominal displacement of 0.3288 mm, a nominal deformation of 0.0011 mm/mm and a stress state of 2.598 MPa. As can be seen, the structural behavior for the mechanical stress to which the mechanical element is subjected is far from its state of collapse or breakage. The state of collapse or rupture of the mechanical element is reached for a uniaxial compression force of 16091.0 N (see Table 7), a value much higher than the load scenario to which the mechanical element is subjected during its nominal operating. In this way, the use of PLA plastic material is validated as well as the manufacturing process by means of additive manufacturing techniques of the FDM type for the mechanical element under study, according to its nominal operating presented in this article.

In accordance with the ISO-604 standard, used for characterizing the compressive elastic properties of PLA plastic material, the maximum nominal deformation used to determine the elastic properties of the material must accomplish the inequality presented in Eq.7

$$\epsilon_c^* \leq 0.4 \cdot \frac{T_s^2}{L_s^2} \rightarrow 0.0025 \leq 0.4 \cdot \frac{4^2}{50^2} = 0.0026 \quad (7)$$

Eq.7 is defined by the geometrical characteristics of the specimens used for the material characterization. Where ϵ_c^* represents the nominal maximum deformation used for determining the elastic properties of the material, L_s [mm] represents the length of the specimens and T_s [mm] represents the thickness of the specimens. As can be seen (see Eq.7) the restriction imposed by the ISO-604 standard is fulfilled since the maximum nominal deformation used for the characterization of the Young's modulus compression is 0.0025 (less than 0.0026, the deformation obtained in the second member of the inequality Eq.7)

The domain of the polynomial function (and therefore of the elastic region of the curve imported into the numerical simulation software) in the numerical simulation is limited by a range of nominal deformations between 0 and 0.0026 mm (as determined by standard ISO-604). It should be mentioned that the numerical simulation has been carried out from the polynomial function that interpolates the uniaxial compression stress curve against the nominal deformations.

Fig.20 shows the displacement field for the mechanical stress analyzed in this paper (see Fig.3 and Fig.18), obtained by means of two types of numerical simulations performed on the mechanical element under study. In the first type of numerical simulation the maximum displacement at the end point where the uniaxial compression load is applied has a value of 0.31475 mm. This maximum displacement occurs in the area where the plastic material PLA is characterized as isotropic from its elastic properties. In this area the Young's modulus compression equals 2528.5 MPa, according to the criteria defined in standard ISO-604 (see Eq.6). In the second type of numerical simulation PLA plastic material is characterized by importing the points of the polynomial function. The results of the second simulation point to the maximum displacement value (in the direction where the load is applied) obtained at the end where the uniaxial compression load of value 0.32761 mm is applied. In the second simulation the polynomial function interpolates the elastic regime of the uniaxial compression stress curve versus nominal strain (see Fig.8) obtained in the experimental tests of the specimens. Comparing these numerical results with the experimental result, it is verified that the numerical model that uses the polynomial function that interpolates the uniaxial compression stress curve versus nominal strain (Case B, see Fig.20) is closer to the experimental solution with an error of 0.36%. For the numerical model where the material is defined as isotropic with constant Young's modulus compression (Case A, see Fig.20), the error in the numerical solution is 4.27% with respect to the experimental solution. We consider that both numerical simulations are analogous, except for the definition of the PLA plastic material.

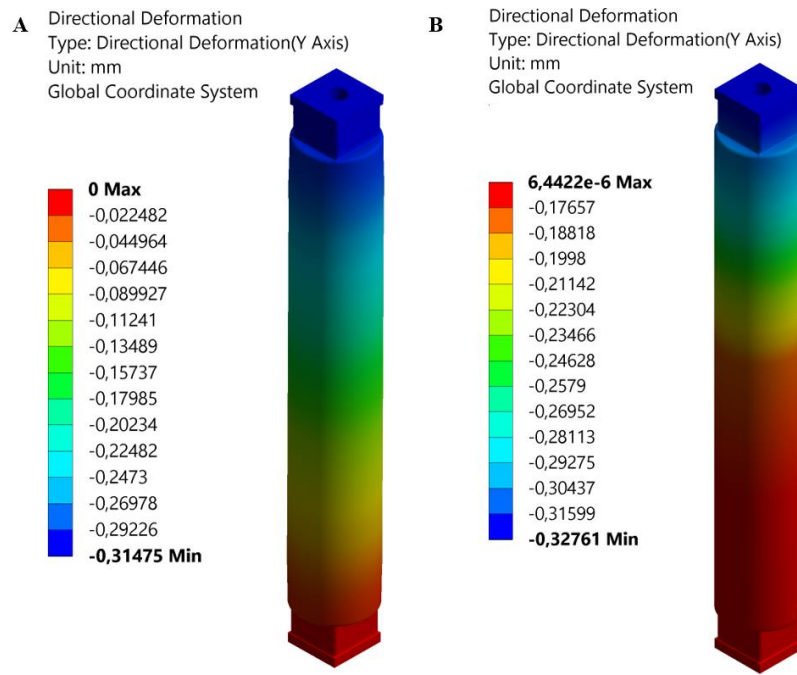


Fig. 20.- Field of displacements obtained in the mechanical simulations. a) Young's modulus Compression $E_c = 2528.5$ MPa. b) Importation of the polynomial function that interpolates the elastic region of the uniaxial curve compression stress vs. nominal strain curve.

In this way, it is verified that in order to numerically analyze the structural behavior of a mechanical element subjected to a tensional state of uniaxial compression the plastic material PLA for 3D printing by means of FDM techniques can be modeled numerically as an isotropic material. This is possible from the importation to the numerical calculation software of the polynomial function that interpolates the elastic regime of the uniaxial compression stress curve versus nominal strain for that material. That is, based on a structural analysis in the elastic region of the plastic material it can be considered and modeled numerically as an isotropic material and the elastic properties can be defined from the experimental results of the specimens tested according to ISO standard-604. In addition, this type of numerical modeling of the material is easier to define in the numerical simulation software, since it does not require the modification of the constitutive equations in the material database and choosing the right material orientation in the numerical model. However, outside the elastic regime anisotropic material properties should be considered for the numerical model of the material.

Finally, it should be noted that the magnitude of the compression yield stress parameter obtained in the experimental tests both for the specimens (see Table 6) and for the mechanical element under study (see Table 7) are analogous. The compression yield stress obtained for the tested specimens is equal to 44.2 MPa (see Fig.8), while the compression yield stress for the mechanical element under study is 48.78 MPa (see Fig.11). However, the fracture process of PLA plastic material is different for the geometry of the specimens and for the geometry of the mechanical element under study. That is, the magnitude of the compression fracture stress parameter differs since in the experimental tests of the specimens the value is 28.3 MPa while in the mechanical element under study the value is 48.47 MPa. As shown in Fig. 11, the compression fracture stress is close to the compression yield stress, which means that the geometry and circular ring-shaped section of the mechanical element under study has a brittle fracture of the PLA plastic material. That is, the plastic deformation after reaching the compression yield stress until the compression fracture stress is very small or even negligible. On the other hand, Fig.8 shows that the compression yield stress of the PLA material for the geometry of the specimens tested is far from the compression fracture stress. This implies that for the prismatic geometry of the specimens there is a more noticeable plastic deformation despite having a completely brittle breakage caused by the rupture and separation between the different layers of the printed plastic material (see Figs.14, 15, 16 and 17). This may be due to the fact that the specimens tested and the mechanical element under study have different geometry and cross section (despite sharing the same parameters in manufacturing using FDM additive techniques). Therefore, as in the present work, both tests can be compared only for the elastic region of the plastic material for 3D printing PLA.

7. Conclusions

This paper presents a numerical-experimental study for obtaining the mechanical properties of FDM for a real part subject to a stress field of uniaxial compression and to the specific requirements of the industrial product into which it is integrated [38]. The new product [38] consists of an innovative mechanical device for the displacement of heavy loads in olive harvesting manufactured completely in PLA and with FDM technology having been designed so that most of its components work under uniaxial compression stresses, a favorable state of operation of the PLA. The part object of study consists of a hollow bar of slender geometry subject to uniaxial compression stresses and to the technical specifications in quality and costs of the commercial product. In order to obtain the mechanical properties of the material that fulfils the manufacturing specifications to perform the part simulation, two experimental tests have been carried out. The first experimental test used a set of specimens manufactured with the same requirements as the final part in accordance with the conditions and requirements established in the ISO 604 standard for a uniaxial compression stress field. A second experimental test allows analyzing the structural behavior of the industrial case, evaluating the compression stiffness, the compression yield stress, the field of displacements and stress along its elastic area until reaching the compression yield stress and the ultimate yield stress data.

In order to numerically simulate the study case, two analytical models have been proposed for characterizing the elastic behavior of the PLA manufactured using FDM technology. The first of the models used Young's compression modulus according to the guidelines established in ISO standard 604. The second model used the interpolation of experimental data to obtain a polynomial function of eight degrees for the uniaxial tension-compression curve versus nominal deformations, which has allowed characterizing the material and fulfilling the specifications of the product with a high level of precision. The results of the simulations and the experimental tests show good accuracy between virtual and physical models both in the test specimens and in the study part. The comparison between experimental tests and numerical simulation results for the study case verify that the new model that uses the proposed polynomial function is closer to the experimental solution with only an 0.36% error, in comparison with the model with Young's compression modulus constant with an error of 4.27%. Additionally, the results of the simulations and the experimental tests indicate that the elastic region of the PLA plastic material manufactured with FDM can be modeled numerically as an isotropic material using the elastic properties from the experimental results of the specimens tested according to ISO standard 604 in the conditions of manufacture of the product.

The results of the numerical simulation point to the fact that the uniaxial compression force as well as the nominal displacements for the experimental test and the numerical simulations of the case show that its structural behavior is not conditioned by the load scenario and boundary conditions to which it is subjected. This validates the use of PLA plastic material and the FDM manufacturing process for the mechanical element under study and for the functional requirements presented in this paper.

The paper presents an application case where the characterization of the material is validated with a real industrial part, presenting research results on which there are very few publications, since most of the investigations present only general results on test specimens. The characterization data of the material under the conditions established in the document are not available either at the research level or at the industrial level. The results have allowed us to validate the rest of the design components that are subject to the same requirements without the need to manufacture the components physically, avoiding costly experimental tests. Additionally, the results obtained have allowed us to simulate the components designed throughout the conceptual validation phase. In this phase of the design process, multiple changes occur in the geometry of the product which has allowed us to save costs and development time. The results presented suggest that the use of FDM technology with PLA material is promising for the manufacture of low volume industrial components that are subject to compression stresses or for the manufacture of components by the user.

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