Methodology to estimate the modulus of elasticity of parts manufactured by FFF/FDM combining finite element simulations and experimental tests

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Abstract: Due to the manufacturing characteristics “layer by layer” of Additive Manufacturing processes (AM) such as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) techniques, the manufactured parts exhibit anisotropic behaviour, and therefore it is complex to estimate their mechanical response. Consequently, finite element (FE) modelling of the performance of this kind of additive parts can be time-consuming, especially for implicit algorithms. For this reason, in this work, a proposal of simplified FEM model is presented to reduce the computation time but keeping accurate results, when predicting the modulus of elasticity of FDM parts. The methodology is based in a combination of experimental and numerical simulation techniques. A FEM model is developed using the commercial finite element software Abaqus/Standard. The parameters considered in this study are the percentage of infill (25, 50 and 75%) and the construction orientation (XYZ). Tensile tests were performed following the guidelines specified in the standards UNE-EN ISO 17296-3 and UNE-EN ISO 527-2. The comparison of the elastic behaviour obtained by both experimental and simulation techniques allowed to adjust the simulation parameters, resulting in a simplified FE model. The methodology presented can be used as a prediction tool to analyse the tensile mechanical behaviour of this kind of samples.

Keywords: Additive Manufacturing, FFF/FDM, Material extrusion, FEM, Tensile properties.

1. Introduction

Due to the manufacturing characteristics “layer by layer” of Additive Manufacturing processes (AM) such as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) techniques, the manufactured parts exhibit anisotropic behaviour, and therefore it is complex to estimate their mechanical response [1]. Cuan-Urquizo et al. have identified three different approaches to the problem: experimental, computational and theoretical [2]. Although there is not a homogeneous regulatory context for the standardization of the mechanical characterization of FFF parts [1,3], many works have attempted to characterize them from an experimental approach by the testing of specimens [4]. Cuan-Urquizo et al. have summarized some of the works developed in this line for FDM parts for different materials and tests, such as tensile, compression, torsion, bending, dynamic loading, failure under fatigue or mechanical fracture [2]. The mechanical properties of the test specimens are influenced by the FDM process parameters such as slicing parameters, building orientation and temperature.
conditions, among others. Popescu et al. collected also the main works developed in this area [5]. As it is difficult to compare results from the variation of all of the parameters involved in the manufacturing of the piece, some works focus on the influence of different key parameters on the mechanical behaviour of the printed piece, for example, the filling pattern geometry and orientation, its density, the building orientation or number of contours deposited at the edges, among others [6–8]. Others, however, focus their attention to the comparison between the mechanical behaviour of different materials, such as ABS and PLA [9,10]. Analytical approaches have also been used to describe and predict the mechanical behaviour of parts manufactured by additive technologies. On the one hand, the classical laminate theory (CLT) has been used to this matter as additive technologies involve a layer by layer manufacture [5,11]. On the other hand, Liu et al. studied the relation of the three material scales involved in the part fabrication: its micro scale, the meso scale of layers and paths through the material deposition and the macroscale of the printed piece. It is important to predict the mechanical behaviour of the microscale and understand the construction of the piece through the mesoscale in order to be able to estimate an orthotropic material characterization from a unit cell behaviour [12]. Other analytical approaches have been used combined with experimental approaches to characterize the printed parts [7]. Works with computational approaches, basically through the simulation of the mechanical response of 3D printed parts using Finite Element Analysis (FEA) can be found in 3D or 2D. Experimental and simulated tests share the same considerations, and each work focus on some printing parameters or materials to analyse their results [13–16]. Another important consideration that directly affects the characterization of manufactured parts by additive manufacturing is the analysis of geometric differences between the design model and the manufactured model [17]. In this sense, comparisons between analytical or simulated results with experimental tests are considered of interest for a greater understanding and prediction of the mechanical behaviour of printed parts [18,19]. Finite element (FE) simulation of the performance of FFF/FDM parts can be time-consuming, especially for implicit algorithms. For this reason, in this work, a proposal of simplified solid FEM model is presented to reduce the computation time but keeping accurate results.

2. Methodology

The methodology is based in a combination of experimental and numerical simulation techniques. FEM models were developed using the commercial finite element software Abaqus/Standard. At the same time, different test specimens were manufactured by a commercial equipment of FDM (model Kossel Mini) to perform tensile testing with a universal testing machine Hoytom HM-100kN. The parameters considered in this study were percentage of infill (25, 50 and 75%) and the construction orientation (XYZ). Tensile tests were performed following the guidelines specified in the standard UNE-EN ISO 17296-3 [20], and more specifically, the standard UNE-EN ISO 527-2 [21]. The last step consists of comparing the mechanical variables obtained by both experimental and simulation techniques, to adjust the simulation parameters, resulting in a simplified FE model that can be used as a prediction tool to analyse the tensile mechanical behaviour of these kind of samples.

2.1. Experimental procedure

A Kossel 3D printer from the RepRap project has been used to fabricate the samples. The main technical characteristics are: a Bowden extruder, a head type E3D with a nozzle diameter of 0.3 mm, an approximate printing volume of 20 mm diameter and 240 mm height, a 3D Printer bed of borosilicate, absence of heated build platform, 3D printer control board MKS Mini of MakerBase and open source Marlin firmware. The open source Ultimaker Cura 3 has been used as slicing software. The material used is the thermoplastic PLA (polylactic acid), commercialized by the company BQ, in white colour. The mechanical properties of samples according to the manufacturer are presented in Table 1 [22]. The international standard ISO 527-2 was used for the mechanical characterization. Due to the limitations in dimensions found with the equipment, samples type 1BA was used, as referred in Appendix A of the aforementioned standard (see figure 1a).
Table 1. Mechanical properties of PLA samples manufactured by BQ [22].

| Mechanical property       | Injected samples | Printed samples (XYZ) | Printed samples (ZXY) | Testing standard |
|---------------------------|------------------|-----------------------|-----------------------|-----------------|
| UTS (MPa)                 | 52               | 50                    | 39                    | ISO 527         |
| Nominal strain at break (%) | 5                | 9                     | 4                     | ISO 527         |
| $E$ (GPa)                 | 1.32             | 1.23                  | 1.12                  | ISO 527         |

Figure 1. (a) Geometry of the specimens according to ISO 527-2 [21]. (b) XYZ Build orientation and infill pattern.

Due to the characteristics of the FFF process, the build orientation is a critical aspect that influences the directionality of the mechanical properties, associated to an anisotropic behaviour. Standard ISO/ASTM 52921:2013 [23] was used as reference. The process parameters used in this work are presented in Table 2 (figure 1b).

Table 2. Process parameters.

| Infill density (%) | Infill pattern | Orientation | Layer height (mm) | Surface thickness (mm) |
|--------------------|----------------|-------------|-------------------|------------------------|
| 25-50-75           | square grid    | XYZ         | 0.1               | 0.6                    |

According to the standard ISO 17296-3:2014 [20], the samples fabricated by AM must be tested following the procedure established in ISO 527-1 [24] and followings. The initial distance between clamps is 60 mm, as established by standard ISO 527-2 [21] and considering the geometry of the sample used. The equipment was a universal testing machine HOYTOM HM-D-100 kN, used in previous studies [9]. Five samples for each infill percentage were tested (figure 2).

Figure 2. XYZ Samples with different infill percentage. (a) 25%; (b) 50%; (c) 75%.
2.2. Finite element modelling

For the finite element simulation, the software Abaqus Standard (Dassault Systemès) was used. Considering the different behaviour of the external wall and the internal infill, both have been modelled as different regions in the FE model (figure 3a). This will also allow to adjust the simulation parameters for each one by comparison with the experimental results. The thickness of the walls was unified to 0.6 mm for all the external walls. Several partitions were applied in different regions to ease the meshing and the application of the loads and boundary conditions.

![Figure 3. FEM model. (a) Geometry of the sample modelled in Abaqus/CAE showing the regions associated to the external wall and internal infill; (b) Sample meshed.](image)

A tie contact condition was applied at the interface of the external wall and internal infill. As indicated in Abaqus/CAE User's Guide, this kind of contact condition implies that there is no sliding between the contact surfaces; thus, the inner subset is solidly connected to the outer sub-set at all contact surfaces between them. It is also necessary to model the connection of the sample with the clamps of the testing machine. For this purpose, two coupling type constraints have been applied at both ends of the specimen. This type of coupling constrains a surface, or sets of surfaces, rigidly to a reference node. This is particularly useful as the loads can be directly applied to that rigid node. One of the nodes was constrained by a socket to define the fixed jaw. This type of constraint limits the displacements in the three directions of the coordinate axes, as well as the respective rotations. For the movable jaw, a coupling connection was used in the same way as for the fixed jaw, but a boundary condition with a fixed amplitude displacement is applied. A displacement of 1 mm was used, since all the specimens tested reach the yield point with a deformation lower than this value. A mesh with elements of type C3D8R was used (figure 3b). These elements are general-purpose solid hexahedra, with a first-order integration point centred on the element. On the other hand, an implicit formulation is used with "hourglass control", which allows better results in meshes with few elements. In this work we are going to focus on the modelling of the elastic behaviour of the material since most of the structural calculations for parts obtained by FDM are aimed at avoiding permanent deformation of the manufactured parts. To model the properties of the material, a series of simplifications have been made. Firstly, it was assumed that the material is isotropic in both regions of the specimen (outer wall and inner infill); this assumption is commonly used in this kind of analysis [25]. Secondly, the material density, \( \rho \), was taken from the product data sheet (table 3) and calculating them in each model as a function of the percentage of infill.

The Poisson’s coefficient, \( \nu \), was assumed to be 0.42, as described in the work by F. Rezgui et al. [26].

| Mechanical property | External wall | Internal infill 25% | Internal infill 50% | Internal infill 75% |
|--------------------|--------------|---------------------|---------------------|---------------------|
| \( \rho \) (g/cm\(^3\)) | 1.24         | 0.31                | 0.62                | 0.93                |
| \( E \) (GPa)      | 1230.0       | 307.5               | 615.0               | 922.5               |
Finally, for the estimation of the Young’s modulus, E, it was assumed that the outer section will have the same elastic modulus as the material tested by the manufacturer; for the inner section, an iterative procedure will be carried out by comparison with the results obtained in the experimental tests. As starting data of the iterative procedure, the initial values established by the manufacturer modified in proportion to the infill percentages were used (table 3).

3. Results and discussion

3.1. Experimental results

The results obtained by experimental tests performed on the printed specimens are presented and analyzed below. Figure 4 shows the images of the specimens after the tests that were carried out.

![Figure 4](image)

**Figure 4.** Samples with different infill percentage after tensile testing. (a) 25%; (b) 50%; (c) 75%.

Figure 5 represents the stress-strain curves obtained after tensile testing of the specimens for the different infill values.

![Figure 5](image)

**Figure 5.** Stress-strain curves of samples with different infill percentage. (a) 25%; (b) 50%; (c) 75%.

| Table 4. Mechanical properties after tensile testing of the samples (UNE EN ISO 527-1). |
|----------------------------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Internal infill | \(\varepsilon_t\) (%) | \(R_p\) (MPa) | \(\varepsilon_t\) (%) | UTS (MPa) | \(E\) (GPa) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 25%             | 1.28 (0.17)     | 8.14 (0.33)     | 4.68 (0.35)     | 26.73 (0.84) | 0.748 (0.11)   |
| 50%             | 1.33 (0.18)     | 8.56 (0.22)     | 4.99 (0.12)     | 30.29 (0.54) | 0.787 (0.14)   |
| 75%             | 1.19 (0.12)     | 8.34 (0.09)     | 4.98 (0.15)     | 35.10 (0.72) | 0.770 (0.13)   |
The mechanical properties obtained by tensile testing are the following ones (table 4): the nominal strain at yield ($\varepsilon_y$), the nominal strain at break ($\varepsilon_t$), the tensile yield stress ($R_p$), the mechanical tensile strength ($UTS$), and the modulus of elasticity ($E$). These values are defined according to the nomenclature established in the standard ISO 527-1 [24]. As previously mentioned, we were going to focus on the elastic behaviour of the FDM parts. For this reason, a linear regression line adjusted by the least squares method is calculated in the interval $\varepsilon_1 = 0.05\%$ and $\varepsilon_2 = 0.25\%$ used to calculate the modulus of elasticity, $E$, as established by the standard ISO 527-1 [24]. The analysis of the results showed that in some tests the deviations are high compared to the mean. For this reason, in this methodology, it is recommended to disregard the two measurements with the greatest dispersion in each of the tests. Thus, finally the evolution of the modulus of elasticity, $E$, versus the infill percentage is presented in figure 6.

![Figure 6](image)

**Figure 6.** Evolution of the modulus of elasticity versus the infill percentage in experimental tests.

### 3.2. FEM simulations and iterative process

As mentioned above, an iterative process was implemented to obtain an estimation of the equivalent modulus of elasticity for the region of the model with percentage of infill, taking as initial reference values those given in table 3; during the iterative process, the values obtained by the finite element method are compared to those calculated experimentally (table 5). The final values of the equivalent modulus of elasticity as a function of the infill percentage are shown in Table 5. By obtaining the equivalent modulus of elasticity for the percentage filled region, it is possible to obtain a first approximation of the elastic behaviour of FDM parts along the longitudinal direction.

| Infill percentage | 25% | 50% | 75% |
|-------------------|-----|-----|-----|
| $E$ (GPa)         | 0.202 | 0.273 | 0.291 |

### 3.3. Validation of the FEM model and methodology

The graphs in figure 7 show the comparison of the stress-strain curves in the elastic region obtained by experimental tests along with the ones predicted by the FE model in red colour. The results show a good agreement of the FE prediction with the experimental tests and demonstrate that the simplified finite element model is able to simulate the mechanical response of samples manufactured by the fused deposition modelling technique, and to predict the elastic behaviour of final parts, so the finite element model and the methodology can be validated.
As general guidelines, the methodology to estimate the Young’s modulus, E, is divided into three steps: 1) Tensile tests according to the standard UNE-EN ISO 527-2; 2) FE modelling: the external wall (same elastic modulus as the material tested by the manufacturer) and the internal infill are modelled as different regions; 3) Iterative procedure for the inner section: comparison with the results obtained in the experimental tests, taking as starting data the initial values established by the manufacturer modified in proportion to the infill percentages.

4. Conclusions
The finite element (FE) simulation of the performance of FFF/FDM parts can be time-consuming, especially for implicit algorithms. The procedure presented in this work allows to simplify the FE modelling of parts made by this type of additive manufacturing processes, using some practical assumptions, but keeping accurate results. Concretely, the elastic response of final parts manufactured by FDM/FFF processes has been evaluated by the estimation of the equivalent modulus of elasticity for the region of the model with percentage of infill; an iterative procedure based in experimental tests considering the infill percentage as the main printing parameter has been applied. This work shows the feasibility of the methodology proposed to predict the elastic behaviour of the samples under tensile testing. FE modelling of parts obtained by AM is an open area for future research because it will contribute to minimize the time to market of new products based in additive manufacturing, but also the costs associated to mechanical testing. The methodology presented in this paper can be used to determine the elastic behaviour of FDM samples in other directions, or even could be extrapolated to predict other mechanical properties such as the yield point of this kind of specimens.

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