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Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory

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ABSTRACT

The Fused Deposition Modelling (FDM) has become one of the most used techniques to 3D object rapid prototyping. In this process, the model is built as a layer-by-layer deposition of a feedstock wire. In recent years, the FDM evolved from rapid prototyping technique towards a rapid manufacturing method, changing the main purpose in producing finished components ready for use. Thus, the prediction of the mechanical properties of this new technology has an increasingly important role. Previous papers have highlighted the orthotropic mechanical behaviour of FDM parts showing that the stacking sequence controls the mechanical properties of FDM parts. The aim of this work is to describe the mechanical behaviour of FDM parts by the classical laminate theory (CLT). In order to reach this objective, the values of the elastic modulus in the longitudinal and transverse directions to the fibre (E_1, E_2), the Poisson's modulus (ν_{12}) and the shear modulus (G_{12}) will be experimentally measured.

1. Introduction

The Fused Deposition Modelling (FDM), developed by Stratasys Inc., has become one of the most used techniques to 3D object rapid prototyping. This technology has many potential fields where it could be used, however, the currently main applications are the design verification, kinematic functionality testing, fabrication of models for visualization and medical applications [1]. In this process, as for many others 3D printing technologies [2], the model is built as a layer-by-layer deposition of a feedstock material. Initially, the raw material is in the form of filament that is partially melted, extruded and deposited by a heated nozzle onto the previously built model [3]. After the deposition, the material cools, solidifies and sticks with the surrounding material. Once the entire layer has been deposited, the nozzle moves upward along the z-axis for the deposition of the next layer. The principle of the FDM technology offers great potential because, without any need for machining, allows the fabrication of complex 3D parts directly from a computerized solid model. Traditionally, the FDM 3D printers have been able to build parts only in thermoplastic materials such as polylactic acid (PLA) and acrylonitrile-butadiene-styrene (ABS). The PLA offers better thermo-mechanical characteristics than ABS having a stronger mechanical resistance and a lower coefficient of thermal expansion. The last characteristic improves the printability of PLA because reduces the effects of warping during the printing phase. Moreover, it shows less health risks than ABS when printing in small and improperly ventilated spaces [4]. Nowadays, many others materials have been used or developed, e.g., bioresorbable polymer (PCL) [5], short fibre composites [6], ceramics [7], metal [8] and metal/polymers mixture materials [9].

In recent years, the FDM evolved from rapid prototyping technique towards a rapid manufacturing method, changing the main purpose in producing finished components ready for use [1,10]. Indeed, this technique is particularly promising for the fabrication of a single piece or, in general, low volume products such as replacement parts for not widespread system. This trend highlights the need for a deep understanding of the mechanical properties and the behaviour of parts produced by FDM. A thorough understanding of the mechanical properties is complex, because this is influenced by many production parameters whose combination is often difficult to understand. Moreover, a FDM part can be considered as laminated composite structure with vertically stacked layers of bonded fibres [11]. As consequence, not only the feedstock material controls the mechanical properties of FDM parts, but also, the stack sequences whereby the layers are overlapped. Several papers deal with the anisotropic characteristics of FDM parts in recent years. Ahn et al. [11] carried out several experiments to determine the effects of air gap, bead width, raster orientation and ABS colour on tensile and compressive strengths. They determine that air gap and raster orientation have an important effect on the tensile strength, on the other hand, the other parameters have negligible effects. Moreover, the factors that they have studied do not affect the compressive strength in a noticeable way. Lee et al. [12] concluded that raster angle, air gap and layer thickness influence the elastic performance of flexible ABS objects. Also Anitha et al. [13] studied the effect of the layer thickness showing that the performance increases when the thickness decreases. Sood et al. [14], using the response surface methodology, analyse the functional relationship between specimens

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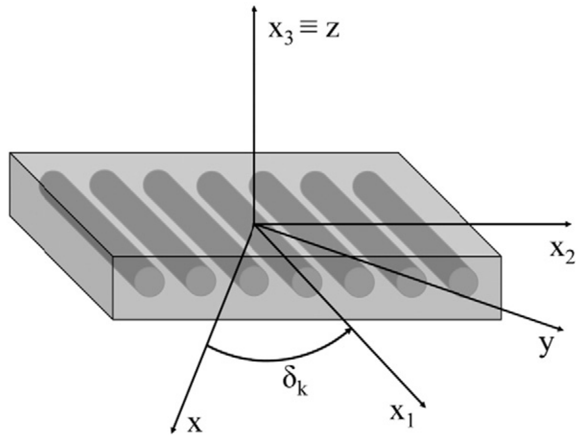

Fig. 1. Laminate {x, y, z} and layer {x_1, x_2, x_3} systems reference.

strength and several factors, e.g., build orientation, layer thickness, raster angle and air gap. Their results show that these factors influence the bonding and distortion within the parts. Lee et al. [15] carried out several experiments on cylindrical layered parts made from three different rapid prototyping processes, i.e., FDM, 3D printer and nano-composite deposition (NCDS). The aim of their work was to study the effect of the build direction on the compressive strength. The results show that compressive strength is greater for axial FDM specimens than for the transverse ones. This empirical approach allows to understand easily the relation between the FDM process parameters and the mechanical properties of the material, but it needs expensive experimental campaigns and, generally, it is difficult to extrapolate the behaviour of the material in other conditions. On the contrary, few papers in literature deal with the development of predictive models to determine the mechanical properties of FDM parts. Croccolo et al. [16] develop an analytical model taking into account some of the 3D printer parameters to determine the final mechanical characteristics of the specimens. However, this model needs to introduce adhesive force between the beads that could be difficult to estimate. Contrariwise, the use of models widely known and implemented, such as the classical laminate theory, already employed for composite materials, could be a real advantage in terms of usability.

The aim of this work is to describe the mechanical behaviour of FDM parts by the classical laminate theory (CLT). In order to reach this objective, the values of the elastic modulus in the longitudinal and transverse directions to the fibre (E_1, E_2), the Poisson's modulus (ν_{12}) and the shear modulus (G_{12}) will be experimentally measured. The determination of E_1 and E_2 will be carried out by single layer tests conducted on specimens with 0° and 90° raster angles. The Poisson's modulus will be determined measuring, on five layers 0° specimens, the longitudinal and transverse deformation by strain gauges. The shear modulus, G_{12}, will be determined according to the ASTM D3518. In this study, two different material ABS and PLA will be employed to prove the validity of CLT on several materials.

2. Materials and methods

In this work the CLT has been applied to describe the mechanical behaviour of FDM printed parts. As requested by CLT, the values of the elastic modulus in the longitudinal and transverse directions to the fibre (E_1, E_2), the shear modulus (G_{12}) and the Poisson's modulus (ν_{12}) have been experimentally determined. Finally, the comparison between the CLT and the experimental results, conducted on ABS and PLA, has been carried out on symmetric and balanced specimens.

2.1. Classical laminate theory

The classical laminate theory allows to calculate the elastic behaviour of a multi-layer orthotropic material using the constants that describe the mechanical behaviour of the single layer E_1, E_2, ν_{12}, G_{12} and h_c. E_1 and E_2 are the elastic modulus in the longitudinal and transverse directions to the fibre, ν_{12} is the Poisson's ratio, G_{12} is the shear modulus and h_c is the layer thickness. The reduced stiffness tensor $\mathbf{Q}_k$ can be calculated, for each layer k and in the layer system reference {x_1, x_2, x_3} (Fig. 1), as:

$$Q_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}. \qquad (1)$$

The terms in the matrix are:

$$Q_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}}, Q_{12} = \frac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}}, Q_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}, Q_{66} = G_{12} \qquad (2)$$

with

$$\upsilon_{21} = \upsilon_{12}\frac{E_2}{E_1}. \qquad (3)$$

The relations between the applied forces **N** and moments **M** and the resulting mid-plane strains $\boldsymbol{\varepsilon}^0$ and curvatures $\boldsymbol{\chi}$ can be summarized as a single matrix equation:

$$\begin{Bmatrix} \mathbf{N} \\ \mathbf{M} \end{Bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B} & \mathbf{D} \end{bmatrix} \begin{Bmatrix} \boldsymbol{\varepsilon}^0 \\ \boldsymbol{\chi} \end{Bmatrix} \qquad (4)$$

where the tensors **A**, **B** and **D**, when thickness h_c of the layers is constant, are:

$$\begin{aligned} \mathbf{A} &= \frac{h}{n}\sum_{k=1}^{n}\mathbf{Q}_k(\delta_k) \\ \mathbf{B} &= \sum_{k=1}^{n}\frac{1}{2}\frac{h^2}{n^2}b_k\mathbf{Q}_k(\delta_k) \\ \mathbf{D} &= \sum_{k=1}^{n}\frac{1}{12}\frac{h^3}{n^3}d_k\mathbf{Q}_k(\delta_k). \end{aligned} \qquad (5)$$

In Eq. (5), k has been numbered from the bottom of the laminate, n is the total number of layers, h is the laminate thickness while b_k and d_k are:

$$b_k = 2k-n-1 \qquad (6)$$

$$d_k = 12k(k-n-1) + 4 + 3n(n+2). \qquad (7)$$

In Eq. (5) $\mathbf{Q}_k(\delta_k)$ is the reduced stiffness tensor of the layer *k* in the laminate reference {x, y, z}. As indicated in Fig. 1, δ_k is the angle between x-axis of the laminate reference and the x_1-axis of the layer k.

Table 1
Fixed printer parameters.

Parameter	Value
Air gap [mm]	0
Layer thickness [mm]	0.35
Bead width [mm]	0.70
Number of contour lines	2