Analytical and experimental characterization of anisotropic mechanical behaviour of infill building strategies for fused deposition modelling objects

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Abstract:
As consequence of the 3d printing extraordinary rising along the last years, product development fields are facing new challenges. In addition, it is notory that low cost additive manufacturing, as such fused filament fabrication (FFF), result in objects with anisotropic mechanical behaviour. Nevertheless, there is still lacking studies that highlight a proper specification of those mechanical proprieties. For that reason, the main goal of this work is to present a mechanical characterization of anisotropic behaviour of FFF objects as a function of infill strategy using a finite element method. In this work, the main effect of building parameters were investigated in addition the identification of generalized elasticity and failure mode formulations. By the end, the general reccomendation for objects building was sketched in order to support new strength based developments.

Key words: *Additive manufacturing, Finite element Method, Anisotropy*

1. INTRODUCTION

Along the last years, additive manufacturing, which is also known as 3D printing technologies, has started playing a new role in several market segments. This might be a consequence of popularization of low cost technologies, which is majorly characterised by fused filament fabrication (FFF) technologies (CUNICO, 2012; CUNICO, 2015).

In spite this extraordinary popularization, several challenges still need to be overcome, whereas several product and fabrication issues has been highlighted. Among these problems, material mechanical anisotropy directly affects mechanical strength, possibly jeopardizing functional parts (CHEN *et al.*, 2013; GUESSASMA *et al.*, 2016).

In addition, several studies have been done in order to better understand the anisotropic behaviour of FFF objects and fabrication parameters. For example, AHN *et al.* (2002) firstly experimentally describes the main effects of Fused deposition modelling as a function of air gap, bead width, colour, temperature and orientation. This work just evidenced the main contribution of each components for the strength of object. . On the other hand, there are studied of the damage and failure mode of FFF object under severe compression (GUESSASMA[1] e BELHABIB, 2016; GUESSASMA *et al.*, 2016). This kind of approach was also adopted by other studies, as such HAMBALI *et al.* (2010), LIU e SHAPIRO (2016), VILLALPANDO ROSAS (2013), (AGARWALA *et al.*, 1996), (ANITHA *et al.*, 2001),(BAKAR *et al.*, 2010), (BERTOLDI *et al.*, 1998), (ES-SAID *et al.*, 2000), (LEE *et al.*, 2005), (MONTERO *et al.*, 2001),(RODRÍGUEZ *et al.*, 2003),(SOOD, A. *et al.*, 2010),(SOOD, A. K. *et al.*, 2010) and(TOO *et al.*, 2002).

Nevertheless, there are few works related to the correlation between process parameters and mechanical strength of FFF objects in a computational environment.

For that reason, the present work exposes the theoretical analysis of mechanical anisotropy of FFF by the application of finite elements analyses. In addition, this work generalised the anisotropy behaviour of and generates numerical formulation which describes the elastic behaviour of FFF parts as a function of bead orientation, air gap and layer thickness.

For that study, we have applied a multivariable full design of experiment (2^4) with 2 levels and no central point where raster orientation (α), distance between lines (d) and layer thickness (h), bead width (w) were the control factors. In addition, the responses were: young modulus, Poisson ratio in z direction, Poisson ratio in y direction, maximum internal stress and maximum equivalent stress (based on specimen cross-section). By the end, we identified the contribution of the control factors for a generalised stiffness matrix .

For the finite element analysis, we used Solid Works Simulation and Ansys Workbench, besides using Minitab for data processing and Matlab for the numerical modelling.

2. MATERIAL AND METHODS

In order to properly analyse the anisotropic behaviour of FDM Parts, we applied a multivariable methodology where the control factors were: raster orientation (α), distance between lines (d) and layer thickness (h), bead width (w). As responses, we defined the maximum stress inside the object at break, in addition to relative young modulus, poisson ratio in z direction, poisson ratio in y direction and directional strains and stresses. In order to compare this work with previous studies, we have also analysed the mean stress (based on specimen dimensions) at break. The virtual experiment design is presented in Table 1, where the variable levels and their values are shown.

Table 1 - Virtual Experiment Design

	Levels	
	-1	1
distance between beads	0.35 mm	0.4 mm
layer height	0.3 mm	0.2 mm
orientation	0 °	90 °
bead width	0.41 mm	0.5 mm

In this table, values of distance between layers, layer height and orientation and bead width were shown and the design of experiment we applied in this study was Full (24) with no centre points.

For the finite element analysis, we modelled the specimens and fabrication filament, reproducing the main fabrication characteristics which effects the mechanical anisotropy. We have also used the standard specimen shape of ASTM 638 type IV in order to compare the results with exist data. In Figure 1, the transversal section of two specimens were put as example of the filament modelling.

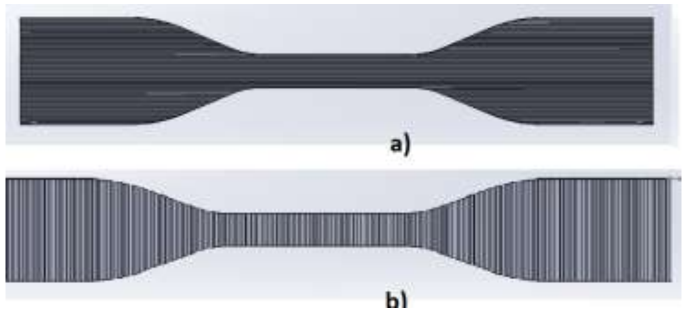

Figure 1 Top view of specimens with a) 0° of orientation bead and 0.35mm of distance between layers b) 0° of orientation bead and 0.45mm of distance between layers

For this analysis, we have also ignored effects of deposition temperature, environment temperature, bed temperature, warpening, and bead width variations. In this way, we can identify the effects orientation, height and distance between layers on the object elastic behaviour.

For the finite elements analysis, we defined a tetrahedral mesh with width of 0.025mm. An example of solid mesh and interaction between bead and layers in transversal cross section is presented in Figure 1.

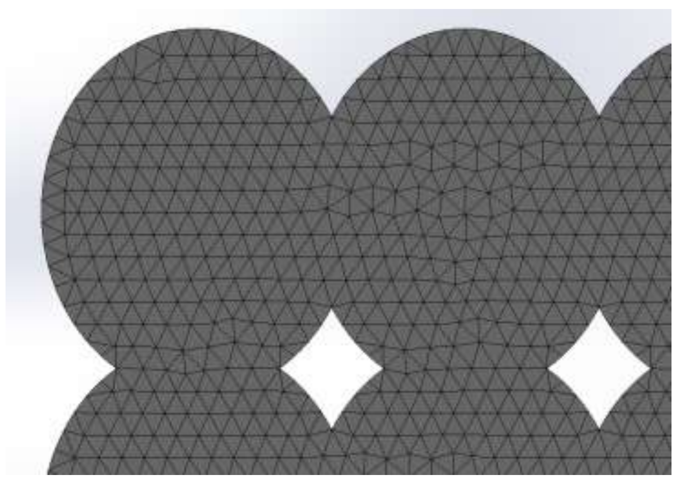

Figure 2 Mesh parameter and interaction between bead with 0.41 mm and layers height of 0.3mm

In order to evaluate elastic behaviour of these specimens, we analysed the strain in xyz directions and shear strain in xy, xz, yz directions, in addition to plane strain. For the analyses of young modulus and Poisson ratios, load combinations were applied and responses were acquired in notch area in order to generate strain-stress (S-S) diagrams.

3. RESULTS AND DISCUSSIONS

With respect to obtained results, we firstly identified the internal stresses of specimens and compared with average stresses in S-S diagram in the elastic domain of material. In this case, the average stress is relative to external area of notch cross section, simulating ASTM 638 procedures in Laboratory environment.

In Figure 3, the S-S diagram of experiment 1 is presented. The maximum internal principal stress and the average stress as a function of strain exposes a divergence that is mainly caused the internal porosity of specimen.

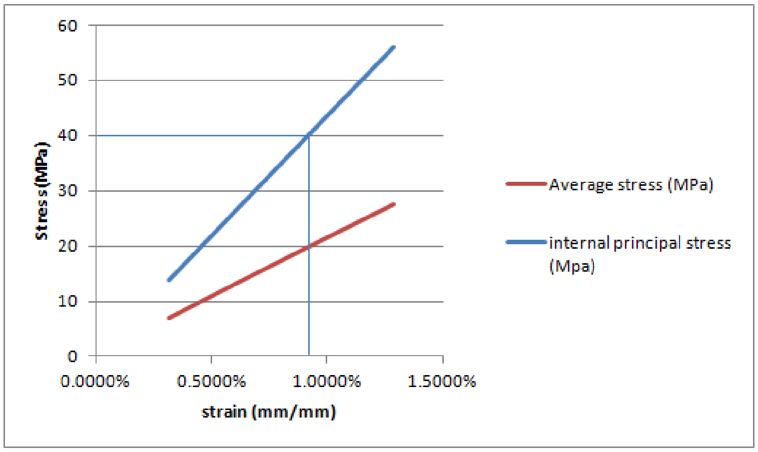

Figure 3 - S-S diagram of maximum internal stress versus average stress of experiment 1 (d-0.4;h-0.2;α-90°;w-0.5)

This figure also points that the yield stress of 40MPa of ABS in internal principal stress leads to 20 MPa in the average stress. Therefore, if we assume that yield stress is the design limit, we can identify that the maximum stress that objects would support is 20 MPa. For that reason, we selected this value as one of the main parameters for the virtual experiment analysis.

Another parameter that we extracted from this figure is the young modulus of average stress, which is obtained by the derivate of S-S curve.

Therefore, we can identify the main and secondary effects of processes parameter on yield stress and young modulus, as presented in Figure 4. In this figure, it is possible to see that orientation is the factor that most contribute for the increase of yield stress and elasticity modulus.

Another point that is also possible to see is that the secondary effects are small, indicating that the interaction between factors is low.

On the other hand, the Poisson ratio in z direction was shown to be most affected by layer height and orientation, as presented in Figure 5. This figure also indicates that Poisson ratio in y direction is most affected by bead width and distance between beads.

Another point that was also exposed in this analysis is that the interaction between control factors is high for Poisson ratio in y direction, where the distance between bead interacts with orientation. In addition, bead width interacts with orientation and layer height.

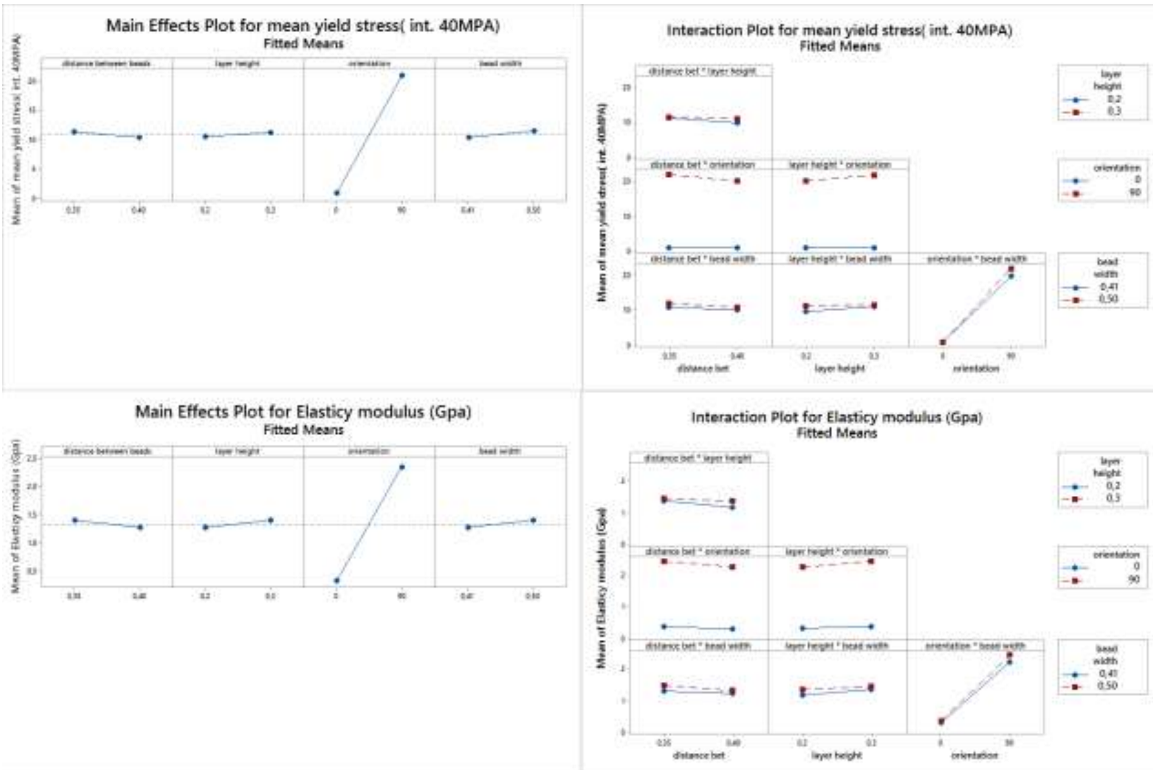

Figure 4 - Main and secondary effects of process parameter on Mean yield stress and elasticity modulus

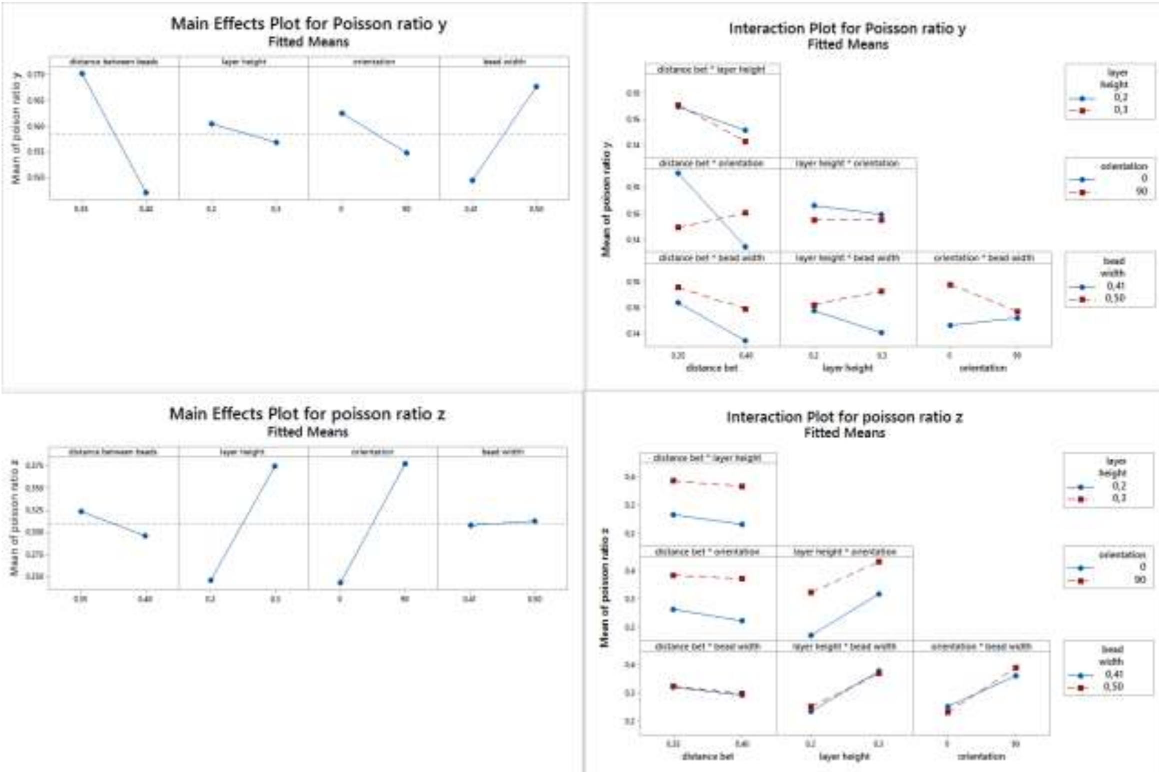

Figure 5 - Main and secondary effects of process parameter on Poisson ratio in z and Poisson ratio in y

Therefore, we could indicate a generalised formulation for elasticity, strain and stress as function of raster orientation (α), distance between lines (d) and layer thickness (h) and bead width (w).

$$\sigma = \begin{bmatrix} E & \frac{-v_Y}{E} & \frac{-v_Z}{E} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \end{bmatrix} \tag{1}$$

where:

$$\begin{aligned} E = & -7.024 + 20.30 \cdot d + 35.23 \cdot h - 0.4334 \cdot \alpha + 17.22 \cdot w - 99.64 \cdot d \cdot h \\ & + 1.086 \cdot d \cdot \alpha - 48.27 \cdot d \cdot w + 1.511 \cdot h \cdot \alpha - 76.91 \cdot h \cdot w + 1.108 \cdot \alpha \cdot w - 3.606 \cdot d \cdot h \cdot \alpha \\ & + 221.1 \cdot d \cdot h \cdot w - 2.692 \cdot d \cdot \alpha \cdot w - 3.658 \cdot h \cdot \alpha \cdot w + 8.917 \cdot d \cdot h \cdot \alpha \cdot w \end{aligned} \tag{2}$$

$$\begin{aligned} v_Y = & -1.214 + 2.416 \cdot d + 11.63 \cdot h - 0.07245 \cdot \alpha + 2.761 \cdot w - 24.10 \cdot d \cdot h \\ & + 0.1905 \cdot d \cdot \alpha - 6.29 \cdot d \cdot w + 0.1798 \cdot h \cdot \alpha - 21.08 \cdot h \cdot w + 0.1787 \cdot \alpha \cdot w - 0.4809 \cdot d \cdot h \cdot \alpha \\ & + 49.65 \cdot d \cdot h \cdot w - 0.4559 \cdot d \cdot \alpha \cdot w - 0.4806 \cdot h \cdot \alpha \cdot w + 1.2661 \cdot d \cdot h \cdot \alpha \cdot w \end{aligned} \tag{3}$$

$$v_z = -3.745 + 11.86 \cdot d + 19.59 \cdot h + 0.03976 \cdot \alpha + 8.759 \cdot w - 59.68 \cdot d \cdot h$$
$$- 0.1225 \cdot d \cdot \alpha - 26.42 \cdot d \cdot w - 0.1970 \cdot h \cdot \alpha - 39.96 \cdot h \cdot w - 0.09198 \cdot \alpha \cdot w + 0.6060 \cdot d \cdot h$$
$$+ 122.5 \cdot d \cdot h \cdot w + 0.2798 \cdot d \cdot \alpha \cdot w 0.4007 \cdot h \cdot \alpha \cdot w - 1.241 \cdot d \cdot h \cdot \alpha \cdot w \quad \textbf{(4)}$$

Therefore, it is possible to predict the mechanical behaviour of objects which were fabricated by FFF processes. In addition, applying this formulation in Finite element Software, we can optimize the fabrication parameters in order to improve mechanical properties.

It was also importance to note that this method indicated the maximum object stress that is acceptable in design as a function of process parameters.

Nevertheless, further studies are still needed to better understand applications, implications and contribution of this method for product and mechanical design.

4. CONCLUSIONS

In conclusion, this work evidenced the anisotropic behaviour of FFF specimens in a computational simulation environment.

The main and secondary effects were also exposed, where the bead orientation most affects the average yield stress and elasticity modulus. In contrast, bead width and distance between layers most affects Poisson ratio in y direction. The maximum design stress was also shown as a function of process parameters .

By the end, a generalized formulation of elasticity was identified, where bead width, distance between beads, layer height, and bead orientation were the variables that control the equation.

Moreover, more studies are still needed to better understand the anisotropic behaviour in addition to consider other process parameters in the analysis.

5. Acknowledgement

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