# BUILD PARAMETERS INFLUENCE ON FDM PARTS MECHANICAL BEHAVIOR

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***Abstract.*** *Obtain parts from Rapid Prototyping (RP) technologies is an important step on new products development process. In some cases these prototypes show worsted mechanical characteristics than the final product, which difficult the maximum potential presented by these technologies. In a especial way, Fused Deposition Modeling (FDM) technics, which deposits a ABS filament to build the parts, has its mechanical properties influenced by filaments deposition orientation. This work has as main goal to evaluate the deposition strategies influence on FDM parts mechanical behavior. Samples with different filaments deposition orientation between layers were then built. Mechanical tests were performed to check the parts final stiffness. The Lamination Classical Theory (LCT) was used to estimate the parts mechanical behavior on these different deposition orientations. The results showed differences between the LCT predictions and mechanical tests data, otherwise parts structurally stronger were obtained if compared to FDM deposition standards.*

***Keywords****: Prototyping, Classical Lamination Theory, Fused Deposition Modeling*

## 1. INTRODUCTION

Some layers manufacture techniques show a high potential to build functional parts with induced local mechanical properties. The Fused Deposition Modeling (FDM) technique has this potential to build parts with desired local characteristics by changing structural voids density and filaments deposition orientation. In this technology, basically, a polymeric material filament is heated and extruded trough a head that moves to x-y plane. When the extruded material is deposited it colds and solidifies generating the filaments. These filaments deposition side by side generate layers which reproduces the part geometry obtained from a 3D CAD system. The layers obtained show anisotropy, properties change at different directions (Bellini e Güçeri, 2003). The parts consist essentially by polymeric bonded filaments and voids. The mechanical properties by FDM prototypes are governed by its mesostructure, which are influenced by manufacture parameters as filament width, deposition orientation and gap between filaments. From these parameters selection, The FDM process may potentially produce prototypes with desired properties, inside process imposed limits.

To explore this potential, solutions around FDM parts fabrication process and mechanical properties must be investigated. According to Li et al (2002), among process parameters, the deposition directions and gaps between filaments are the most important to mechanical properties control. It is essential to analyze these parameters variation influence on FDM parts mechanical properties.

In Stratasys Inc. FDM machines, used in this job, the standard deposition strategy is defined by user as 45° raster angle followed by a 90º alternate angle between next layer. Is too possible select one or more layers and change angles individually. In this job is used the RP3 system (Rapid Prototyping Process Planning), developed by NUFER, Prototyping and Tooling Nucleus from UTFPR (Paraná Federal Technological University).

According to Volpato et al (2006), this is strategy planning system that reads part geometry, slice it and generates layers deposition information and send these data to RP machine. With RP3 system is possible to prototype parts in different angles between layers and there is freedom to manipulate other parameters as gap and filaments width, opening the possibility to investigate the mechanical behavior of parts with different build configurations. By the way is possible to obtain samples with different angles between layers, analyze its mechanical behavior and predict the best build configuration to show a better performance under a specific load condition.

To deposition configuration definition Classical Lamination Theory (CLT) was used.

This job has as main goal to evaluate the mechanical behavior of parts obtained by FDM process, using CLT concepts to filaments orientation deposition on building layers.

## 2. THE RAPID PROTOTYPING

In 80´s final, a new factory process based on layers material addition was developed. This process used part geometrical information directly from a CAD (Computer Aided Design) 3D for process planning. The generated information were directly sent to the machine, which once was set, started the job without operator assistance, no tools or moulds were need. (Carvalho e Volpato, 2007).

The great advantage on using RP is possibility to produce a physical part on any complexity in relatively short time. We observe that the products released on market last years have increased its complexity on shape and project. As a example, compare 70´s cars and nowadays, there is a great difference on design, and this improvement is accomplished by a relative reduction on product development time (Chua et al, 2003).

The process does not require special tools for fixation. Generally the parts are fixed on building platforms by supports created by technology itself, avoiding any apparatus project. The part is fabricated in a one process step. One machine is necessary to build the part, from start to the end. (Carvalho e Volpato, 2007).

### 2.1. The FDM process

The FDM process builds the prototype by extruded material deposition. The extrusion head with movements on X-Y axles, over a table that moves on Z axle, receive continuously the material on a wire shape, heating it until a semi-liquid point. When the extruded material filament gets the part surface it solidifies and there is the adhesion to previous layer. The table has a elevator mechanism that moves on Z axle the value by a layer thickness and the process is repeated until part complete construction. The Figure 1 shows the technology scheme.

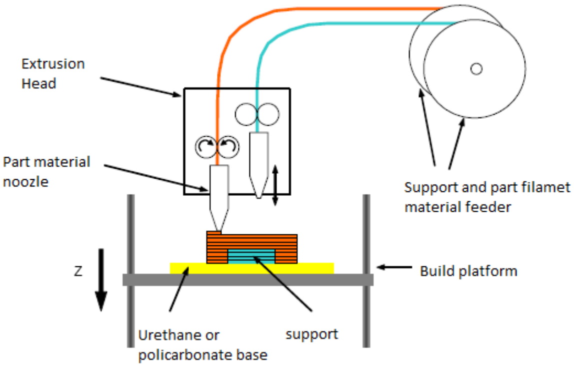

Figure 1 – FDM Stratasys Inc. process scheme.

Some of main build parameters that may be controlled are: layer thickness, filament thickness on boundaries and fillings, gaps between filaments, raster angle (for this deposition strategy) and angle between alternate layers (Volpato, 2007). The figure 2 shows a scheme by these parameters representation. It may be also adjusted the envelope temperature (inside build chamber) and extrusion temperature.

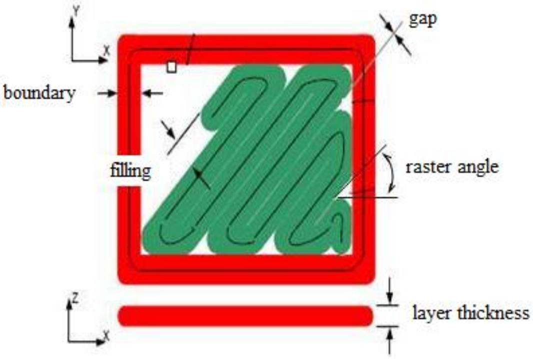

Figure 2 – FDM deposition layer scheme.

### 2.2. FDM parts structural quality

Several jobs (Rodriguez et al, 2000; Ahn et al, 2002; Li et al, 2002, Bellini e Güçeri, 2003), tried to identify the build parameters influence on FDM parts mechanical behavior. Ahn et al (2002) showed that two parameters are too important: gaps between filaments and deposition orientation. The first one is important on mesoestructure configuration, negative gap values results in minor structural voids and consequently more strength parts. Depending on deposition orientation, FDM parts may show good mechanical characteristics in some direction, but not satisfactory in another one. Figure 3 shows the mesoestructural difference obtained changing gap values only.

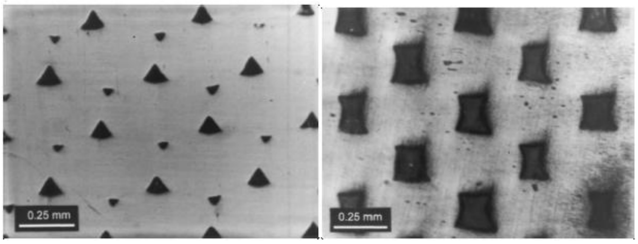

Figure 3. Structural voids changing the gap values. Left, g = -25.4 µm. Right, g = 76µm.

Figure 4 shows the tensile strength as function by deposition angle variation when samples are loaded axially. It is clear the part greater strength when all filaments are on load direction, where the own filaments resists to the load, when transverse orientation (90°) is used only bonding forces between filaments resists to loads, carrying to minor strength values.

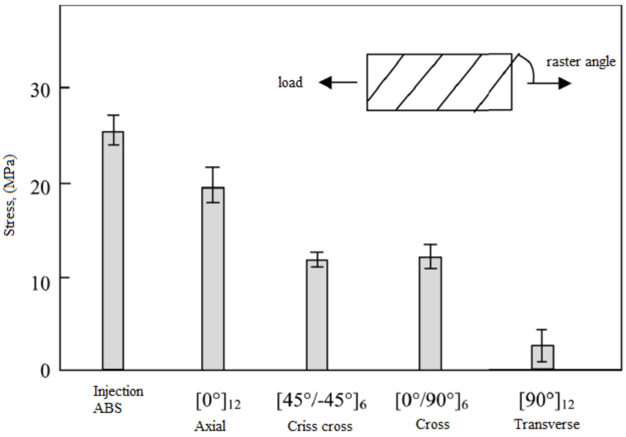

Figure 4 – Tensile strength for different deposition orientation.

## 3. LAMINATED COMPOSITE MATERIALS AND LAMINATION THEORY

According to Rodriguez et al (2000) the material produced by FDM process results in a composite laminated shape with layers vertically stacked constituting a fibers and voids structure.

Li et al (2002) says that FDM prototypes are orthotropic composite by ABS filaments, bonds between these filaments and voids. The analogy between fiber reinforced composite materials and FDM parts allows the use of some recently develped analytical tools to predict anisotropic products behavior (Bellini et al, 2003). According these assumptions, the mechanics of laminated composite materials knowledge may be used to predict mechanical behavior of FDM parts, as made by Kulkarni and Dutta (1999). In this way laminated composite materials and CLT are introduced and used as theoretical reference on this work development.

Laminated composite materials consist on thin layers integrally bonded. These layers may be by different or same materials. Generally the layers are disposal on different fiber orientations to generate optimized characteristics on a certain direction. The composite layers properties (as strength, stiffness, thermal conductivity) depends on laminated material reinforcement shape. These properties are strongly dependents on directional orientation by laminated composite (Jones, 1975). Isotropic materials show the same properties on any direction. Anisotropic are those with different properties on different directions.

Generally, the matrix material on composite which keep fibers united are isotropic. The fibers, which in general are stiffer than matrix, are isotropic too. But when combined, macroscopically, the properties aren`t isotropic. Stiffness is a example by property that varies as direction function in composite materials reinforced by unidirectional fibers.

We may consider, as example, the laminated composite showed at Figure 5 loaded in fibers direction, L, so as transversally fibers, T direction. When loaded on fibers direction, the longitudinal strain is lower, when compared under same load, to the transversal strain. Once strain under a specific load shows the material stiffness, the composite has different properties on longitudinal and transversal directions (L and T, respectively).

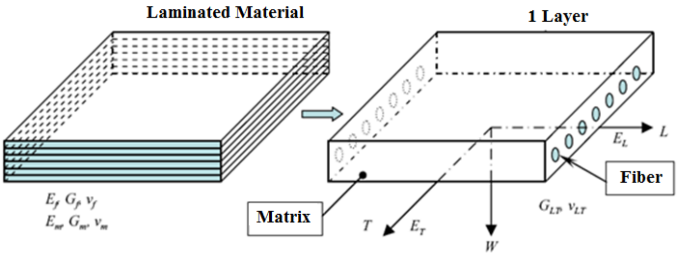

Figure 5. Laminated material main load directions scheme.

The stiffness on fiber direction (L) is closer to the fiber reinforcement material, Ef, Gf, vf , (Young Modulus, shear modulus and Poisson, respectively) while the transversal stiffness on fiber direction (T) is closer to the matrix material, Em, Gm, vm. The mechanical properties by a orthotropic layer on its plane may be completely described by four stiffness elastic properties. These properties are the two Young modulus EL e ET, longitudinal e transverse to fiber direction, respectively, the shear modulus, GLT and the greatest Poisson, vLT (Jones, 1975).

A way to prevent laminated composite materials behavior, once are known the four stiffness elastic properties to a orthotropic layer on its plane, is using CLT. Trough this theory different efforts may be related (membrane efforts Nx, Ny e Nxy), moments (Mx, My e Mxy) with medium plane strain (ε0) and curvatures (k) on laminated, trough Eq. (1) (Jones, 1975). Where Aij represents the membrane stiffness matrix components, Bij represents the matrix components by coupling and bending and Dij the matrix components by bending stiffness. As example, as greatest the A11 value to a laminated, as greatest its stiffness value to tensile or compression on x direction and as greatest the A22 value as greatest its stiffness on y direction. The same happens to B11, B22, D11 e D22, values but in these cases, the coupling and bending stiffness, respectively, on each direction, will be greater.

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{1}$$

## 4. MATERIALS AND METHODS

The flowchart presented on figure 6 shows the methodological approach adopted in the present work.

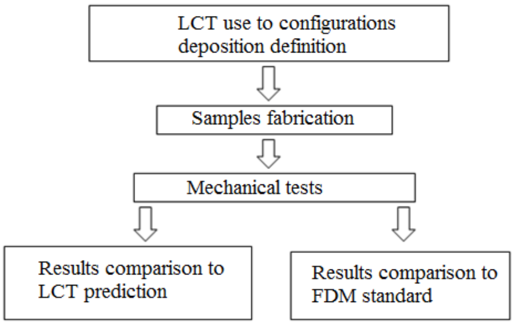

Figure 6 – Methodological approach.

Previous knowledge about CLT were used to prevent optimized deposition orientation to obtain parts with better stiffness performance on longitudinal direction. A computer program developed using MATLAB was used to generate matrix [A], [B] and [D] from equation (1) to different build configurations and laminate orientations. Basically, the program relates the four material elastic properties, E1, E2, v12 and G12 on two main directions (direction 1 = 0° and direction 2 = 90°, in relation to x axle), to prevent the behavior in different build configurations and deposition. These elastic properties, which were input to the program, were extracted to the work by Li e al. (2002) that conduct tests in unidirectional FDM samples to 0°, 45° and 90° to different gap values between filaments, reaching the four properties values.

Due to freedom offered by the computer program in varying fiber orientations an layer thickness, a sandwich (two crossed layers are followed one in another direction, example: : [(15/-15/0)2 / (0/-15/15)2]) stacking configuration study was performed, to check on which configuration a optimized stiffness should be obtained in relation to FDM standard deposition [45/-45].

On this way, the selected configurations to sample fabrication, as well as its complements (90° rotation) to direction 2 (transverse) properties evaluation, are as follows: 1 Longitudinal - [(15/-15/0)2 / (0/-15/15)2]; 1 Transverse - [(-75/75/90)2 / (90/75/-75)2]; 2 Longitudinal - [(75/-75/0)2 / (0/-75/75)2]; 2 Transverse - [(-15/15/90)2 / (90/15/-15)2] and 3 - [(45/-45)3 / (-45/45)3] – FDM machine standard orientation used as reference.

The configuration 1 showed the higher A11 and D11 values and configuration 2 higher A22 e D22 among configurations evaluated using computer program, by this reason were chosen to experimental analysis. Table 1 shows FDM process parameters used to samples fabrication.

Table 1 – FDM process parameters.

| N | Description | Value |
|---|---|---|
| 1 | Envelope Temperature | 70 C |
| 2 | Extrusion Temperature | 270 C |
| 3 | Filament width | 0.508 mm |
| 4 | Gap | -0.05 mm |
| 5 | Ø noozle | 0.304 mm (T12) |

The samples were then submitted to tensile and bending tests to determine its properties on two material main directions.

### 4.1. Materials

In this work a FDM 2000 prototyping machine was used, it presents a 250 x 250 x 250 mm volume capacity. ABS P400 was used to samples fabrication. This equipment allows only this material use.

The Solid Works CAD system was used to STL files generation, which were handle by RP3 (Rapid Prototyping Process Planning) software developed at NUFER (UTFPR Prototyping and Tooling Nuclei).

### 4.2. Tensile tests

Tensile tests samples were fabricated according ASTM D3039/3039-95A standards, in dimensions and geometry showed at figure 7. Strain gages type 250 B were used to strain measurements. Sandpapers were used on machine grips to improve samples constrain. The stain rate was adjusted to 50 mm/min. Sample were kept on environment standards conditions, 20°C, 50% relative humidity per 48 hours. Tensile tests were performed at Caxias do Sul Polymers lab, using machine universal tests EMIC DL 3000. Figure 8 shows a sample fabrication and figure 9 shows tensile tests apparatus.

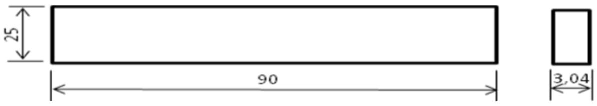

Figure 7 – Tensile tests sample geometry according to ASTM D3039 (dimensions in mm)

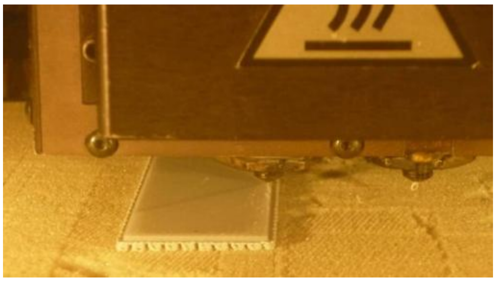

Figure 8 – Samples fabrication on FDM machine.

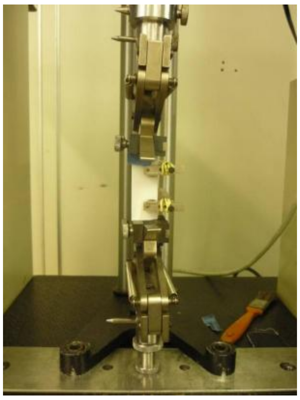

Figure 9 – Tensile tests apparatus.

### 4.3. Bending tests

Bending tests samples were fabricated according ASTM D790 standard on dimensions and geometry presented at figure 10. The three points bending tests was adopted where samples is supported in two extreme points and loaded at center. Figure 11 shows test scheme. Samples were kept on environment standards conditions, 20°C, 50% relative humidity per 48 hours. Tensile tests were performed at Caxias do Sul Polymers lab, using machine universal tests EMIC DL 3000.

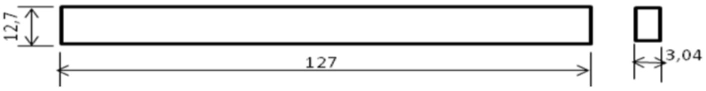

Figure 10 – Bending tests sample geometry according to ASTM D790 (dimensions in mm).

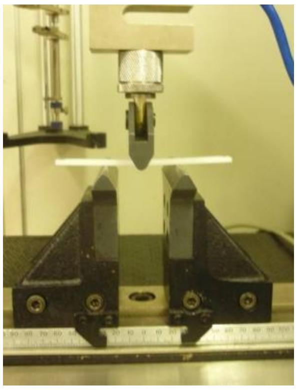

Figure 11 – Bending tests apparatus.

## 5. RESULTS AND DISCUSSION

### 5.1. Tensile Tests

Figure 12 shows stress-strain profile to sample on fabricated deposition configurations. Is observed that configuration 1 longitudinal [(15/-15/0)2 / (0/-15/15)2] presented a great climb on stress-strain curve and smaller strain in direction 1 (longitudinal), in other words, greatest elastic modulus. On this way, it presented greatest stiffness than on direction 2 (transverse), which presented greatest strain rates before fail, showing a ductile behavior.

The configuration 2 [(75/-75/0)2 / (0/-75/75)2] showed a great climb on stress-strain curve in both directions with smaller strain till fail. The configuration 3, FDM machine deposition standard, showed great strain rates before fail.

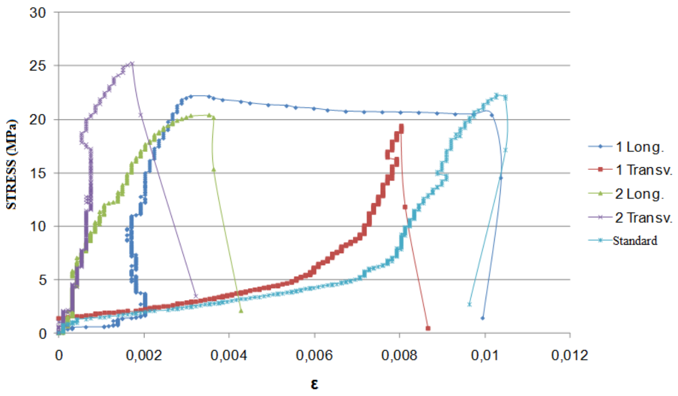

Figure 12 – Stress – strain curves from tensile tests.

Is observed that configuration 1 [(15/-15/0)2 / (0/-15/15)2] in longitudinal direction and configuration 2 [(75/-75/0)2 / (0/-75/75)2] in transverse direction showed a tensile strength greater than FDM standard deposition. Considering data as a Young Modulus, in other words, stiffness, is observed that in all studied directions the values are always superior than FDM standard, so, in both configurations 1 and 2 stiffener parts are obtained. These analyses may be seen in figure 13 graphics.

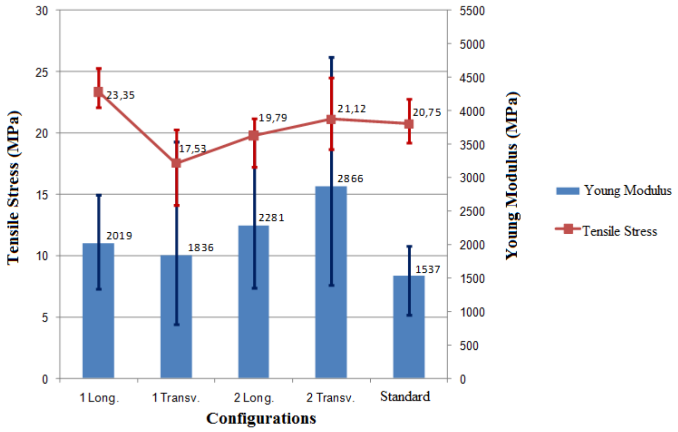

Figure 13 – Tensile stress and elastic modulus comparison to each configuration.

Trough Aij stiffness coefficient relation in direction 1 and 2 and sample total thickness is possible to calculate the effective Young Modulus or equivalent Eef, valid when membrane load only happens, which is given by (Jones, 1975)

$$Eef = \frac{1}{h_t} = \left( \frac{A_{11}A_{22} - A_{12}{}^{2}}{A_{22}} \right) \tag{2}$$

Where ht is sample total thickness. This modulus, analytically calculated, is related to the experimentally obtained, which are presented on graph by figure 14. A tendency is observed when the modulus are compared but some unexpected differences are check. According LCT the configuration 1 sample in longitudinal direction should present greater elastic modulus than configuration 2 transverse, what was not observed.

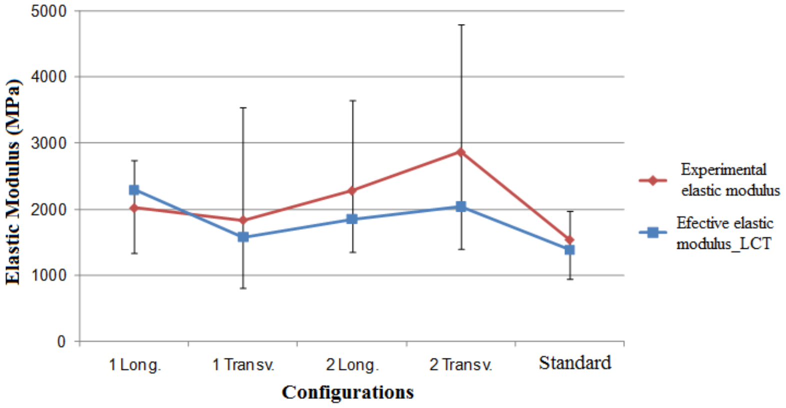

Figure 14 – Elastic modulus from tests versus effective elastic modulus prediction by LCT.

## 5.2. Bending Tests

Figure 15 shows average values by force-dislocation relation to studied configurations under bending load. Is observed that configuration 1 presents the greatest strength in both directions. The configuration 2 in longitudinal direction too, considering error limits. Considering elastic modulus values, in other words, stiffness, all configurations, except 2 transverse, show higher values than FDM deposition standard. In average, configuration 1 presents a 7% greatest stiffness than FDM standard in direction 1 and 6% in direction 2. Configuration 2 presents a 16% greatest stiffness than FDM standards in direction 1 and around 2 % minor in direction 2. These analyses are better evaluated on figure 16 graph.

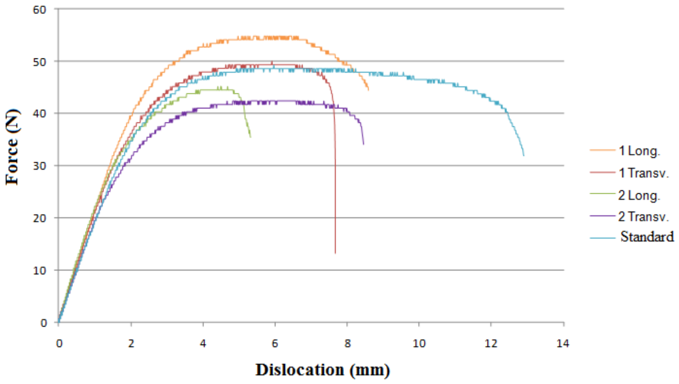

Figure 15 – Bending force x dislocation profiles comparison for studied configurations.

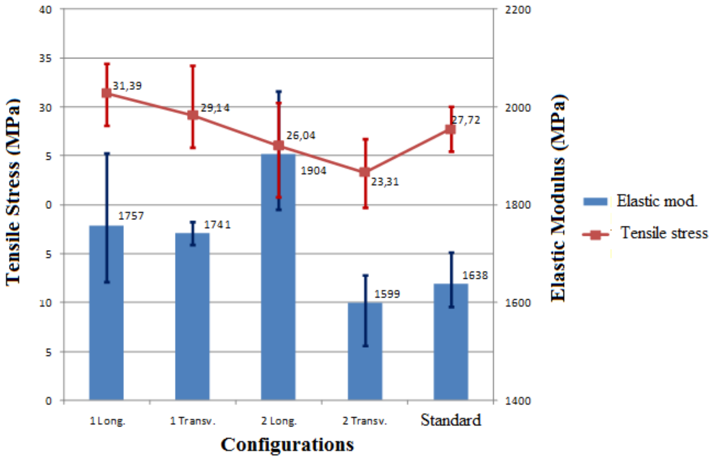

Figure 16 – Tensile stress versus elastic modulus comparison from bending tests to each configuration.

## 5. CONCLUSIONS

Using sandwich deposition layout on FDM parts, in all studied configurations, equal or optimized stiffness are observed on two material main directions if compared to FDM standard deposition configuration, in other words, orthogonal successive layers. On this way, this configuration type may be used to obtain stronger prototypes or final parts, allowing development teams to maximize gains using this technology.

Sandwich configuration parts did not follow LCT simulation results. According methodology used in this work, it was observed that analytical model did not perfectly predict configurations behavior, instead stiffer parts were obtained.

Is important remind that LCT does not consider structural voids presence. FDM parts presents structural voids and its geometry change according deposition configuration.

Several process parameters may influence FDM parts mechanical behavior, different deposition angles together sandwich configurations generate considerable gains in final parts strength. In thesis, these gains may be related to obtained mosoestructure, were structural voids were minimized.

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