Material coextrusion modeling and characterization in additive manufacturing

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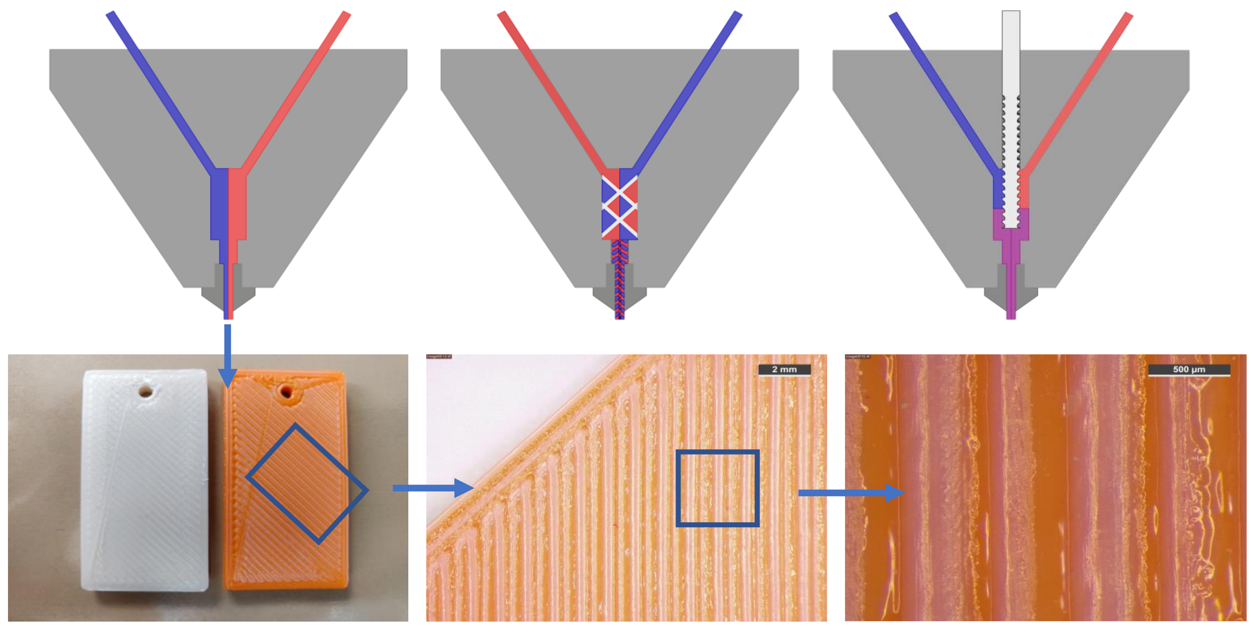
Abstract *Latest innovations in additive manufacturing have made it possible to use multiple materials simultaneously, allowing to locally change the properties of the parts produced in a way that has never been done before. A wide range of properties achievable by FDM printing are available, but models describing physical properties as function of the material combination and the extruder path are essential for the designer. In this work, a model of the elastic modulus of coextruded parts produced by Fused Deposition Modeling is proposed. The chosen materials for this work are PLA and TPU. In order to do that a basic model is developed to compute the young's modulus and compared with a FEM analysis of the tensile test on variable composition specimens. The results are then validated by mechanical characterization of the manufactured parts.*

Introduction Until recently, Additive Manufacturing has been mainly relegated to the prototyping of single-material structures for form fit evaluation. However, a possible disruptive step in the evolution of AM will be to increase the functionality of the manufactured components. It is possible to do that by varying the material composition inside the domain to achieve tailored characteristics for highly specific applications. In Fused Deposition Modeling, multi-material can be obtained by assigning different materials to confined spaces in the object and then placing them with multiple extruders or by switching filaments with a splicer; in one other way, it is possible to use a multiple materials – single nozzle hotend that can extrude multiple filaments together and so varying the composition gradually by controlling the fraction of each filament. By doing this, Functionally graded materials (FGM) are produced. In literature it is possible to identify three ways to extrude filaments at the same time. In the first alternative, the extruder pushes the flows side by side in a process called **Coextrusion** (this is typical of the Reprap project called diamond hotend); a slightly more advanced way will be to introduce a static mixer to passively mix the materials in a process called **Interlocking** [Khondoker et. Al. 2018]; lastly, the most advanced way to produce multiple material FGMs will be to use an active mixer in a process called in-situ **Blending** [Kennedy et. Al. 2020];.

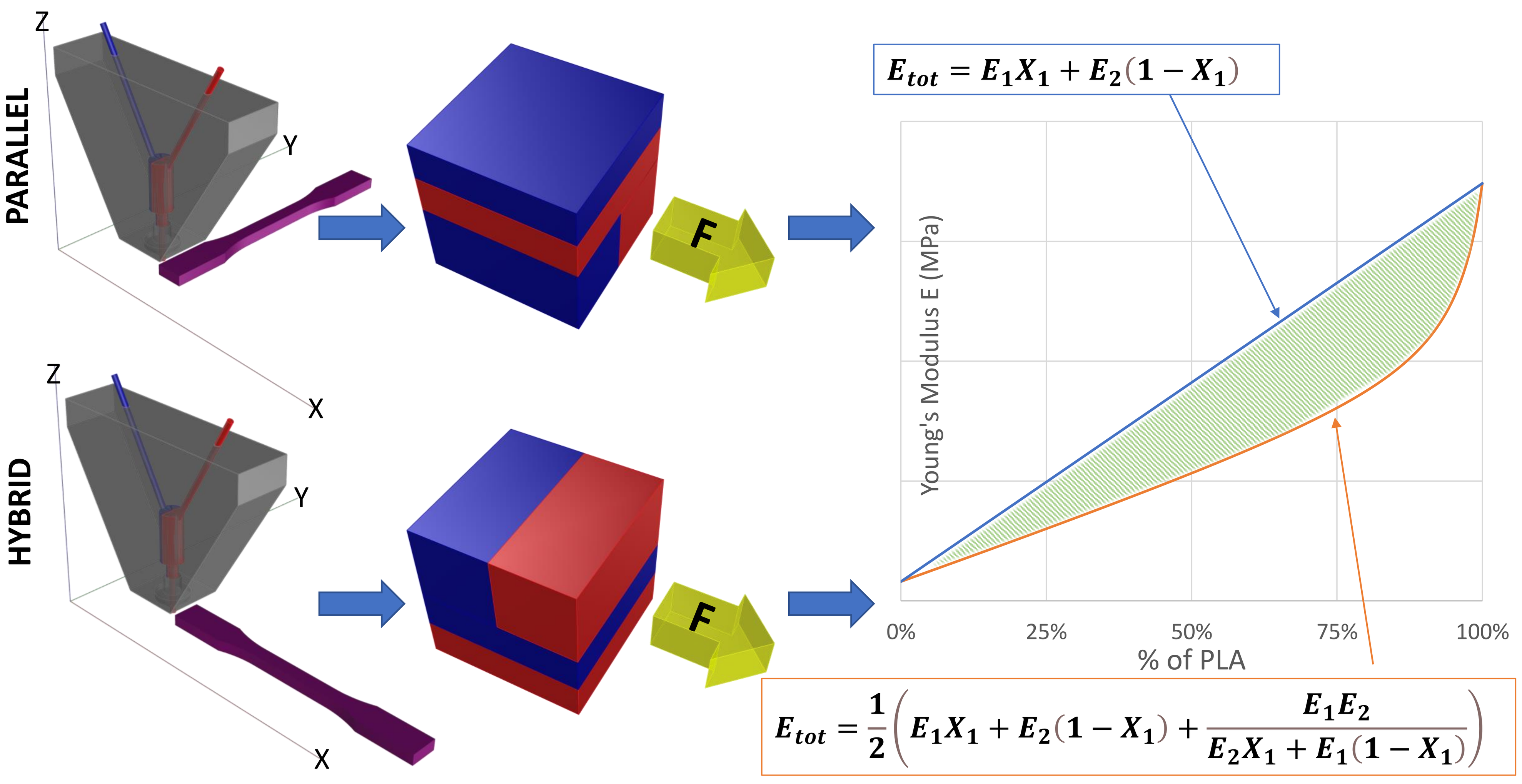


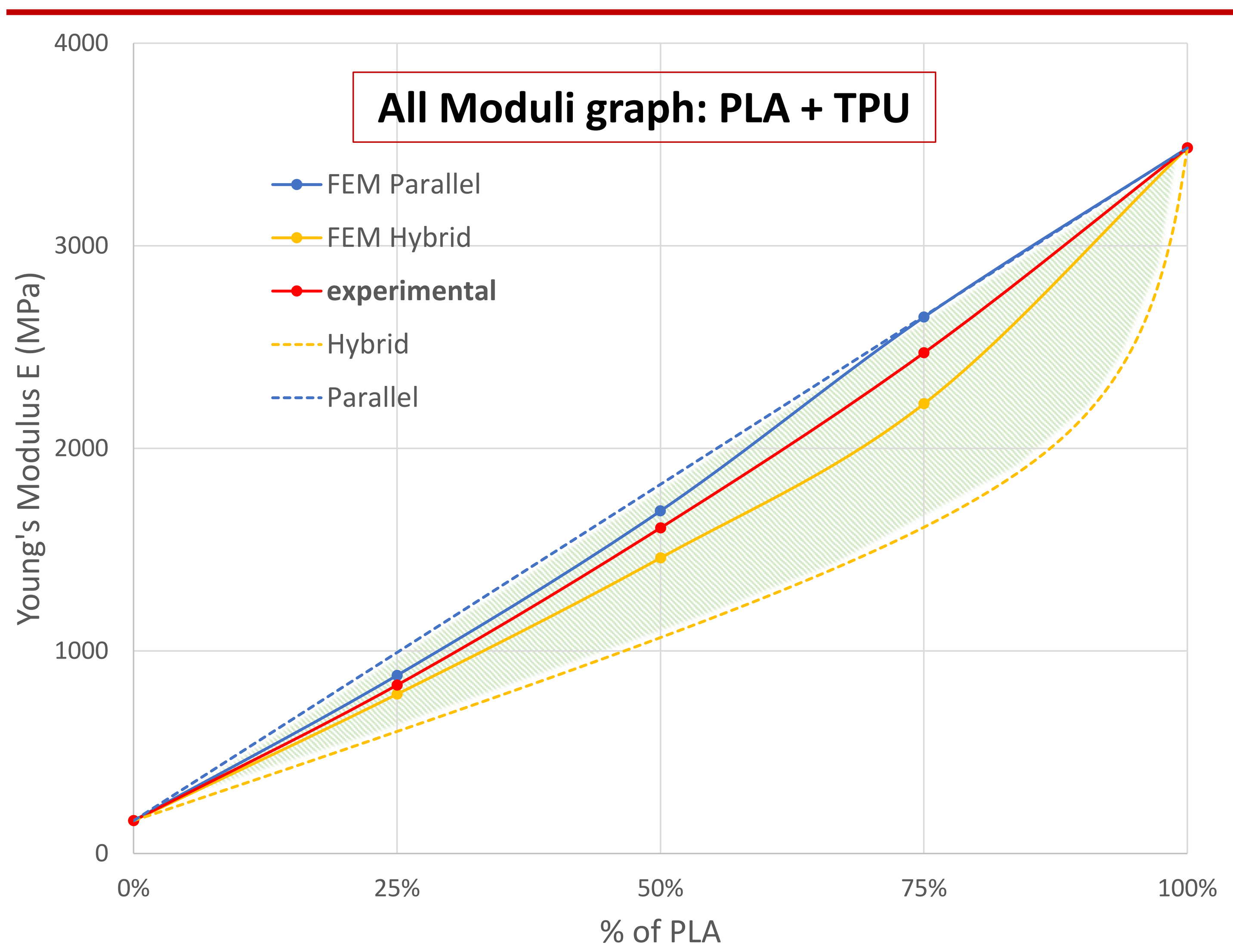
On top from left to right: (1) Coextrusion; (2) Interlocking; (3) Blending
On the bottom, Coextruded samples made with ASA and 50% ASA, 50% TPU

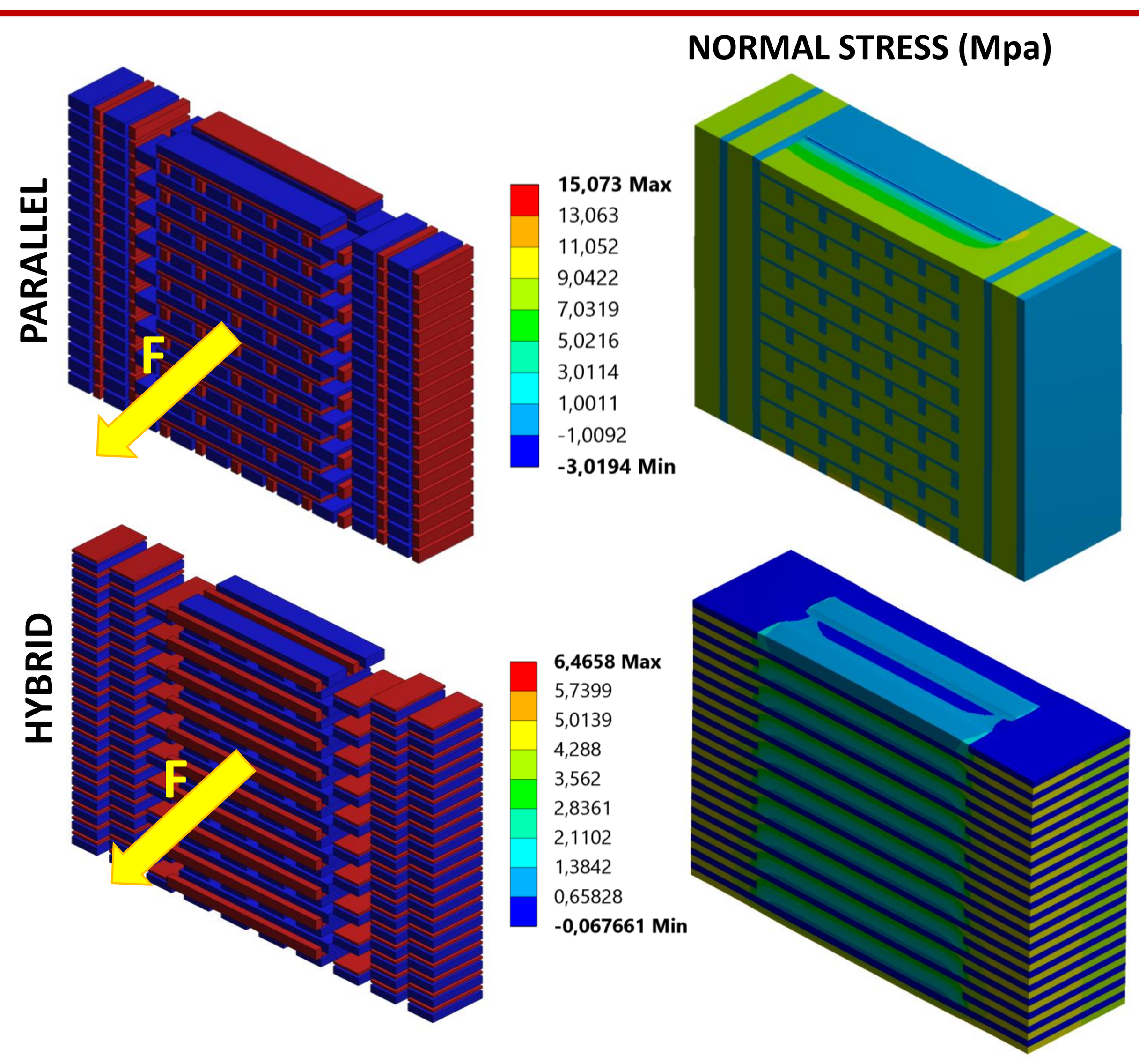
Theoretical Model the definition of a theorical model to explain the stiffness behavior of coextruded parts starts from understanding how the nozzle deposits the fused material, that comes out side by side. Given Y and X axis in figure:

- Going along Y the extrusion splits side by side.
- Going along X the extrusion splits top and bottom, respectively along X+ the blue filament comes on top of the extrusion and vice versa along X-.

With these concerns it is possible to analyze a reference volume with the width and length equal to the hatching and the height equal to the layer thickness. Assuming that there is no mixing between the coextruded materials, it is possible to treat the coextruded parts as continuous fiber composites. The models were developed considering only the infill. When applying the force F The specimen fabricated along the Y axis present a '**parallel**' configuration of the materials and the correlation between the fraction X_1 and the elastic modulus E is linear (blue curve in fig.). The specimen fabricated along the X axis present a '**hybrid**' configuration of the materials with the bottom layer in parallel and the top layer in series, producing the lower model in fig.(red curve).

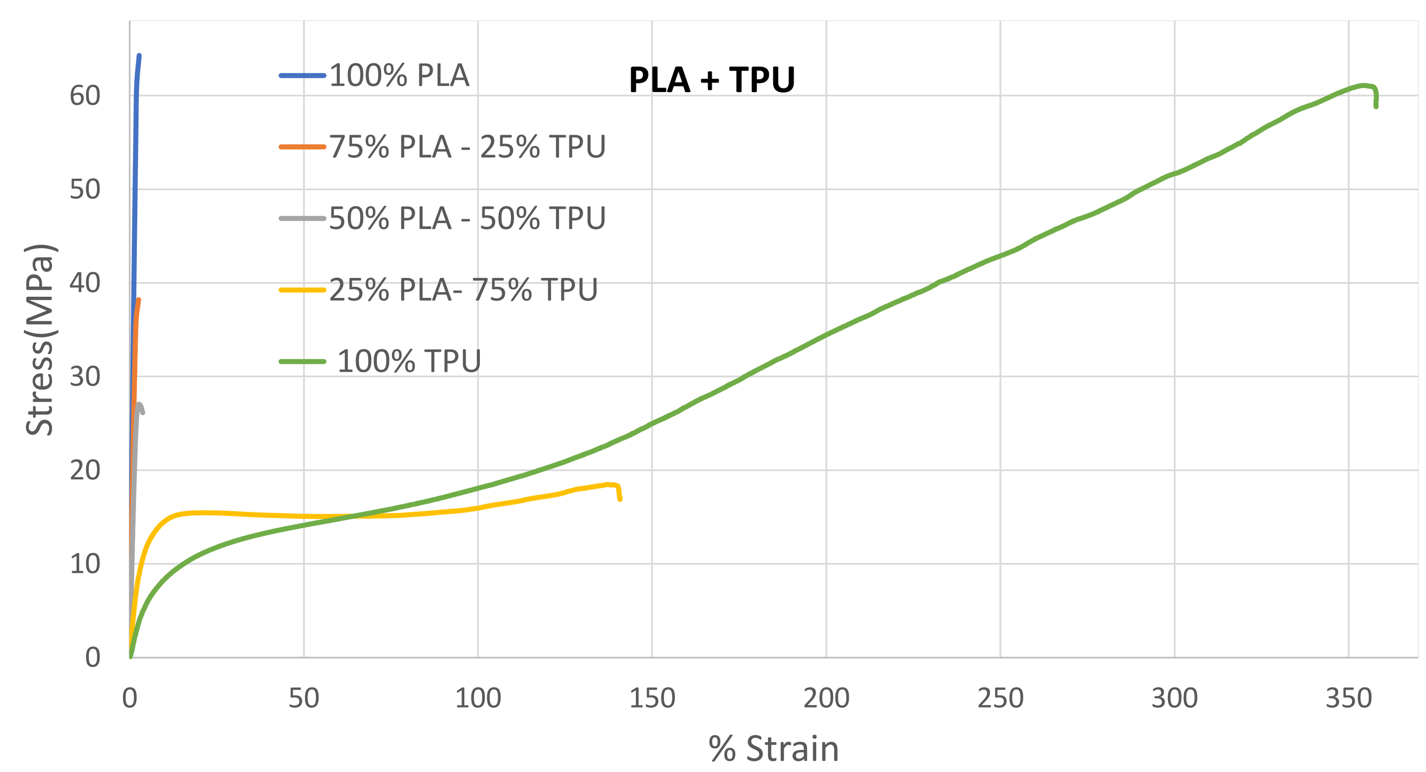






FEM simulation A FEM simulation was performed using ANSYS. The simulation replicated the tensile test executed on the 3d printed specimen. The material was allocated based on the machine path during the manufacturing. To simplify the model, a depth equal two times the hatching is assumed. Due to the non-axial symmetry, it was necessary to use the entire cross section of the specimen. Here are some parameters of the simulation:

- Statical linear analysis
- Bonded contact
- Solid 186 brick
- mesh uniform size 0.05 mm
- Constrain along the displacement in Z on the bottom faces
- Displacement of 0.005 mm along Z on the top faces



Experimental Parameters Specimens comply to ISO 527 type 1BA, were printed on a modified Prusa I3 with Reprap Diamond Hotend, with an orientation of 45°, 100% infill (lines at 0° and 90°), 2 perimeters. Layer height of 0.2 mm and width of 0.4 mm. Printing temperature was 230 °C. Filaments were produced by Fillamentum with the name of PLA extrafill, and Flexfill TPU 98a. Tensile test was also performed according to ISO 527 with a strain rate of 0.25 mm/min considering an extensometer base of 25 mm. Young's moduli were computed as the slope of the curve on the tract between 0.05% and 0.25% strain.

Experimental Data Interpretation On the graph in the left side are represented the stress-strain curves for the analyzed specimens. As predictable PLA alone shows a brittle behavior with breaking without yielding at low strains, whereas TPU breaks at strains of more than 300% with stress intensification after strain. It is evident that at low percentages of the minority material, the fracture behavior that prevails is the one of the main material, but when approaching the median composition, a transaction between the fragile and ductile behavior occurs. Ultimate tensile are negatively influenced when mixing the materials while the energy absorption seem to generally increase when adding TPU to PLA. Elastic moduli are reported on the figure above .

Conclusions *By developing a theorical model, a range of properties were defined (highlighted in green on the graphs). The upper limit of the elastic modulus was identified as the specimen sprinted along the Y direction (PARALLEL) while the lower limit was identified as the specimen sprinted along the X direction (HYBRID). The 'All Moduli Graph' shows the trend of both the FEM derived Young's moduli and the experimental data as the percentage of the material changes. The FEM simulation produced results that are within the range considered, with a more visible deviation from the theoretical data for the hybrid specimen probably due to the presence of the printing perimeters that increase the fraction of the 'PARALLEL' part. The experimental data shows that E increases with the composition, lying in the middle of both theoretical and FEM results. This could be explained because of the 45° orientation of the printed specimens that might show an intermediate behavior of the two considered models. The results are encouraging and offer a good starting point to move forward and increase the range of the data needed.*

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