FDM (Fuse Deposition Modeling) : mechanical strengths

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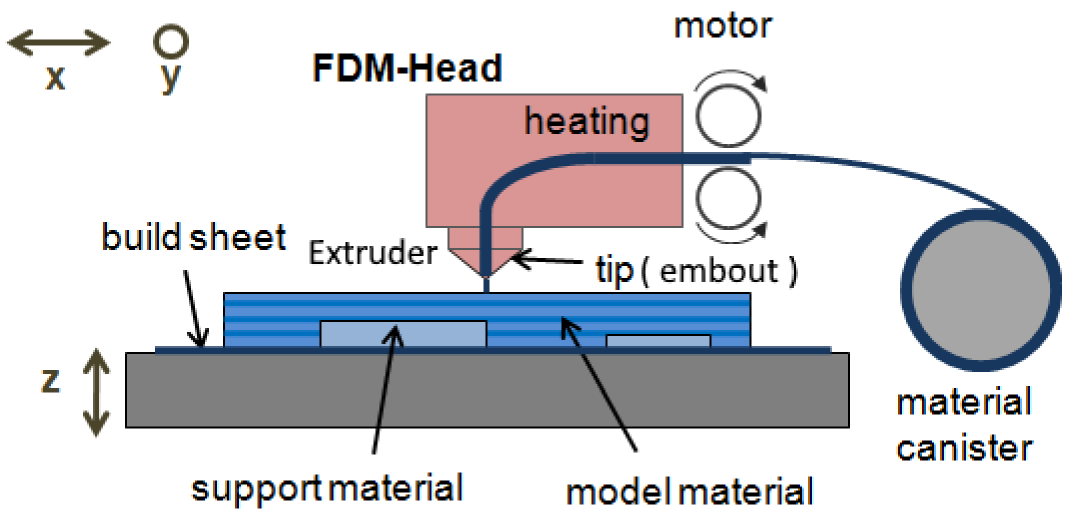
Vers 1.0

Obtaining a good mechanical resistive part is a complex problematic with this technology.

The **printer** :



Process and results:

In FDM, a solid filament is extruded in a **semi-molten state** (above Tg (Glass transition t° for plastic)) and solidified in a chamber (enceinte) at a temperature below Tg of the material. The temperature decreases rapidly.
As a consequence, volumetric shrinkage (retrait) takes place, developing weak fiber bonding (adhesion) and high porosity of the structure. These consequences depends also of the **deposition parameters and the method used for**.
The **bond quality between filaments depends on the envelope temperature** (around the tip and the material) **variations in the conductive and convective conditions. The molecular diffusion and crosslinking in and between the depositied polymer lines** (curves) **is needed.**
The deposition parameters has a significant effect on the part stresses and deflections.
The accumulation of residual stresses can bring about warp (gauchissement), inner-layer delaminating or cracking.
There are **many variables** that may have an effect on the characteristics of the manufactured object : surface quality, dimensional accuracy and mechanical behavior (comportement mécanique).

What influences the mechanical properties of the part?

1. **Definitions and Influences**

a. The height of the extrusion nozzle (buse d'extrusion) against the plateform = the

Physical Layer Height (PLH) must allow the deposition of the filament. Normally 0,3 mm for a layer of 0,1 mm.

A too high bed levering (hauteur) causes layers detachment and warping.

b. The **Nozzle Pressure** (NP) is the pressure exerted on the hot filament by the extruder against the cooler deposited filament of the preceding layer or on to the plateform.

High pressure = warpage ; bad corners (not exact or too much deposition); shaking (tressautement).

Can be due also to a too low PLH.

Low pressure = poor adhesion ; holes (trous). Can be due to a too high PLH.

c. The minimal **Bead Width** (Largeur du Cordon) = **Nozzle Diameter**.

Ex : a T16 tip extruder = 0,016 inch x 25,4 = 0,4 mm. It is the normal width.

In this case the **Extrusion Multiplicator or Fudge Factor = FF** = 1.

It implies a minimum adhesion with the preceding deposited line.

You can increase the bead width by a parameter of the machine program till 1,8 certainly.

2. **Extrusion temperature** : for a good PLH the increase of this t° decreases the NP an allow a good adhesion. To get a good adhesion the t° must be high enough versus Tg.

The adhesion depends also of the temperatures around the nozzle and the ambient t°.

The adhesion process takes place during 3 sec. It assumes the molecular diffusion and crosslinking In and between the depositied polymer lines.

During the short time of extrusion the t° decreases quickly. Too quick decreases adhesion.

The increase of the volumetric flow of the semi-molten plastic during the extrusion increases the adhesion.

If extrusion t° too high :

- No good deposition because hot plastic too fluid.
- If plastic don't cool quick enough it changes shape (it is necessary to cool with the fan (ventilateur)); too much cooling is not good for the adhesion.
- Carbonization then the nozzle becomes blocked.
- Can deliver toxic fumes.

3. **Printing Speed** (vitesse de déplacement de la tête)

Speed too high = bead (cordon) not uniform .

Too slow = excess of material.

NB : do not confuse with **Extrusion Speed** which is the speed of the extruder for delivering the hot filament. It implies the filament flow. These two speeds must be in accordance.

Generally you set the printing speed and the system computes the extrusion spe ed.

The shortest the deposited line is, the better it is for adhesion with the preceding line.

Travel Speed = time lost without extrusion (due to holes, gaps, change of start point for a new deposited line, to layer change). Limit travel speed to allow a better positioning of the print head.

Increase of bead width and extrusion t°, decrease of printing speed and travel speed allow better adhesion with the neighbouring deposited line.

4. **Direction of deposition** and **raster type**.

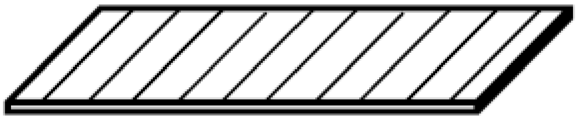
Ex: lines <u>side by side</u> (parallel) deposited without voids according to X or Y to make the **plate** below.

Here its longer side is parallel to the front (X axis) of the printer.

If you want a better adhesion work with **FF** = 0,95 or 0,90 or **Bead Width** = 0,38 or 0,36 respectively.

Bellow Two rasters : according X and Y

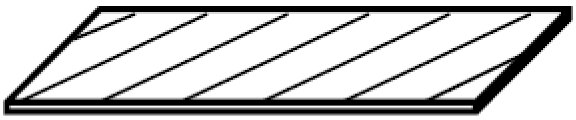
alongside X: longitudinal



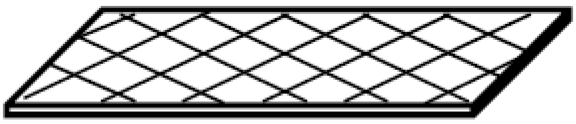
Transversal

Two more rasters :

At 45° in Diagonal or Alternated deposition at +45°/ -45° every layer = **rectilinear** method.



At 45°



On layer at 45° and the next one at - 45°

The scanning direction is the deposited direction (longitudinal X for the first specimen) on the scanning plan XY (plan de balayage).

The Z direction is the building direction (construction).

5. If FF > 1 you get **lateral Air Gap** or **voids** (vides). We get **Sieving** (tamissage) or spaces (voids) between deposited lines (curves).

6. **Fan Cooling** (refroidissement par le ventilateur) : the more the adhesion decreases but increases of Shinkrage (retraction) and curling (enroulement).

After the first deposited layers cooling serves to keep a good shape (forme).

For layers 1 to 5 it is preferable not to cool and use a warm plateform (ABS: 90 to 120°C; PLA: 60 to 70°C) because if plastic cools too quick it shrinks.

7. **Adhesion according to Z** :

If total time between two layers increases the adhesion decreases.

This time depends mostly on the surface of the layer and the deposition method.

We shall see later that the adhesion is influenced by the layer height , the perimeter thickness, the infill type and density.

8. **Mechanical Strengths** of the 4 **plates** with the 4 different rasters seen above.

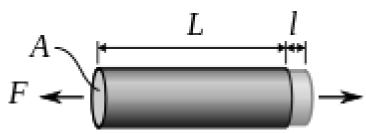
A part in an assembly or a machine must resist to different loads (force, couple) which apply on it.

Normally a part can't overcome the elastic limit stress (see below) otherwise a permanent deformation stay or worst it breaks.

It is the reason why different stress tests are realized.

For exemple : a traction force on a rod produce tension or stress (σ) inside the rod :

The more the force is, the more the deformation l (see below) is and also the stress (till the Ultimate Strength : see the diagram F-I below)



σ = F/A with F = traction force and A = area (surface).

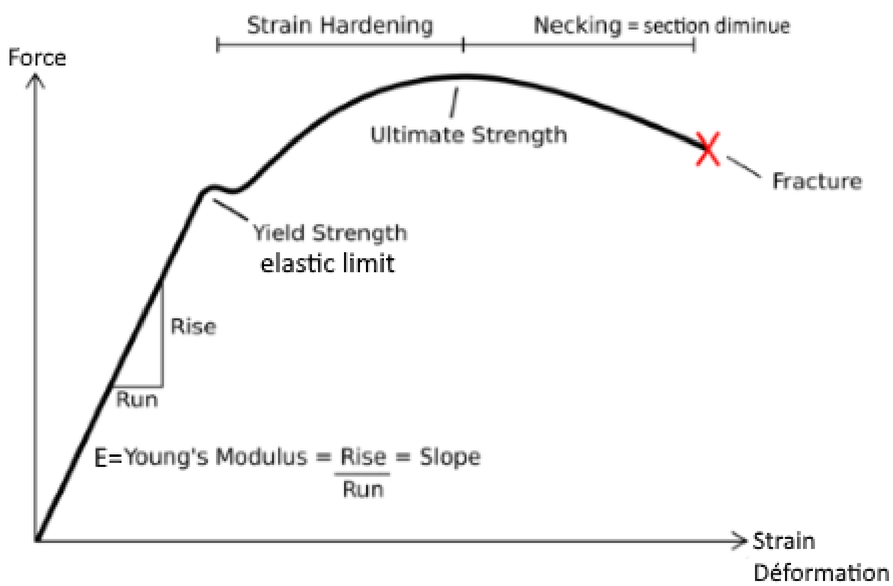
Units : **σ** in MPa (Méga Pascal) with 1Pa = 1N/m² like a pressure (pression).
This unit for the USA is PSI. 1 PSI (Pounds per square inch) = 6850 Pa.

and **e (elongation) = 100 * l/L** |%| with l the strain (deformation; ici allongement).

Different Stress Points reached under traction force : (see diagram F-I also)

- the Yield Strength is the stress at the elastic limit σe.
  Why elastic limit is important ? :
  If strength (stress) inside the material don't exceed the elastic limit, when F (the load) decreases to 0 the deformation disappears.
  If strength exceeds the elastic limit, when F decreases to 0 a deformation stay.
- the Ultimate Strength or Tensile Strength before break : Force max / A = σm (hard plastic breaks quickly after).

Find here the curve between F and l :

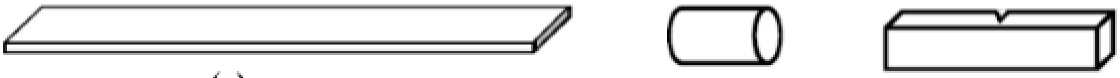


Relation of Young : σ = e * E avec E in MPa. See later the importance §15.

Here are comparative values with <u>an</u> **ABS** part submitted to **traction** , **Flexure** and **Fatigue** with a **plate** (figure a below) according to the ASTM standard specifications (USA mostly used).

For traction and Fatigue tests we apply forces according the longest dimension X of the part a.

Standard specimens for tests :



(a) (b) (c)

Dimensions in mm : 190 x 12,7 x 2,6

(b) length : 25,4
Diameter : 12,7

(c) length : 63,5
width : 25,4
Thickness : 25,4
V notch is also determined

Manufacturing conditions:

Layer of 0,18 mm

Tip 12 = 0,3 mm

I don't have all the building parameters, so i give you the result values for comparison.

The <u>Flexure</u> tests were conducted with the standard 3 points test as viewed below on the specimen a.

<u>Tension-tension Fatigue</u> tests were conducted at <u>70% of</u> the Ultimate Strength at a frequency of 0,25 Hz because we increase and decrease the force.

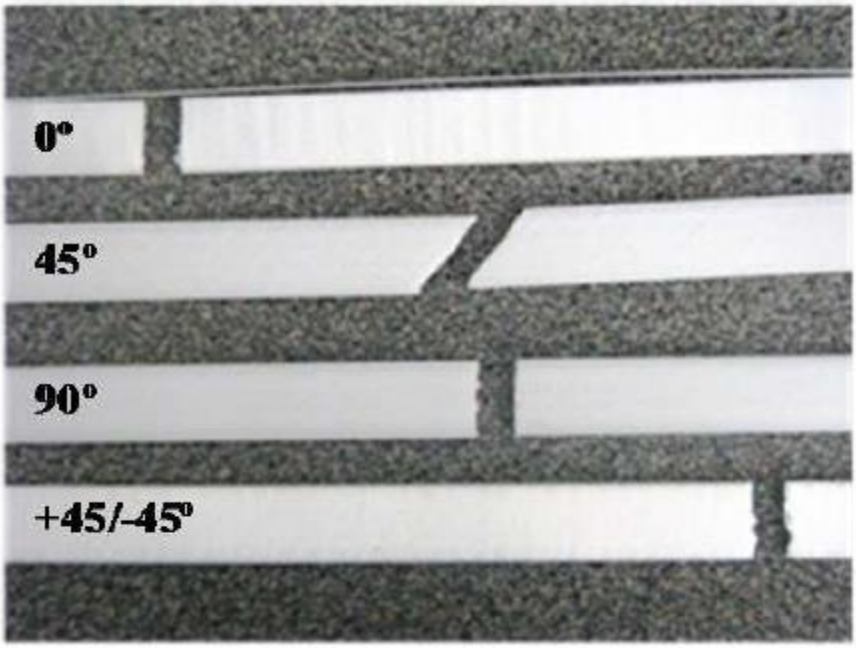
Under <u>traction force</u> and <u>bending (flexion) force</u> here are the resulted tensions (stesses) :

	Longitudinal effect	Transversal Effects	Diagonal Effects	Rectilinear Effects	Raw filament
Tension X axis Ultimate Strength (US) at Break |MPa|	25,72 Break	**14,56** Layers dislocation	**16,22** Break at 45° due to shear and tension on filament	19,36 Multiple filament failures by shear and traction	**27,00**
Yield Strength (YS) |MPa|	25,51	**14,35**	**15,68**	18,90	
Tension Young's Modulus E X axis |MPa|	987,80	**738,77**	**741,78**	768,01	
Flexure X axis Ultimate Strength |MPa|	38,1 Permanent Deformation	**23,3** Break by tension on the back side	**25,7** Break by tension on the back side	32,2 Permanent Deformation	
Yield Strength |MPa|	34,2	**20,8**	**21,3**	26,5	
Tension-tension Fatigue X axis |Cycles|	5745	**1616**	**1312**	4916	

Colors of values : Orange value = max ; Blue value = next ; Red value = worst

Shear stress is due to shear (cisaillement) force (see later).

Here a view of breaks for the four rasters under traction :



For Flexure stress and Shear stress see later. Flexure creates traction and compression (σ) in the material.

Big difference between tensions according to X for Longitudinal and Transversal deposition.

The difference between Ultimate and Yield Strengths is very low !

At the right you find the value for tension obtained for injection molded part.

Interlayer porosity and the air gaps serve to reduce the actual load bearing area (surface sur laquelle s'applique la force) across the layers providing easy fracture paths (chemins ou criques de fracture) .

Value for the raw filament seems to be low!

Very often Fatigue Flexure tests are realized (think about the airplane industry).

In a word :

If you print a plain tower with square layers (XY) with lines deposition next to next :

According to the deposition lines direction you get the better strength.

Perpendicular to this direction the strength decreases strongly (variable).

According to Z the strength is the lowest.

For Flexure there is also a Modulus.

Compressive tests were conducted with the rod (figure b) according to the ASTM standard specs.

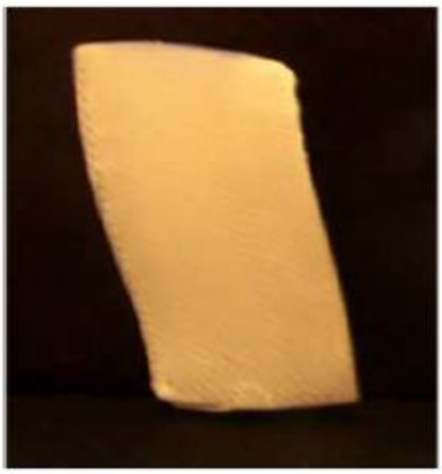
	Longitudinal	Transversal	Diagonal	Rectlinear	Raw filament
Ultimate Strength (US) |MPa|	**32,32** Layers Separation	**34,69**	**33,43** Diagonal Sliding	**34,57**	**35,50**
Yield Strength (YS) |MPa|	**28,83**	**29,48**	**24,46**	**28,14**	

Values are higher than with traction.

The Transversal specimen is the most strong; the Longitudinal surprisingly high (FF < 1); the Rectilinear not far from; the Diagonal the worst.

There is also a Modulus for Compression.

Many specimens fail by separation between layers resulting in two or tree pieces.



Left image: for the test the scanning direction is vertically placed.

Right image : the scanning direction is horizontal and the layers slide between them.

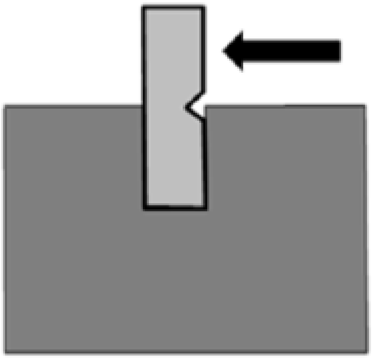
For Diagonal specimens according the vertical there are sliding between layers due to the weak adhesion.

Value for the raw filament seems to be low!

Compressive result is greater than for traction.

Impact tests were conducted with a test model also according to ASTM standard specs (figure c).

This test was realized with this mounting :



The results are expressed in energy absorbed per unit of thickness at the notch in units of Joule/cm.

	Longitudinal	Transverse	Diagonal	Rectilinear
Impact | J/cm |	2,991 Curvature at the V before break	**1,599** break	**2,339** break	**2,514** break

Longitudinal specimen with deposited lines vertical in the mounting resist the better; then the rectilinear ; the transverse with deposited lines perpendicular to the test specimen is the worst.

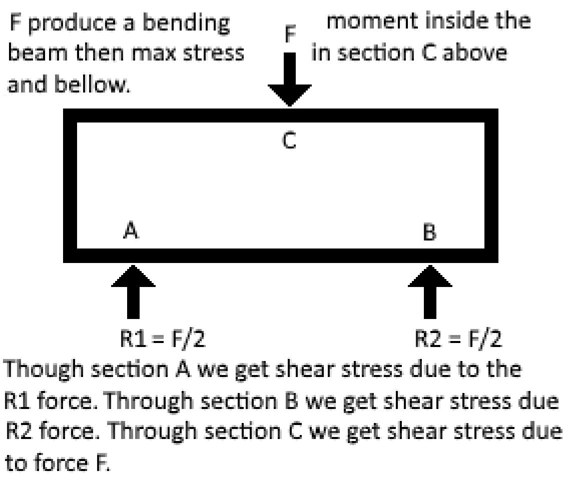
Conclusion :

From all these tests we can conclude that the rectilinear model resists well in most situations of load.

The Grid model is better.

NB : 1) A part can be submitted at a torsional torque according to an axis witch implies torsional stress noted **τ** (MPa) if the part is restrain at one end.

2) A force can act according the transversal section of a part (force de cisaillement) and produce shear stress.



NB : a bending moment is a flexure moment.

The beam could slide horizontally due to an other force F not vertical.

Shear stress in section C is naturally 2 x greater than in A or B. Shear stress is noted **τ.**

The bending moment creates max stress in C. Above we get compression (σ)

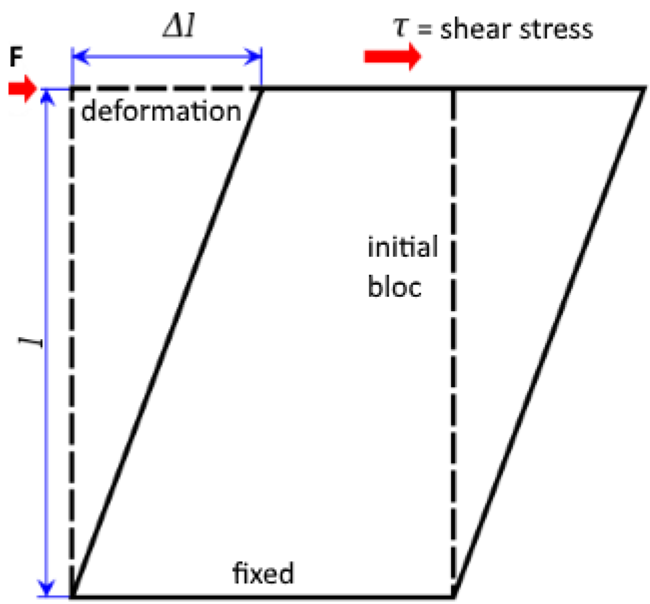
and bellow we get traction (σ). In the middle of section C it is σ = 0.

What is Shear stress **τ** (in MPa) ? :

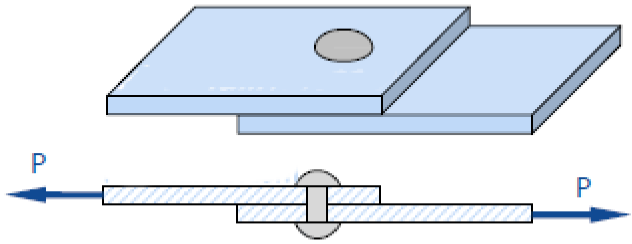
A vertical beam is fixed at its back.

A force F acts according the transversal rectangular section above of the beam and produces a deformation Δl. Consequence : a shear stress τ inside the transversal section.

Between the back and above the material layers slide between them.



Here we get shear stress in the rivet.



Single Shear

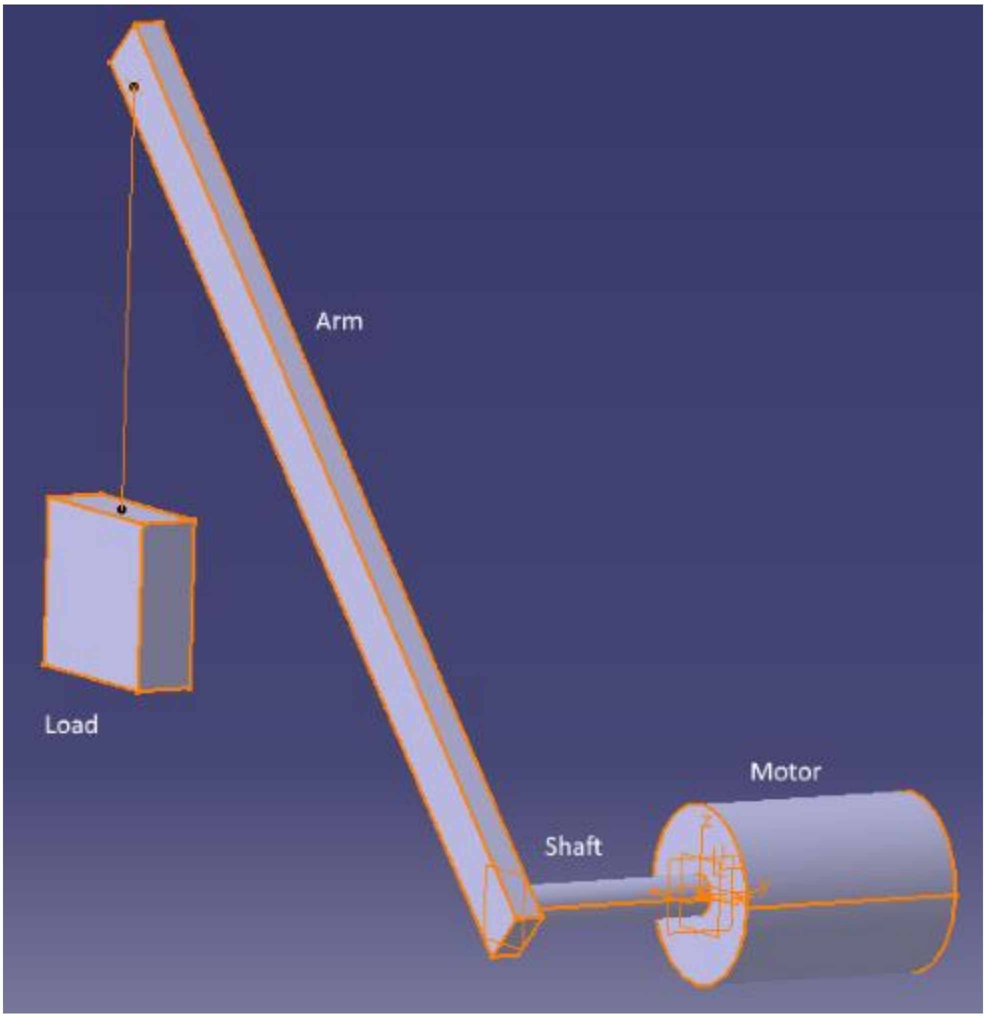
3) There are filaments for FDM process which resist more than the PA or ABS. Some materials can reach an Ultimate Strength of 70 MPa to build more resistive and light components in serie produced. But these filaments need a stainless steel extruder which can heat up to 400 °C.

4) A part of a building (a beam, une poutre), an assembly (a rocking chair, a table) part or a machine part can be submitted to different stresses. Some stresses can add each other to create a greater stress which must stay at or bellow the elastic limit. Ex : there is an addition of the torsional stress (τ) and the shear stress (τ) to get the τtotal due to the weight of the arm and load inside the shaft (axe = 40 cm ici) of a motor maintaining the position of the arm of a crane (grue). According the position of the arm and the weight of the load the τtotal change in value in the shaft. This τtotal is propagated in all transversal sections of the shaft.

It is important to know the τtotalmax to calculate the diameter of the shaft.

More, the shaft is submitted to a bending moment due to the weight of the arm and load and the shaft weight which implies traction stress above and compression beneath.

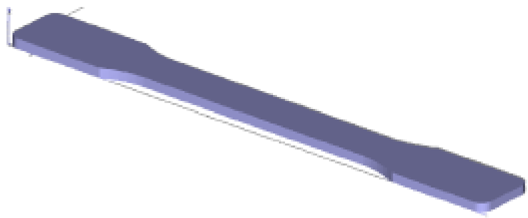
Here an image of the crane.



9. Effect of **layer height** on the Max Stress (tension) before breaking according to the length for a **PLA**.

It depends on the time between the two layers and the cooling by air fan.

We have printed pallet test of 3 mm with 5 different layer heights : 0,10; 0,15; 0,20; 0,25; 0,30 mm.



Other parameters : Speed: 60 mm/s

Number of lines next to next at the perimeter : 2. See later.

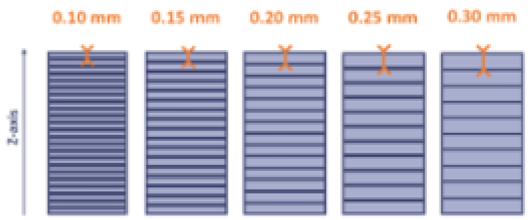
Infill: **rectilinear**

Raster Angle : +45°/ -45°.

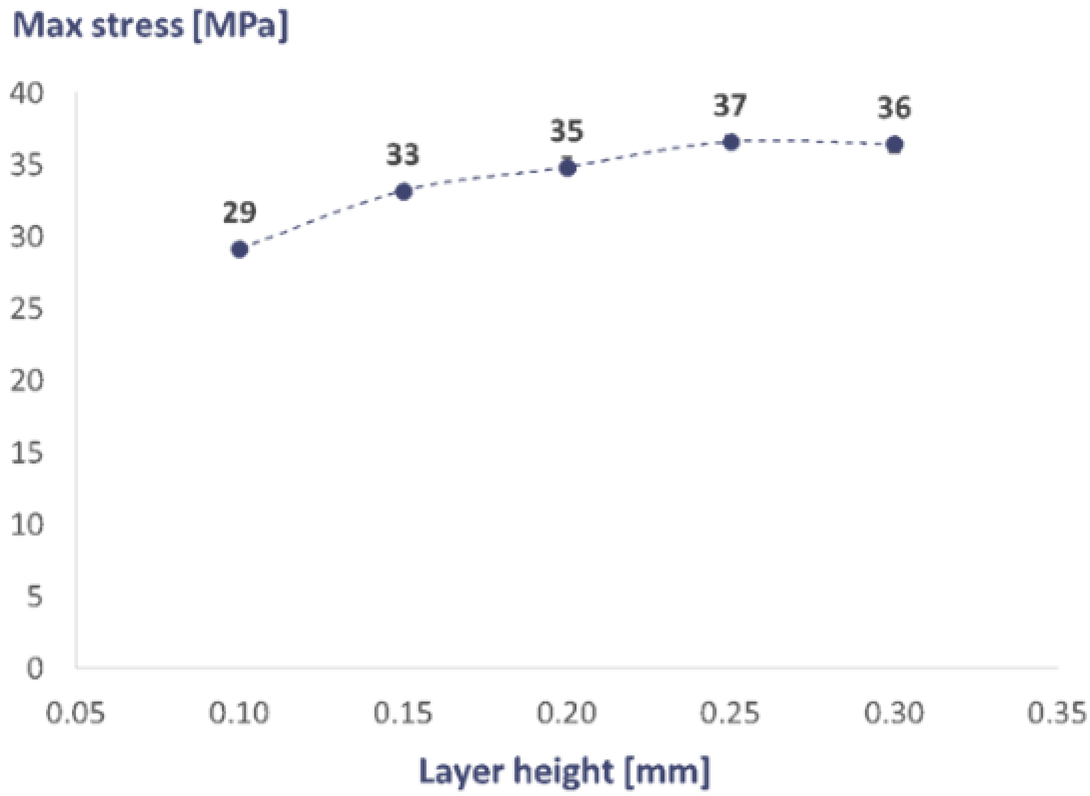
Density : **80%.**

Temperature: 210°C

Other parameters not known.



Results :



The height promotes the strength.

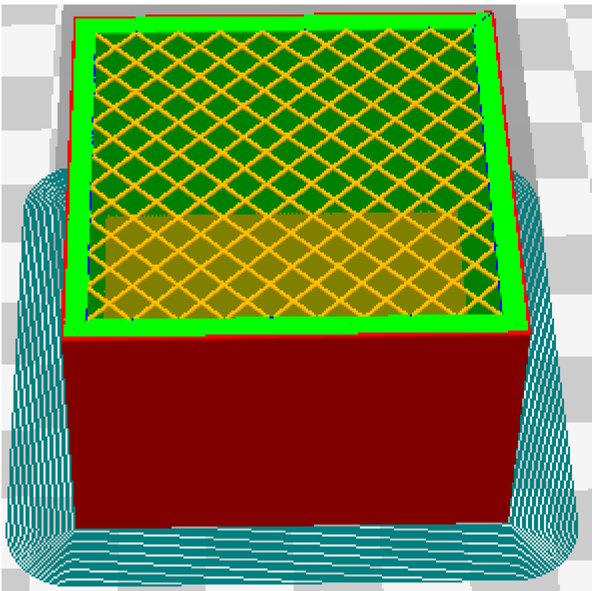
For mold injection PLA Max Stress ~= 50 MPa.

10. A Part normally is constitued of a shell (peau) and the interrior is the infill to reinforce it.

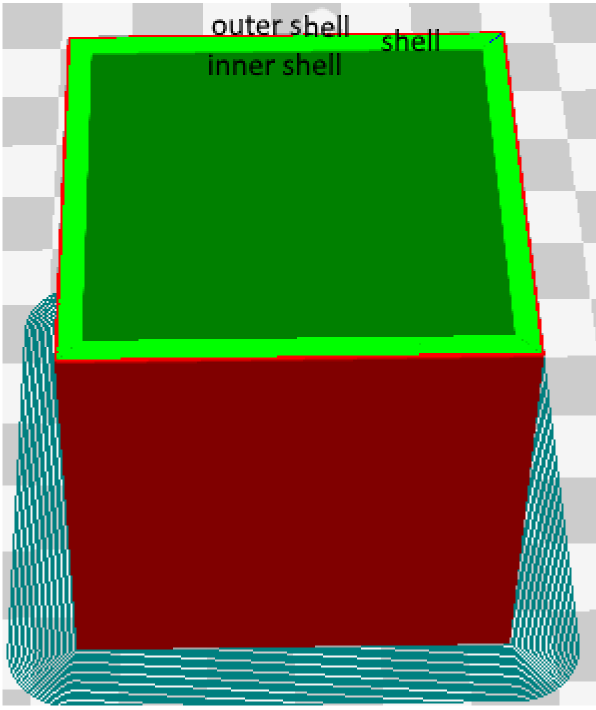
The shell in also named the perimeter with constists of a number of deposited lines (curves) next to next during the layer manufacturing. You will find the term: " perimeter lines ".

Shell is given in mm = number of lines (perimeter lines) x tip diameter.

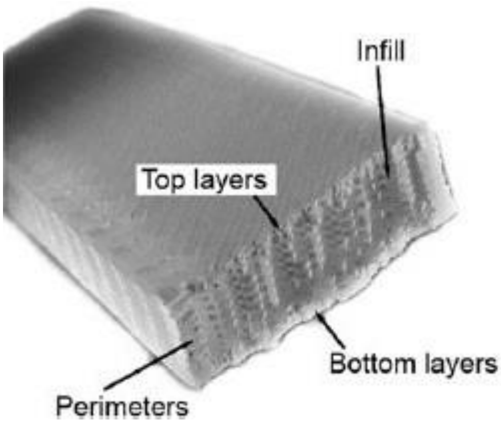
Here is a cut in a cube with a Grid Infill (crosses printed every layer) at a density of 20% :



Here is a recessed (évidé) cube with a plain back which explains what is the outer shell (the deposited plastic line to the exterior) and the inner shell.



Moreover there are the Top and the Bottom Layers :



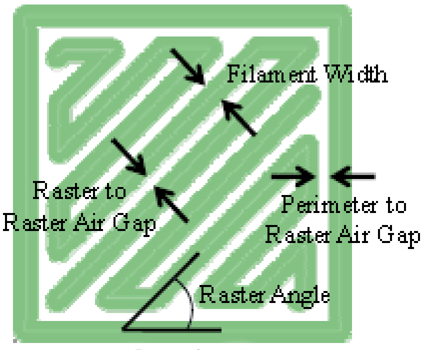
11. Infill models :

You manufacture a part by creating a **shell** (peau) around (surface latérale avec l'air) and **infilling** the interrior with an infill pattern (modèle de remplissage avec des vides pour renforcer la pièce).

Bellow a Type of Infill : Zig-Zag pattern with raster lines at 45°; the next layer the raster will be -45°.

You see two types of air gaps : between the infill and shell (perimeter) and between raster lines.

Air Gap can be positive (space) or negative.



Normally the Perimeter to Raster Air Gap must be 0 or negative for better adhesion.

Types of Infills : 2 types. Characterized by its Density according the mechanical consistency that you want.

2D models (patterns) in the XY plan elevated according to Z becomes a 2D1/2 by construction.

Types :

Rectilinear (alternated // lines at 45°/-45°), Linear or Lines (See §14), Triangular , Concentric , Zig-Zag, Honeycomb (nid d'abeille), Wiggle, Grid very often used by default.

Linear alternates direction at each layer from 90°. Lines not necessary parallel. It seems to be at high density.

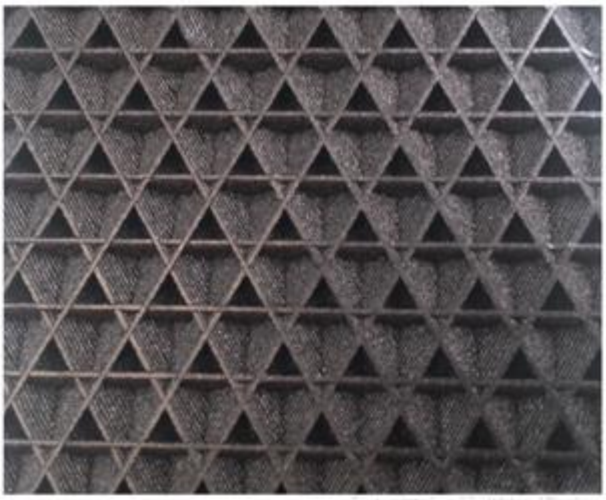
Zig-Zag : // lines. The nozzle extrudes along the inner shell before printing in the other direction. Make a better adhesion according to FF, Infill overlap and Skin overlap.

Wiggle : permits the model to twist.

Grid (cross) at 45° (often): strong in 3 directions.

3D models : to resist more in 3 directions.

Cubic : mostly a cube printed turned on a corner from ~60° according to a diagonal of the volume. It makes equal strengths in all directions.



Tetrahedral : pyramid (4 faces) printed on the top.

Generally you create the infill at the time you realize the layer to promote the adhesion.

12. **Infill Overlap** with shell : an overlap (recouvrement) with the inner shell allows a good adhesion.

Normal = 15%.

The **Skin Overlap** or **Outline Overlap** permits a good adhesion with the infill but also with the top and bottom layers.

13. **Influences of shell thickness and top/bottom layers.**

Shell thickness Influences for the same infill rectilinear density of 30% on the Max Stress at elongation at break.

Parameters : Speed: 60 mm/s

Number of perimeter lines : 2.

Infill: **rectilinear**

Raster Angle : +45°/ -45°.

Temperature: 210°C

I don't have the other process parameters.

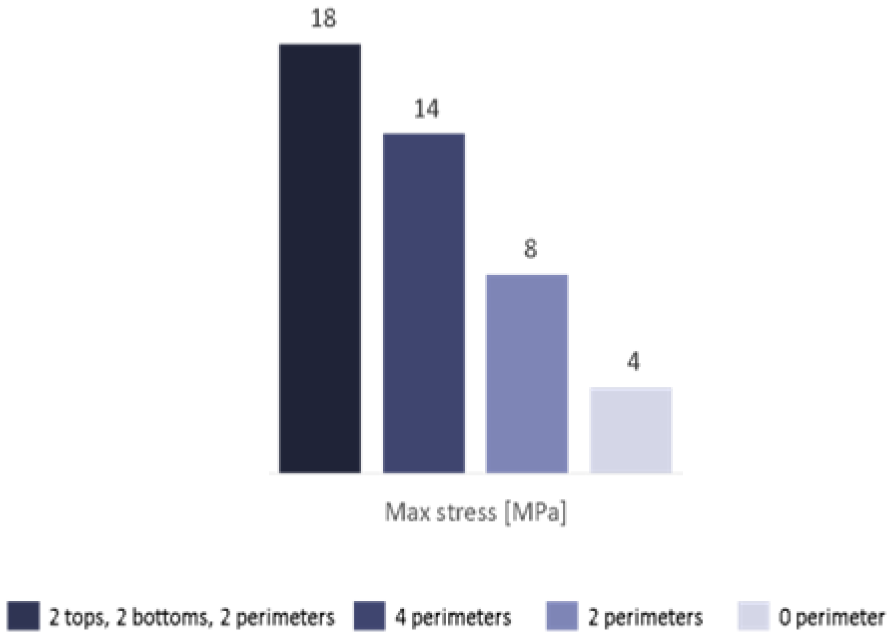
Here the Ultimate Tensile Strength for a **PLA** according to the vertical. Parts were printed horizontally.

This tests shows the influence of upper and lower layers also.

NB : # = number

Infill %	30%	30%	30%	30%
# of perimeters	2	4	2	0
# of top solid layers	2	0	0	0
# of bottom solid layers	2	0	0	0

Here the results for the 4 specimens in the same order:



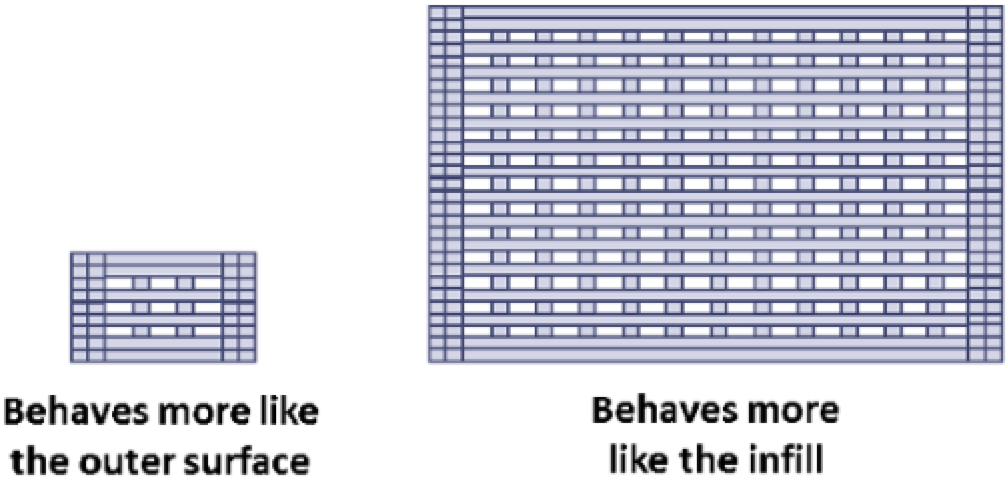
Results are also valid for 100% infill.

Influence of the perimeter relatively to the volume of the part for stress tests.

The more the perimeter is thick relative to the volume of the part, the more it influences.

A little object is more influenced by its perimeter than a big one.

A big object is more influenced by its infill model and density than a little.



14. Effect of Infill percentage on Max Stress at elongation

Material : a **PLA**

Infills : rectilinear at 45°.

Densities : 10; 30; 50; 70; 90 ;100 %

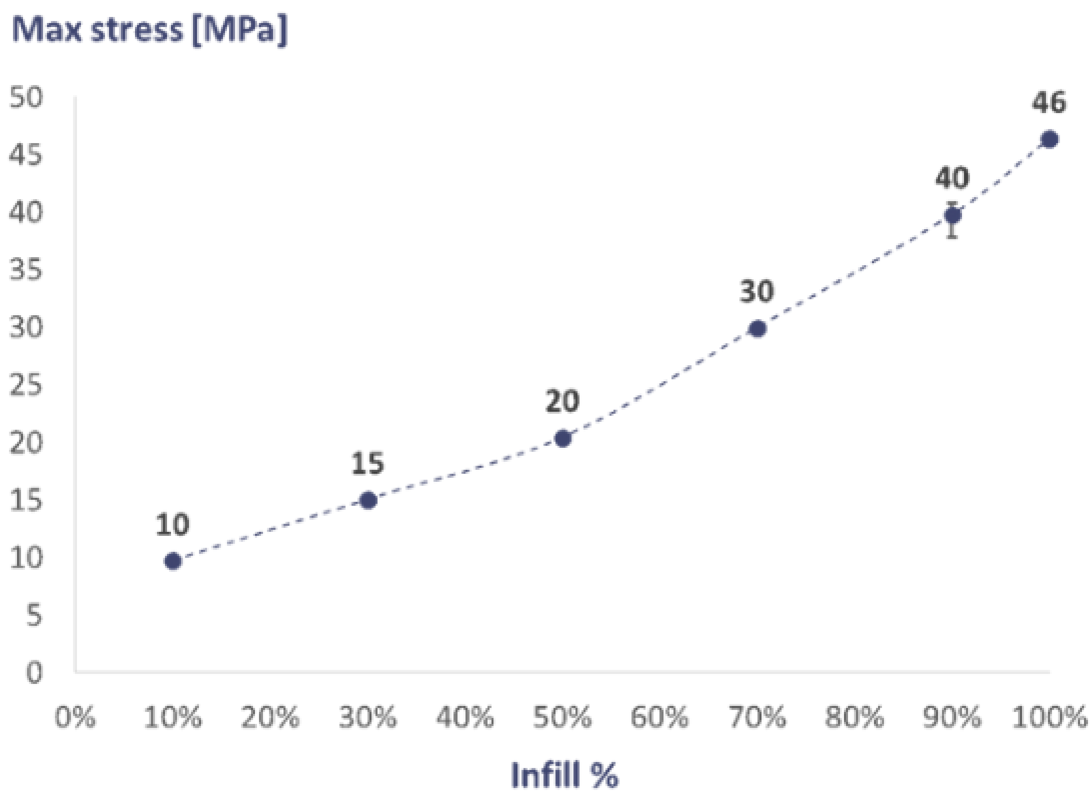
Other parameters : Speed : 60 mm/s

Layer height : 0,2 mm

Temperature : 195°C

Number of layer for perimeters, top, bottom layers : 2

Some parameters are not known.



Max Stress for molding by injection : ~50 MPa.

The max value of 46 MPa seems to be very high even with very well adjusted parameters!

15. Effect of Infill Model and **Density :** Ex with 2D models

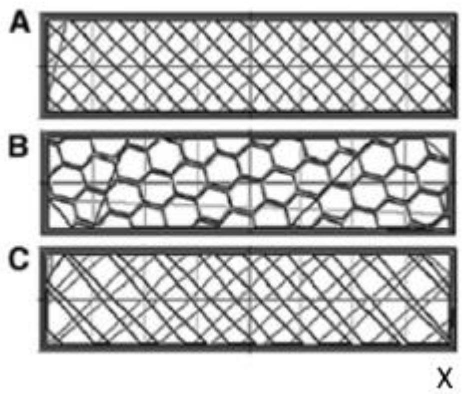
Material : an **ABS**

Infills : A: Rectilinear at 45°/-45°.

B: Honeycomb turned at 15°.

C: Linear at 45°/-45°.

Here are the models at Density 20%:



Densities : 20%, 50%, 100%.

Parameters :

Layer thickness = 0,3 mm

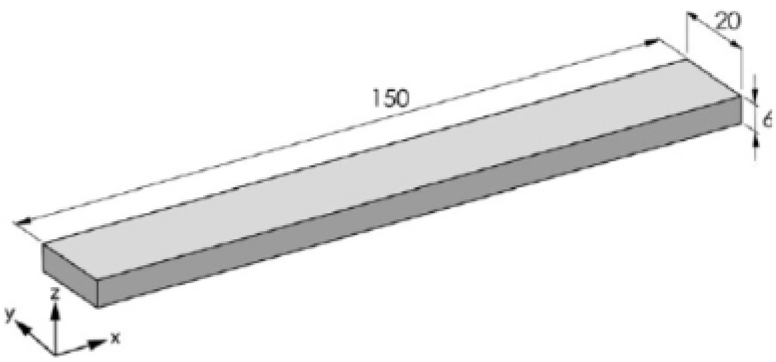
Nber of perimeter lines = 3

Nber of Solid top layer = 3

Nber of Solid bottom layer = 3

I have not all the process parameters.

Laminate dimensions tested:



Test specimen dimensions in mm and print orientation.

Results :

Infill pattern	Infill density	Tensile strength (MPa)	Tensile strain (%)	Elastic modulus (MPa)	Weight (g)
Line	20	16.00	4.76	499	11.06
Line	50	20.06	4.86	640	13.98
Line	100	35.68	5.30	784	17.54
Rectilinear	20	15.62	5.30	408	10.64
Rectilinear	50	19.58	4.62	659	13.98
Rectilinear	100	36.40	5.36	834	19
Honeycomb	20	16.52	4.44	568	11.22
Honeycomb	50	21.78	4.38	745	14.76
Honeycomb	100	36.10	5.42	802	18.88
Raw ABS	—	36.56	5.44	1826	

Tensile Strength according to X: See the big differences between 50% and 100%.

Tensile Strain is the max elongation before break.

The performances at 50% are rather low compared or worst to 20%.

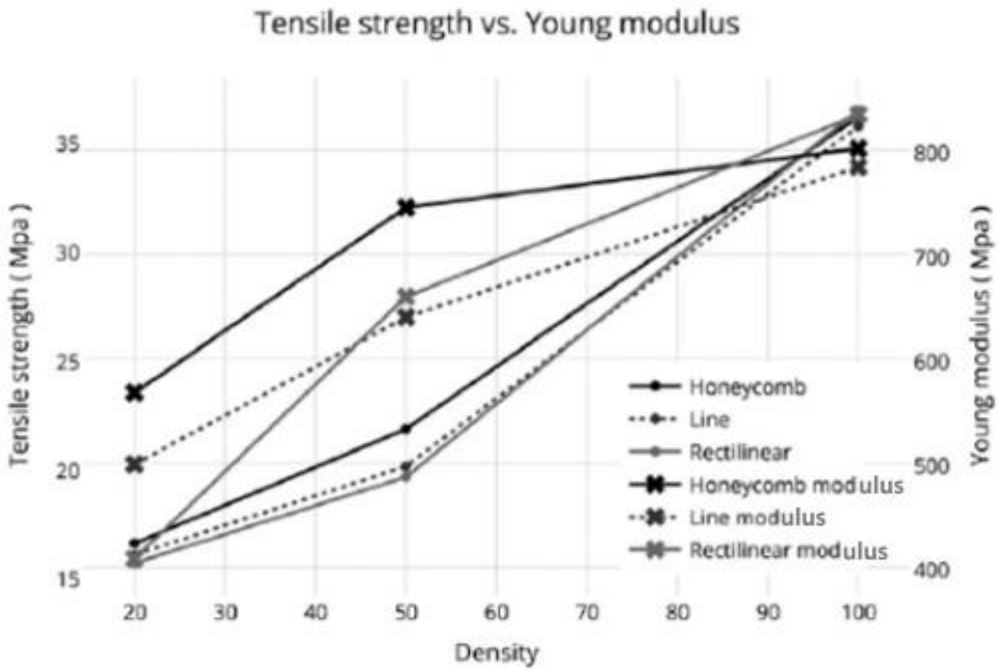
Elastic Modulus of Young is more proportional.

Weight at 50% compared to 100% is more than the half.

Last line : Value for raw filament ABS. Here the differences are rather low except for the Elastic Modulus which is more than double.

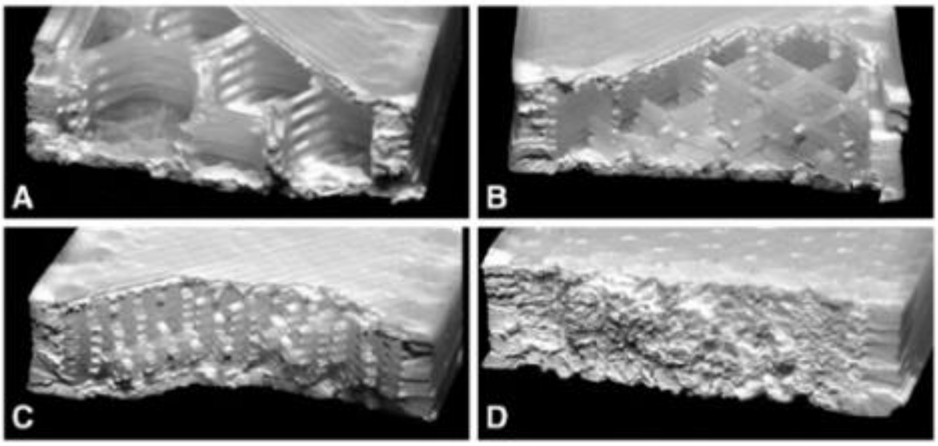
Normally Ultimate Strength = 40 MPa.

You find here a diagram with Max Stress and Elastic Modulus versus Infill Density



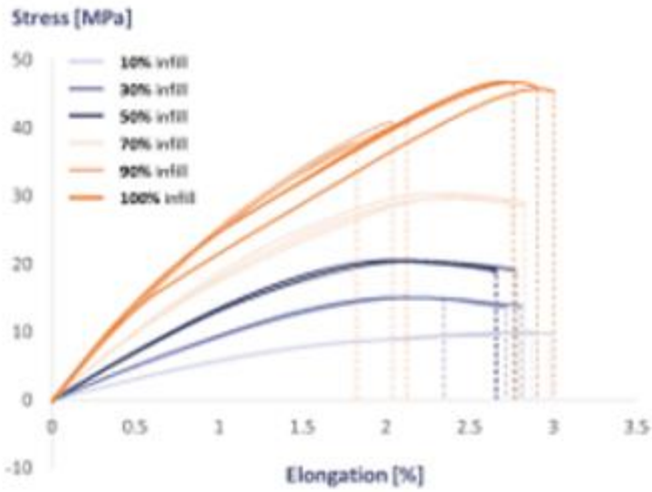
Young Modulus (E) : from 20 to 50% it increases quickly then from 50% to 100% it increases slower. A high E implies a rigid material.

You find here the fractures details for respectively : A : Honeycomb at 20%, then B : Rectilinear at 20%, then C : Rectilinear at 50% and then D : Rectilinear at 100%.



16. Elongation at Stress

This has been done with the parameters for the **PLA** of paragraph 14.

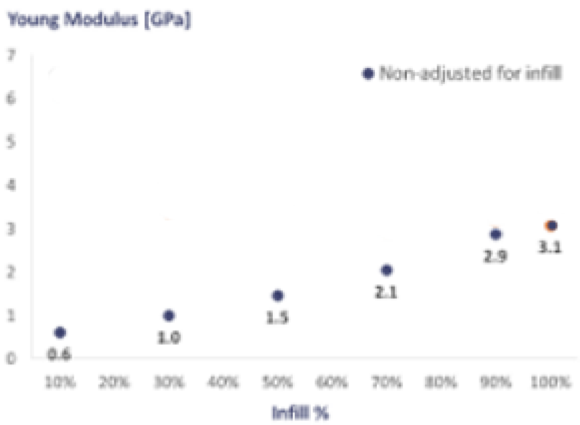


The most surprising result of this study probably lies in this test. Elongation at break is remarkably constant around 2.8%, except at 90% infill where it drops to 2.0% because of the better adhesion.

Sometimes for a part or detail of part it is necessary to get more flexibility.

It is given by the Elastic Modulus of Young :

Find here the results according to the parameters for **PLA** of paragraph 14.



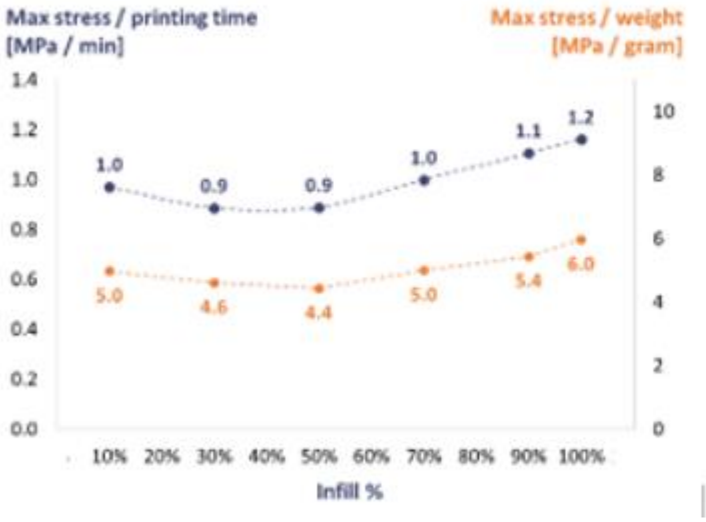
A part molded by injection with PLA has an Elastic Modulus of ~3,5 GPa.

17. Strength according to Z : if we print a cylinder vertically, the tension (strength) according to Z is not good. The compression according to Z is far better.

If we load it with a torque (couple) according to the Z axis, the shear (cisaillement) is also bad.

18. Effect of Max Stress/Printing Time according to infill density

This has been done with the parameters for the PLA of paragraph 14.



The graph shows that the **30% to 50% range is less efficient** from <u>both cost</u> (material usage) and <u>printing time</u> standpoints, as they have the lowest ratios.

Conclusion : it is not easy to get a good mechanical part with this technology.