FLEXURAL PROPERTIES AND FAILURE MECHANISM ASSESSMENT FOR ADDITIVE MANUFACTURED LOM BARS ON DIFFERENT BUILDING ORIENTATIONS.

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Abstract

Plastic Laminated Object Manufacturing has not been assessed from the flexural properties point of view. The deflection range in parts manufactured by this technique is wider than in parts fabricated by other additive manufacturing methods like SLS or FDM. This fact has increased the interest on the final application of these parts rather than restricted to Rapid Prototyping applications. In this study it will be compared the impact of building orientation and geometric features of parts over the flexural properties. Through optical observation it will be studied the failure mechanism.

Introduction

Additive Manufacturing can be defined as a group of techniques to fabricate final parts, prototypes, cores, injection molds for plastics, electrodes for erosion, etc., in a short period of time from a 3D file elaborated with CAD software [1]. As a result of these processes it is possible to carry out, in a relatively short period of time, several tests of geometries to validate the definitive one, and to undertake the production in series with reduced development times, possibly with lower development costs. Another frequent arguments when choosing AM techniques, is the complexity of parts and the confidentiality required for new parts under development.

Rapid Prototyping was the first application of Additive Manufacturing. The first references to Rapid Prototyping Systems at 1986, appeared with stereolithography process from the North American company 3D Systems. Through this process, it can be obtained parts with solidifying photosensitive resin layers by means of laser. System SLA-1 was the first RP System available in the market. Other companies like the Japanese NTT and Sony/D-MEC began to commercialize machines of stereolithography in 1988. The technologies known like Fused Deposition Modeling (FDM) from Stratasys, Solid Ground Curing (SGC) from Cubital and Laminated Object Manufacturing (LOM) left to the market at early 90´s. Originally, LOM was used to make laminated paper models. However, as this technique and its available build materials were improved, interest evolved into making functional parts out of metals, ceramics and polymers. Engine components, medical devices and manufacturing moulds are some of the parts that could be manufactured using LOM. Previous work has demonstrated that LOM can successfully produce funtional parts [1]. RP techniques have been increasingly improving service properties of finished parts, through material´s properties enhancement, improved accuracy, new CAD software capabilities and simplified post-processing requirements.

Additive Manufacturing Techniques

The process of Additive Manufacturing is developed with different technologies by means of constructing layered 3Dsolids from the sliced 3D CAD model of a part. The part is built from the superposition of these horizontal layers.

The most common technologies are:
1. Stereolithography (STL).
2. Photopolymerization by UV light (SGC).
3. Selective laser sintering (SLS).
4. Fused Deposition Modeling (FDM).
5. 3D Printing
6. Laminated Object Manufacturing (LOM).

Depending upon the final properties and mechanical characteristics obtained, a rapid prototype can be used as final part, if it is found that its characteristics comply with the service requirements of the part. Otherwise, if the mechanical properties of the part obtained are below the required standards, it still can be useful for design validation of geometrical features, assemblies, ergonomics, marketing analysis, etc. For this reason, performing a characterization of the mechanical properties exhibited by a part fabricated with any of these techniques is currently of high industrial interest.

Building parameters have a significant effect on the final properties. Several studies on FDM technique [2, 3] have shown a relationship between raster orientation and the alignment of polymer molecules along the direction of deposition during fabrication. As a consequence, tensile, flexural and impact strength depend on raster orientation. The present study evaluates the relationships between different building orientations and the resulting flexural properties for LOM technique´s manufactured specimens. It has also been analysed the failure mechanism that a LOM bar exhibits under flexural load, in order to have a clearer understanding of the capabilities of this process.

Laminated Object Manufacturing

With Laminated Object Manufacturing, parts are manufactured by means of the superposition of thin PVC film layers which are strongly glued to each other by adhesive´s jetting trough special adhesive pens. Each layer is formed by cutting with a high precision diamond blade which draws the contour of the part, defining the border between the usable part of the layer and the support material to be discarded. The device, its positioning control systems and dispensing glue system are similar to a traditional printer. When building is completed, a compact layered block has been formed. A secondary postprocessing operation will be required to peal off the layered support material, revealing in this way the final part. The build accuracy of this system is +/- 0.1mm (XY axis tolerance), 0.168mm (Z axis resolution) [6]. The SD300 build system and its components, used to fabricate the specimens of this study can be seen at Fig. 1.

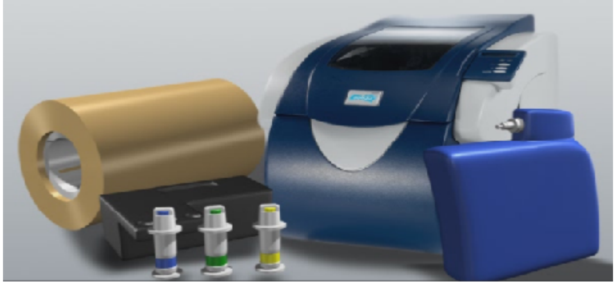

Figure 1. SD300 RP System

Materials and Methods

A Solido SD300 build system was used to manufacture 80 mm (length), 10 mm (width), and 4 mm (thickness) bars, the flexural test specimens specified at ASTM-D790M Standard. Stock building materials where used: SolVC-105 PVC laminated sheet, SolGL-101 as adhesive agent and SolAG-154 as anti-adhesive agent. Five specimens for each condition were built, the controlling software SDView supported the 3Dprinting array as can be observed at Figure 2.

Flexural properties were evaluated with a Universal Testing Machine MTS100. A MTT flexural testing device with four loading points (according to ASTM D 790M Standard) was used. Considering the orientation of the specime at building with respect to the orientation and deposition of extruded SolVC-105 PVC sheet, it was selected four possible conditions to be tested. (Fig. 2).

Tipus 1. Specime is oriented parallel to SD300 machine build plattform´s x-axis and layers are perpendicular to load application direction at testing.

Tipus 2. Specime is oriented parallel to SD300 machine build plattform´s y-axis and layers are perpendicular to load application direction at testing.

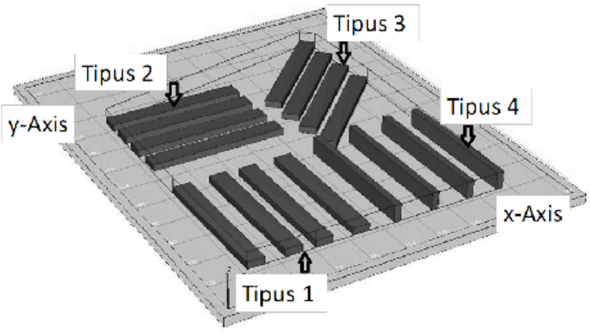

Figure 2. Building array for specimens fabrication.

Tipus 3. Specime is oriented at 45 degrees to SD300 machine build plattform´s x-axis and layers are perpendicular to load application direction at testing.

Tipus 4. Specime is oriented parallel to SD300 machine build plattform´s x-axis and layers are parallel to load application direction at testing.

ASTM-D790M standard establishes calculation and test inputs required; they are shown in tables 1 and 2.

Table 1. Required Calculation Inputs

Parameter	Value	Units
Loading Span	21,3	mm
Lenght of Yield Segment	2	%
Lenght of slope segment	2	%
Support Span	64	mm
Yield Offset	0,002	mm/mm
Point at Strain 1	3,5	%

Four experiments, one for each build condition were performed. Experiment 1 corresponds to specimens tipus 1, experiment 2 with those of tipus 2 and so on.

Table 2. Required Test Inputs

Parameter	Value	Units
Final Strain Point	3,5	%
Failure Sensitivity	90	%
Acquisition Data Rate	10	Hz
Initial Speed	1,9	mm/min

In order to analize the failure mechanism of the material, the appearance of tested specimens was visually analyzed and failure features were manually measured. Stereomicroscope Leica M60 was used to observe the exhibited crack formation at specimens layers.

Results and Discussion

The SolVC-105 layered manufactured specimens were tested as a first approach with a three points flexural test. It was applied the loading span of 64 mm, the biggest admisible for the selected specime geometry, and it was not found any specime failure within the deformation range specified at the ASTM D790 Standard. Then, the four points test was prepared taking 64mm as Support Span and 31,5 mm as loading span. When loading specime, it was observed a moment in the test, when an outer layer of the edge was opened due to cracking. When stopping test and checking specime behaviour, it was found a considerable springback of deformation showing an important component of elastic deformation. Taking a closer look to the specime, it was found that the small crack opened at the outer layer had propagated in the Z direction, covering the entire thickness of specime. This propagated crack can be observed at Figure 3a.

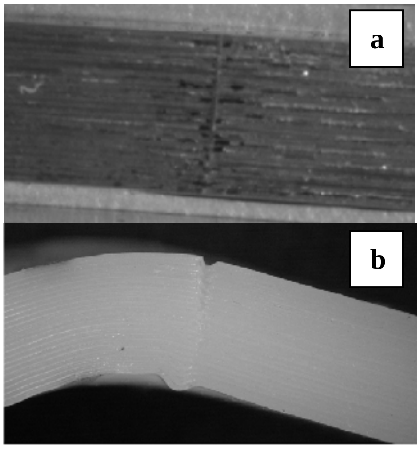

Figure 3. Failure crack propagation through thickness

It was observed crack formation at both edges of the specime; as internally they were opaques, it was not possible to observe how this effect had penetrated to the internal area. It was found when a sample was tested only once, the crack propagated was apparently superficial, but, if twenty tests with both sides deformation were performed, it was observed a deeper failure remaining the form of a zipper. It can be observed at figure 3b.

There were some samples with two lines of cracks by edge, others with three. In some cases the cracks on both sides of sample were parallel and at other cases they were not parallel. So taking a little closer look, it was found a trend in crack formation for every set of conditions. The distance between cracks was measured and it was found an interesting repeteability which lead to decide the schematization of this crack formation phenomena.

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It is interesting to understand the concurrence of several kinds of macroscopic and microscopic bonding of material, affecting the global macroscopic behaviour of the layered material. At the Z direction it is found the stacking of succesive homogeneous layers of material adhered to each other with the help of a chemical adhesive bonding. Internally, the extruded PVC sheet has intrinsecally some polymer molecules orientation which promotes the anisotropic behaviour of mechanical properties, leading to a higher strenght in the direction of orientation and lower strenght at the transversal direction. Depending on the array of this heterogeneous contributions to macroscopic mechanical properties, different responses are expected to be obtained.

At Figure 4, it has been represented the different contributions to macroscopic behaviour corresponding to the conditions of experience 1. It is also shown the failure pattern observed for this experiment 1.

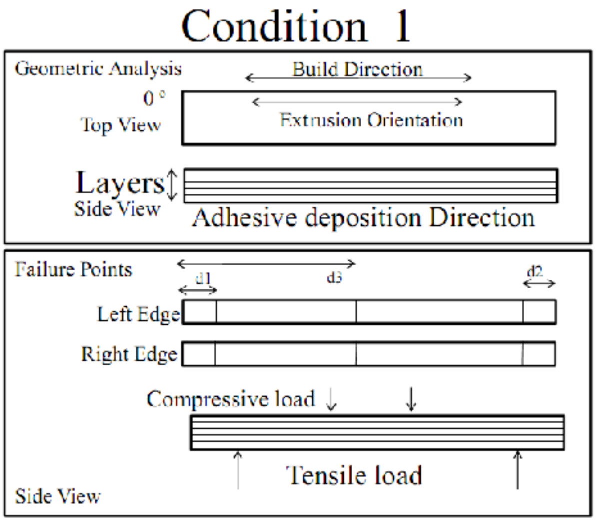

Figure 4. C1 Schematic representation of failure points

Table 3. C1 Measured values for characteristic distances

Tipus 1	Left Edge (mm)			Right Edge (mm)		
	d_1	d_2	d_3	d_1	d_2	d_3
Mean	9,44	6,54	36,68	9,57	6,63	36,49
EstDev	0,08	0,37	0,26	0,06	0,20	0,22

At Table 3 are shown the distance values obtained for a set of five samples tested at each condition and its respective standard deviation. In this case, it was observed three failure points at each edge, one approximately at the center, and other two corresponding to the lower support points. The central crack was visually the deepest. Failure points at both edges were symetric as it is evidenced at Table 3. For all cases, extrusion orientation is parallel to build direction; it has been designed this way for this LOM process, because material feeding is made with a laminated roll. In condition 1, the long dimension of specime is oriented parallel to build direction and layers are stacked forming the thickness of specime. It means when applying load, polymer chains, as well as adhesive bonding are aligned to resist load.

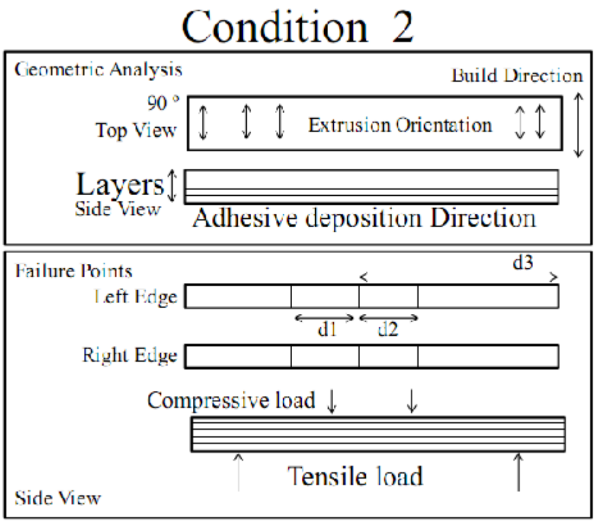

Figure 5. C2 Schematic representation of failure points

Table 4. C2 Measured values for characteristic distances

Tipus 2	Left Edge (mm)			Right Edge (mm)		
	d_1	d_2	d_3	d_1	d_2	d_3
Mean	20,69	20,14	38,38	20,44	19,98	38,40
EstDev	0,25	0,43	0,17	0,59	0,67	0,72

In figure 5 it is represented the configuration of bonding contributions for experience 2. It were observed three failure points at each edge, one approximately at the center but slightly displaced and two additional failure points equidistant to it and separated by 20 mm by each side. Experimental values for the distances obtained are shown at Table 4. Failure points at both edges were symetric. For this case build direction, which means polymer chains, are oriented forming a 90 degrees angle with the long direction of specime and with adhesive deposition direction. The load device is parallel to polymer chains orientation which means that load is applied at the weakest configuration of the microscopic contribution of polymer orientation.

In Figure 6 are represented the findings for experience 3. It was observed two failure points at each edge of the specime and those points were not symetric with respect to the top view of specime representation as observed for exp. 1 and 2. Considering the location of failure points from one edge to another, there is a displacement measured as d_3 as can be observed at table 5. Even tought the values obtained for failure points distances d1, d2 had a considerably higher dispersion on this experience, the displacement value d3 obtained was very consistent. In this case, polymer chains oriented as a result of extrusion are located forming a 45 degrees angle with the long direction of the specime. It means that stronger direction of the PVC sheet is forming a 45 degrees angle with respect to the load device.

From the displacement measured at the failure point of the specime, it seems that stress concentrantion in it takes place in the load application direction; it is, following the flexural inserts direction. It seems that the crack propagates through a perpendicular direction with respect to the orientation of the polymeric chains.

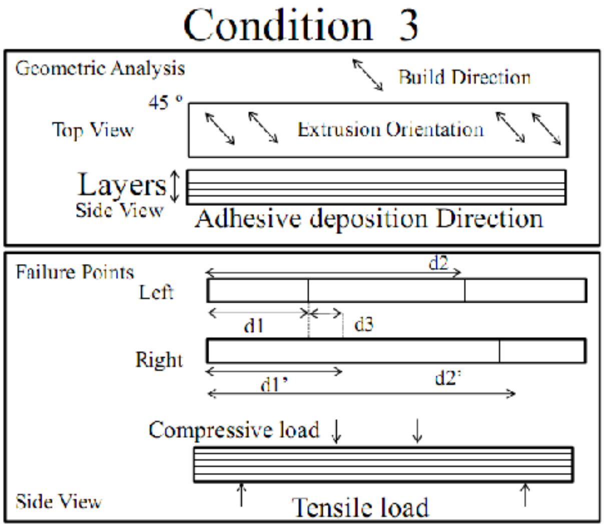

Figure 6. C3 Schematic representation of failure points

Table 5. C3 Measured values for characteristic distances

Tipus 3	Left Edge (mm)			Right Edge (mm)	
	d_1	d_2	d_3	d_1'	d_2'
Mean	18,82	47,29	4,72	23,54	51,68
EstDev	3,74	4,64	0,60	3,97	4,22

C4 At Figure 7 are shown the findings for experience 4. For this case there was only one failure point, located approximately at the center of specime going through the entire thickness showing the mark of plastic deformation. Table 6 shows values measured for failure location. Condition 4 is specially different from the other set of conditions because load is perpendicular to the stacked layers of PVC binded with polymeric adhesive.

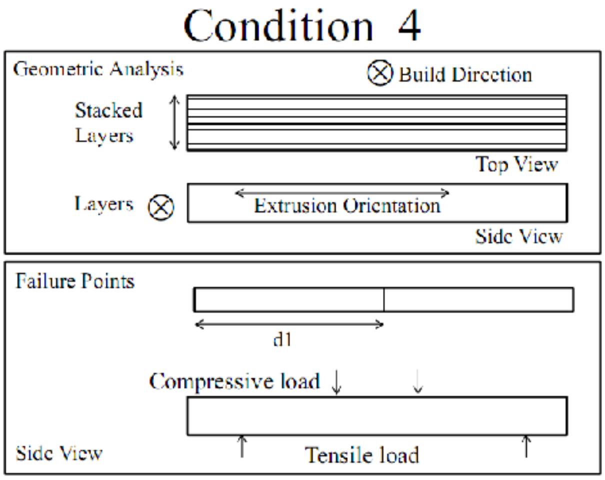

Figure 7. C4 Schematic representation of failure points

Table 6. C4 Measured values for characteristic distances

Tipus 4	Up (mm)	Down (mm)
	d_1	d_1'
Mean	39,90	40,05
EstDev	0,39	0,72

The influence of macroscopic and microscopic contributions to internal bonding at the resulting layered material, was reflected over flexural strenght measurements as can be observed at figure 7.

Even though the heterogeneous nature of this layered material, determined by layers glued together under chemical adhesive application, every curve shows the typical behaviour of plastics material under flexural load. It can be observed an initial step of load with pure elastic behaviour, then an inflexion region that opens a new plastic-elastic deformation region. At 3,5% deformation point, the beaviour of all conditions is clearly differentiated. It can be seen a higher resistance for condition 3, a lower but very similar strenght for conditions 1 and 2 and a considerable lower strenght for condition 4. This behaviour is in acordance with the failure points obtained for each condition and can be explained as a consequence of the overall contribution of the different bonding mechanism present internally. At Exp. 3, it is overlapped the influence of adhesive in the z direction of the specime with the polymer orientation located orthogonally to loading device, thus loading application. The higher resistance shown in this case can be understood as a result of the knitted overlapped influences mentioned before. In the case of C1, load is applied perpendicular to polymer orientation and this leads to the sum of contributions in the long specime direction, which gives good resistance properties. Failure observed located at the lower supports would be due to tensile stress applied to the lower side of the specime. At C2 they are found two failure points besides the central one. In this case, the weakest direction of the oriented film is located parallel to the application of load. This explains the defect formation, located close to the loading supports which load specime mainly in a compressive fashion. For C4, plastic deformation is reached with lower loads and a lower strenght is registered, because of the heterogeneous contributions present in this configuration.

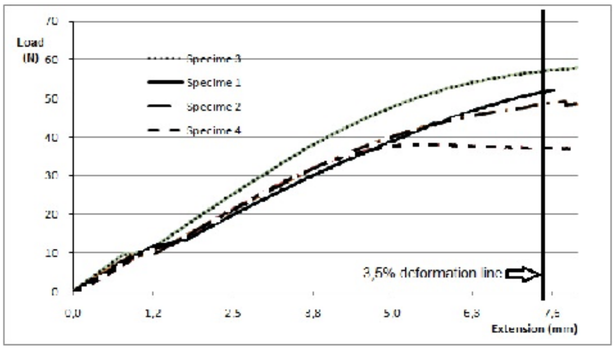

Figure 8. Flexural Curve according to ASTM D790

Conclusions

The analysis of the failure mechanism under flexural testing for additive manufactured LOM bars lead us to understand that:

- Build orientation is the stronger direction
- A 45 dregrees angle at manufacturing improves strenght.

On further research it will be studied why crack formation had not propagated internally and it will be also developed fatigue strenght measurements.

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