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Analysis of the Mechanical Properties of 3d Printed Structures and Comparison of Results through Simulations in Solidworks Software

Gisela Aguilar[1], Stephanie Santos[2], María Elena Perdomo[3]
[1]Universidad Tecnológica Centroamericana UNITEC
San Pedro Sula, Honduras
Gisela_aguilar_@unitec.edu; stephanie.santos@unitec.edu
[2]Universidad Tecnológica Centroamericana UNITEC
San Pedro Sula, Honduras
Maria_perdomo_@unitec.edu
[3]Universidad Tecnológica Centroamericana UNITEC
San Pedro Sula, Honduras

Abstract **-** Additive manufacturing, also known as 3D printing, has revolutionized the way components are designed and manufactured across various industries. This innovative approach allows for the creation of complex and customized three-dimensional objects from digital data, overcoming many of the limitations associated with traditional manufacturing methods. Unlike subtractive manufacturing, additive manufacturing builds objects layer by layer, reducing waste and enabling complex designs. The significance of extends to multiple fields, including medicine, aerospace, automotive, architecture, and consumer goods production. However, to ensure the structural integrity and safety of components manufactured through additive manufacturing, it is crucial to understand and study their mechanical properties. This includes analyzing the tensile strength, compression, bending, and material fatigue. Therefore, the purpose of this research is to study the mechanical properties of IPR and IPS beam-scale structures manufactured using the 3D printing technique known as Fused Deposition Modeling (FDM). The analysis of the mechanical properties will be conducted by comparing results obtained from simulations in the SolidWorks software.

Keywords**:** mechanical properties, additive manufacturing, simulation, infill, fused deposition modeling

1. Introduction

The dynamic evolution of market needs has driven the adoption of new manufacturing techniques to enhance and meet product requirements. In this context, additive manufacturing has emerged as an innovative and highly adaptable solution. Although its concept originated in the 1980s, it has flourished in the last three decades due to its ability to produce complex structures, offer high customization, and significantly reduce material waste, among other benefits. This technology has found diverse applications in industries such as aerospace, biomedicine, and engineering, among others. However, for 3D printed components to compete with and eventually replace those produced by subtractive manufacturing, a comprehensive understanding and detailed characterization of the mechanical properties associated with 3D printing is imperative, as well as considering the various manufacturing factors that influence these properties, such as printing parameters.

2. State of the Art

2.1. Additive Manufacturing

Currently, there are two methods for manufacturing three-dimensional objects: additive and subtractive, the latter also known as "traditional" manufacturing. Subtractive manufacturing involves obtaining the final product by removing material, either by cutting or drilling it [1]. On the other hand, additive manufacturing refers to 3D printing, where a three-dimensional object is created by progressively depositing layers of material on top of each other until the desired final product is achieved [2]. Additive manufacturing offers several advantages over traditional methods, among which can be highlighted greater design flexibility, dimensional accuracy, fabrication of complex geometries, customization, among others [3]. Furthermore, a wide variety of materials have been developed for 3D printing, such as polymers, metals, ceramics, glasses, and biomaterials [4].

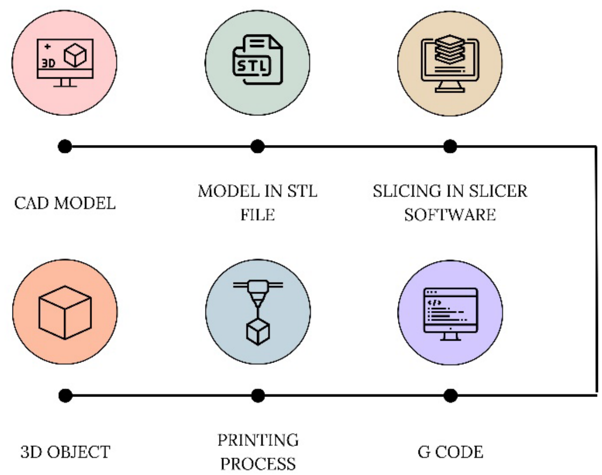


Fig. 1: Basic Process Flow of 3D Printing.

The general description of any 3D printing process can be broken down into six stages, which are detailed in Fig. 1. However, the 5th step corresponding to the printing process may experience variations, as there are different 3D printing techniques [5]. One of the major challenges is the classification of these techniques due to their wide variety [6]. Some of the most recognized 3D printing techniques include Fused Deposition Modeling or FDM, Selective Laser Sintering or SLS, and Stereolithography or SLA [7].

2.2. Fused Deposition Modeling or FDM

This technique was developed and patented by Scott Crump in 1989 [4]. Some of the advantages provided by this technique are that the piece accuracy is ±0.08 mm, the equipment has a compact size, and its maintenance cost is low [8]. With this type of technology, it is straightforward to create complex geometries, and the filaments used have stable mechanical properties [2]. However, [9] asserts that, although the FDM method allows for the use of a wide variety of filaments, the technique itself could have a negative impact on the surface quality and mechanical properties of the final product. FDM has been widely used in fields such as biomedicine and aerospace [10].

2.3. 3D Printing Filaments

PLA, along with ABS, are among the most used thermoplastics in additive manufacturing [6]. In several of the studies reviewed, authors like [11] point out that previously PLA was not as researched as ABS, and this is the reason why there has been a significant increase in research focused on PLA in recent years, thus creating the disparity reflected in Figure 2. Another reason that has driven the research of PLA is its biodegradable nature, as this allows it to meet the current market demands in terms of environmental sustainability [12].

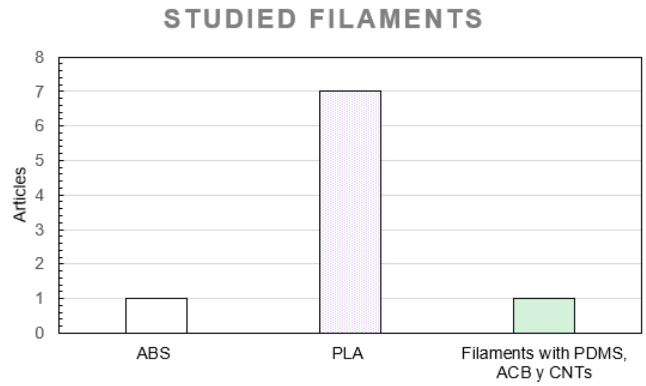


Fig. 2: Filaments Most Used in Research

The PLA is one of the most commonly used filaments in 3D printing and is characterized by being biodegradable and having a low melting point ranging from 190°C to 250°C [13]. Its biodegradable nature is attributed to it being derived from organic acids naturally present in starch, sugarcane, and tapioca roots [14]. One of the significant applications given to this filament is in the manufacturing of components used in the medical field, such as screws required in orthopedic surgeries [15].

2.4. Printing Parameters

Investigating the mechanical properties of components printed with 3D technology is of vital importance, as it allows us to validate their use in specific applications [16]. It's important to consider that printing parameters have a substantial effect not only on the mechanical properties but also on the surface quality and manufacturing time [13]. Figure 3 reflects the printing parameters and their relevance highlighted in recent research.

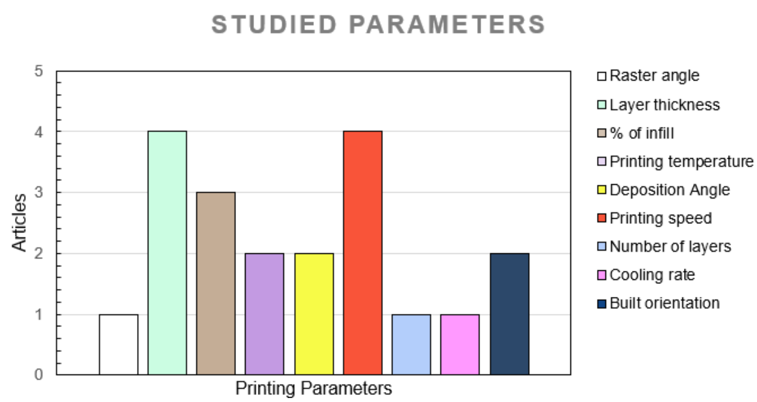


Fig. 3: Studied Printing Parameters

The infill percentage is one of the most important printing parameters, as it plays a crucial role in determining the strength of the component, as well as the time it will take for its fabrication and the final cost [17]. This parameter refers to the amount of material inside the printed component [14]. When selecting the infill percentage to be used, it is important to consider that this represents the foundation of our structure, and that the lower the percentage, the lower the quality and the less satisfactory the mechanical properties will be [2].

In addition to the infill percentage, different infill patterns can also be chosen. Figure 4 shows examples of these two parameters.

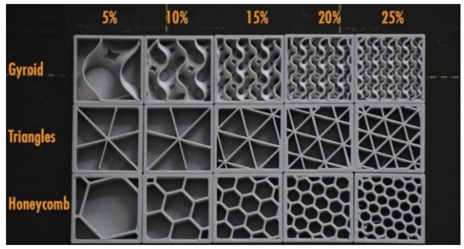


Fig. 4: Different infill patterns and percentages

3. Methodology

Considering the classification proposed by [18], the present study adheres to a quantitative approach. This approach is characterized by following a rigorous sequential process that involves observations, data collection, and statistical analysis with the purpose of providing answers to the hypotheses previously formulated, which are derived from the conclusions obtained during the literature review. In Figure 5, the research variables identified for the development of the present study are detailed and consist of one dependent variable and three independent variables.

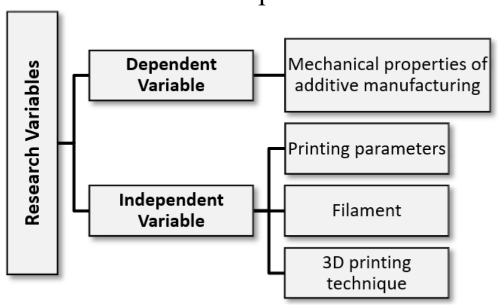


Fig. 5: Research variables of the study

In this context, the research is given an experimental design since there will be an intentional manipulation of the independent variables to observe their effect on the dependent variable [18]. The design is a pure experimental one, as there will be manipulation of one of the independent variables, meaning that there will be multiple study groups. The summarized study methodology is shown in Figure 6.

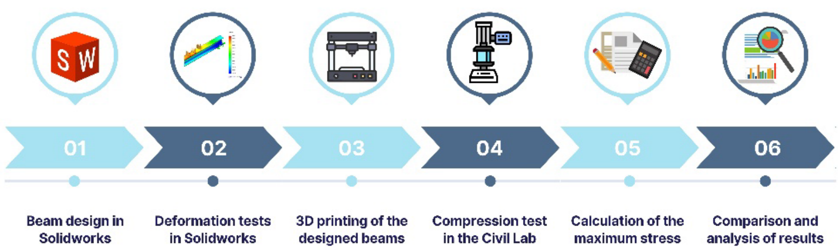


Fig. 5: Study Methodology to Evaluate the Mechanical Properties of Additive Manufacturing

4. Results

Using the SolidWorks software, 12 beams were designed, of which 6 corresponded to W profile IPR beams, and the rest were S profile IPS beams. The measurements for each of the beams are specified in table 1 and 2, where h is the height or also called depth, b is the base or flange, tw is the web thickness, and tf is the flange thickness. The length for each of the beams is 6 inches.

Table 1: Measurements for W profiles

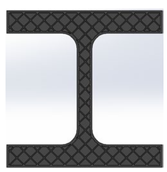
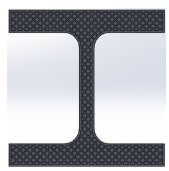
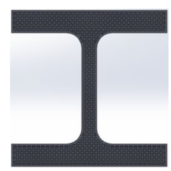
Description	h (m)	b (m)	tw (m)	tf (m)
W 5x16	0.063627	0.0635	0.006096	0.009144
W 4x13	0.052832	0.051562	0.007112	0.008763

Table 2: Measurements for S profiles

Descripción	h (m)	b (m)	tw (m)	tf (m)
S 4x7.7	0.0508	0.0338328	0.0049022	0.0074422
S 4x9.5	0.0508	0.0355092	0.0041402	0.0037338

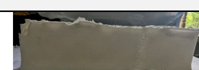
The design of the profiles was carried out in SolidWorks according to the previously mentioned specifications. And for each profile, variants were developed with a fill of 10%, 20%, and 30%. For the creation of these infills, the linear pattern, shell, and rib tools offered by SolidWorks software were used. Table 3 shows images where the 10%, 20%, and 30% infill can be appreciated in one of the profiles. The wall thickness used inside for the grid creation is 0.4 mm or 0.015748 inches, and a 45% angle was considered.

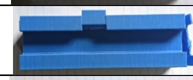
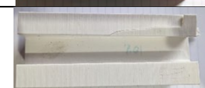
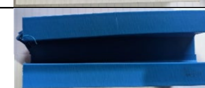
Table 3: Infill at 10%, 20% and 30%

	Description	10% of Infill	20% of Infill	30% of Infill
Beams IPR	W 5x16			

Once the designs were completed, the fabrication of the 12 beams was carried out using 3D printing with PLA filament in three different colors. This color choice aims to differentiate the various infill percentages in each structure. Specifically, the white color corresponds to the pieces with a 10% infill, the blue to the pieces with a 20% infill, and the red to the pieces with a 30% infill. Compression tests were conducted using the ELE International compression machine, located in the civil engineering laboratory. The machine's configuration was set to apply compression increments of 10 pounds to determine the force at which deformation of each piece occurred. The detailed results of these tests are presented in Table 4.

Table 4: Compression test results

	Description	Infill	Applied force (N/m)	Imagen
Beams IPR	W 5x16	10%	557.0152	
	W 5x16	20%	789.764	
	W 5x16	30%	1,180.6915	
	W 4x13	10%	543.457	
	W 4x13	20%	745.6999	
	W 4x13	30%	1,181.8214	

Beams IPS	S 4x7.7	10%	540.0675	
	S 4x7.7	20%	1,229.275	
	S 4x7.7	30%	1,067.707	
	S 4x9.5	10%	543.457	
	S 4x9.5	20%	1,059.798	
	S 4x9.5	30%	2,161.3999	

Upon obtaining the compression test results, the maximum stress was calculated. Firstly, Equation 1 was used to determine the maximum moment based on the applied force (w) in Lbf and the length of the beam (L). Then, tools within SolidWorks were used to define the y-coordinate of the centroid and the moment of inertia about the xx-axis. With these data in hand, the formula for maximum stress, represented in Equation 2, could be applied. Similarly, simulations were conducted in SolidWorks using finite element analysis. The results obtained using the equations are presented in Table 5, while those acquired from the simulations and the percentage difference between them are found in Table 6.

$$M_{máx} = \frac{1}{8} w L^2 \quad (1)$$

$$\sigma_{máx} = \frac{M_{máx} * c}{I} \quad (2)$$

Table 5: Results of the maximum stress calculated with the equations

	Description	**Maximum stress for beams with 10% infill (Pa)**	**Maximum stress for beams with 20% infill (Pa)**	**Maximum stress for beams with 30% infill (Pa)**
Beams IPR	W 5x16	136,571,381.29	218,623,188.41	264,890,028.82
	W 4x13	231,651,084.54	234,027,358.35	298,687,654.27
Beams IPS	S 4x7.7	370,764,902.99	636,918,324.85	451,075,442.3
	S 4x9.5	414,546,532.63	661,425,419.55	1,187,068,216.61

Table 6: Results of maximum stress in SolidWorks simulations

	Description	**Maximum stress for beams with 10% infill (Pa)**		**Maximum stress for beams with 20% infill (Pa)**		**Maximum stress for beams with 30% infill (Pa)**	
Beams IPR	W 5x16	140,272,204.53	2.71%	229,606,447.97	5.02%	227,049,669.74	14.29%
	W 4x13	201,684,110.37	12.94%	219,250,610.18	6.31%	217,601,594.07	27.15%
Beams IPS	S 4x7.7	298,560,446.23	19.47%	345,687,957.64	45.72%	269,237,165.43	40.31%
	S 4x9.5	387,302,637.93	6.6%	356,566,486.02	46.09%	629,626,994.30	46.96%

Upon observing the results, we can detect that all the beams with 30% infill have a higher percentage of difference. This is also notable in the case of the IPS beams with 20% infill. The reason for this is that both the beams with 30% infill and the two IPS beams with 20% infill are subjected to a force greater than 1,000 N/m. Since during the compression tests carried out in the civil engineering laboratory, the pieces broke rather than just reaching their elastic limit, SolidWorks software faces limitations in conducting simulations with such applied force. On several occasions during the simulations, pop-up dialogues from the software mentioned that it was not possible to fully apply the progressive load or there was simply a failure during the simulation.

5. Conclusions

Using the SolidWorks design software, drawings of 4 types of beams corresponding to two types of profiles, the IPR and IPS, were created. The selected beams were W 5x16, W 4x13, S 4x7.7, and S 4x9.5. Each of the beams was drawn with its respective standardized measurements, but with a slight variation, as they were scaled down by 50% to facilitate their 3D printing, and the established length for all was 6 inches. Subsequently, by using operations such as extrusion, cut, linear pattern, and rib, infills of 10%, 20%, and 30% were applied to each of them.

Based on the results obtained in the compression tests carried out in a previous research project, the maximum stress for each of the beams was calculated using their maximum moment values, y-coordinate of the center of gravity, and moment of inertia about the xx axis. These last two data points were obtained using tools within the SolidWorks software.

Compression simulations were carried out in SolidWorks, using finite element analysis (FEA) and considering conditions similar to those to which the beams were subjected in real life, to obtain the maximum stress and thus make a comparison with the calculated maximum stresses. From this comparison, the conclusion drawn is that the software may have limitations regarding the load that can be applied since its objective may be only to reach loads that exceed the elastic limits; however, it cannot handle loads that are too large to break the pieces. However, for small loads, the simulations and their results have a good level of accuracy.

Acknowledgements

Perform this study on the mechanical properties of additive manufacturing applying some of the standards defined such as ASTM D638 (Standard Test Method for Tensile Properties of Plastics), ASTM D790 (Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics), ASTM D695 (Standard Test Method for Estimating Compressive Properties of Rigid Plastics), ISO 178:2010, ISO 604 Plastics, and Differential Mechanical Analysis (DMA).

Consider the alteration of different printing parameters, that is, not only the infill percentage, in order to generate more significant knowledge regarding the factors that will influence the mechanical properties.

It is recommended to carefully evaluate the type of conditions under which the compression tests will be carried out so that a comparison of results with SolidWorks simulations can be possible. Since the software presents some limitations regarding how the load can be distributed within the simulations.

This work would not have been possible without the help of Saul Sánchez, who contributed to the 3D printing of the beams and the compression tests carried out on them.

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