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RESEARCH ON COMPRESSIVE BEHAVIOR OF A WILLOW STRUCTURE MANUFACTURED USING FDM TECHNOLOGY

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Abstract: *In the context of industrial product remanufacturing, internal structures can be optimized beyond those automatically generated by slicing software, through innovative geometries. This study investigates the compressive behavior of a Willow structure proposed by Snapp et al, which demonstrated a mechanical energy absorption efficiency coefficient of* K_S*=75.2%. To rigorously evaluate the potential of this geometry as an infill in applications requiring high energy absorption capacity and low weight, it is necessary to assess the influence of the material on the performance of the Willow structure. The structure was manufactured using the FFF/FDM technology with a 0.6 mm nozzle and three different materials: PLA, PETG, and carbon fiber-reinforced PET (PET CF15). The aim of the paper is to offer to the readers a comparative study on comprehensive behavior of Willow structure manufactured using FDM technology and the selected materials. Standardized tests on cylindrical specimens, according to ASTM D695, revealed the superior material performance of PET CF15. However, in the case of Willow structure with thin walls, material performance rankings changed due to the tendency of PET CF15 layers to slide and delaminate under load, caused by the random orientation of carbon fibers. Specimens were microscopically analyzed both before and after compression testing to identify material defects and failure modes. This study highlights the influence of carbon fibers on the performance of Willow structures and proposes future research directions.*

Key words: *Remanufacturing, FDM technology, Willow structure, Energy absorption efficiency, Compressive behavior*

1. INTRODUCTION

Nowadays, in the context of rapid industrial development and escalating environmental challenges, the need for sustainable engineering solutions has become more necessary than ever. The increasing depletion of natural resources and the alarming growth of industrial waste have been accelerating the global transition toward a circular economy [1]. Within this framework, remanufacturing of industrial products has emerged as a strategic and impactful direction.

Unlike conventional recycling or simple reusing, remanufacturing is the process of completely restoring a product to a “like-new” condition through systematic inspection, disassembly, component replacement or reconditioning of it, followed by reassembly and testing, ensuring compliance with original specifications. In addition, the remanufactured product could be sold as new, with a warranty [2], [3].

This approach not only contributes to substantial reductions in raw material consumption and manufacturing-related emissions, but also offers significant economic benefits by expanding the product lifespan and maintaining high functional integrity. Through intelligent reuse of existing components, remanufacturing plays an important role in reducing the environmental footprint of industrial systems and strengthening the sustainability of production cycles.

In this context, additive manufacturing (AM) has become one of the most promising technologies for remanufacturing processes, due to its flexibility, material efficiency, and the ability to restore or enhance components with complex geometries. Among its many advantages, AM allows targeted material deposition, enabling the repair of reinforcement of worn areas without affecting the rest of the structure – a key factor in remanufacturing high-value components [4], [5].

A crucial element within the additive manufacturing process is the infill structure, generated by the slicing software, which plays a decisive role in determining the mechanical behavior of the 3D printed component. The geometry, density and orientation of the infill pattern directly affects not only the strength and stiffness of the part, but also its wight, thus generating a higher or lower material consumption [6], [7], [8].

Yin et al. [9] classified 2D and 3D energy absorption lattice structures and discussed their mechanical features, fabrication processes, and applications. They found that honeycomb and auxetic absorb energy well, especially under out-of-plane compression, but most studies are descriptive and did not consider in deep the manufacturing faults and industrial application. Snapp et al. [10] combined experiments with machine learning to design novel geometries, achieving very high energy absorption efficiency and showing the potential of new, unexplored structures. Limitations include limited multi-axial loading research and the gap between lab and industrial results. In addition, additive manufacturing has specific issues, for example accuracy is higher in the XY plane, but the Z direction suffers from the "step effect", reducing surface quality and strength [11].

While standard slicing software offers predefined infill patters, some of them are not proper for demanding applications. In the search for optimized internal structures, a geometry known as Willow, developed by Snapp et al. [10], has shown remarkable potential. Developed through a campaign using a self-driving laboratory after over 25.000 tests, this geometry was designed to maximize mechanical energy absorption efficiency (Ks) under compressive loading. Unlike conventional infill patterns, the Willow structure could present a unique balance between lightweight design and high structural performance. Its architecture and capacity to deform under load in a controlled manner it's suitable for additive manufacturing scenarios, where material savings and structural integrity are important.

Although the Willow structure has demonstrated a high mechanical energy absorption efficiency when manufactured from PLA, it's not known if its performance is affected by the base material. Thus, it raised a question: if is changed the material to a better one is still have the same mechanical properties of this structure, the mechanical hierarchy of materials remains valid when it comes to this structure?

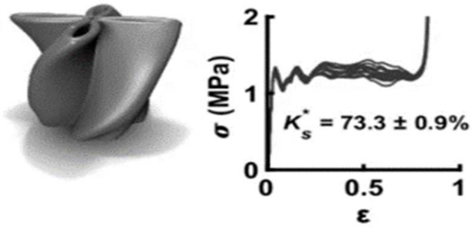


Fig. 1. The Willow structure and its energy absorption efficiency [10]

The purpose of this study is to evaluate the compressive behavior of the Willow structure manufactured thought FDM technology using three different materials: PLA (the one that was used by Snapp et all), PETG and PET CF15. By comparing their performance in both standardized and complex geometries, this research aims to assess the suitability of the Willow structure as infill in remanufactured components. The paper is structured as follows: Section 2 describes the Willow structure, the used materials, the testing methodology and the experimental setup. Section 3 presents the results and comparative analysis and the Section 4 discusses future directions and conclusions.

2. MATERIALS, GEOMETRY AND EXPERIMENTAL CONFIGURATION

2.1 The Willow Structure

The Willow structure is a parametrically generated 3D geometry developed by Snapp et al. [10] within the Bayesian Experimental Autonomous Researcher (BEAR) laboratory, aiming to maximize the mechanical energy absorption efficiency under compressive loads (Fig. 1.). The shape is derived from a basic cylindrical form whose cross-section is modified by mathematically controlled undulations generated by trigonometric functions. It is defined by 11 parameters: three classical dimensional parameters (height, average perimeters, wall thickness) and eight additional parameters governed by trigonometric expressions.

Among them, four control (Fig. 2.) the base and top cross-sections (C4_base, C8_base, C4_top, C8_top) while the other influence shape variation, rotation along Z-axis and the difference in perimeter between top and bottom (Table 1) [10].

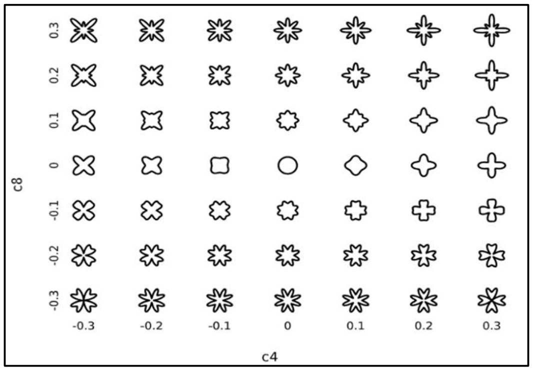


Fig. 2. The influence of top and bottom parameters [10]

Table 1

Parameter values used by Snapp et al. [10] to generate Willow structures

Parameter name	Value [mm]
Height	26.296
Mass	2.277
Thickness	0.771
C4_base	0.137
C8_base	-0.223
C4_top	0.990
C8_top	0.281
Twist_linear	1.652
Twist_amplitude	0.136
Twist_cycles	0.892
Perimeter_ratio	1.535

2.2 Materials Used

In this research three thermoplastics materials were selected: polylactic acid (PLA), polyethylene terephthalate glycol (PETG) and a composite material – PET reinforced with 15% short carbon fibers (PET CF15). The selection was based on their commercial availability, popularity in FDM/FFF printing and mechanical characteristics relevant to lightweight structural applications.

PLA from Ultimaker is a biodegradable polymer derived from renewable resources, it is widely used due to its ease of printing, dimensional accuracy and stiffness. However, it tends to be brittle, which may limit its use in applications with impact [12], [13]. PETG, provided by Fillamentum, offers a balanced trade-off between strength and ductility, it's more flexible than PLA [14], [15].

The PET CF15 from Ultrafuse is a high-performance composite filament that combines the strength and thermal resistance of PET with the stiffness by carbon fiber reinforcement [16]. Although it offers superior compressive strength in standard geometries, pervious research [7], [17] indicate that its performance can be influenced by print orientation.

In addition, potential layer delamination due to fiber misalignment can cause differences in the mechanical properties [17].

For all materials, printing parameters were carefully picked to ensure optimal results, with consistent settings across all samples, including 0.6 mm nozzle diameter, layer height (0.15 mm) and print speed, to minimize the influence of non-material factors on the experimental outcome (See Table 2).

2.3 Testing Methodology and Experimental Setup

All specimens were generated based on values from Table 1 and fabricated using a BCN3D Sigma R19 3D printer based on FDM technology. Before testing the Willow structures, a comparative test was carried out to determine which of these three materials has better mechanical properties.

Table 2

Parameters suggested by the manufacturers and scientific articles that were used in the manufacturing of the parts [7], [18], [19], [20]

Filament	PLA	PETG	PET CF15
Nozzle temp [°C]	190-210	235-255	250-285
Bed temp [°C]	50-60	65-75	65-85
Printing speed [mm/s]	40-70	40-60	30-80
Cooling [%]	100	0-30	-
Retraction speed [mm/s]	25-45	20-25	20-30
Retraction distance [mm]	4,5-6,5	6-7	6,5-7

For this, a standard compression test was purposed, based on the standard ASTM D695. Five cylindrical specimens (Fig. 3.) were manufactured from each material with dimensions conforming the standard (ø12.7 x 25.4 mm).

Fig. 3. Cylindrical samples according to D695 standard

Additionally, six Willow samples were printed for each material (Fig. 4.): five were intended for mechanical testing and one was reserved for pre-test microscopic analysis. The compression tests (Fig. 5.) were carried out using a WDW-150S universal testing machine equipped with a 20kN load cell. The force-displacement data collected during testing were used to generate engineering stress-strain curves for further analysis. Unlike the method proposed by Snapp et al., which estimates the effective cross-sectional area based on a hexagonal prism enclosing the entire structure this study opted for another approach. The effective area was approximated as that of a cylinder inscribed within the structure, this decision was motivated by the fact that the hexagonal method considers significant peripheral material that is not structurally engaged during compression.

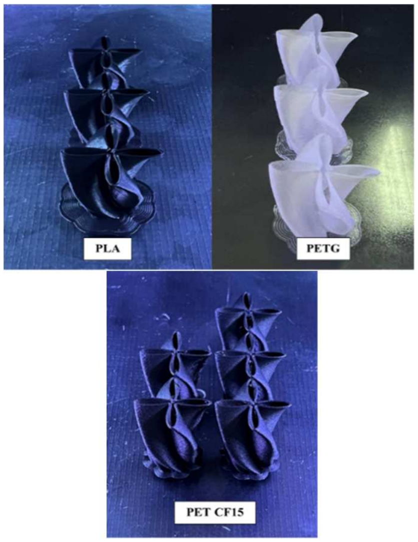


Fig.4. Willow structures on the BCN3D Sigma R19

After testing all of the Willow structures a microscopic inspection was carried out with structures that were tested and structures that were not tested. This analysis was conducted with the help of a digital microscope, Leica Emspira 3. Performing a microscope analysis internal defect, surface discontinuities and delamination process were remarked, especially in the case of carbon fiber-reinforced specimens.

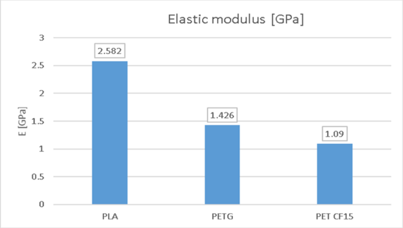
Fig.5. Willow structures during testing

3. EXPERIMENTAL RESULTS AND COMPARATIVE ANALYSIS

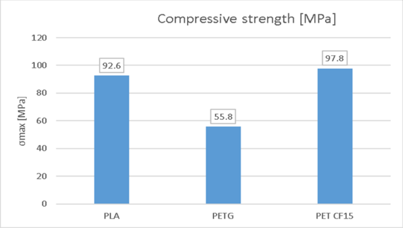
3.1 Results from Standard Cylindrical Specimens

To determine the mechanical performance of the selected materials, five cylindrical specimens were fabricated from type of considered material (PLA, PETG and PET CF15), following the dimensions specified in ASTM D695. The cylindrical specimens were tested under axial compression force using the WDW-15S universal testing machine. For each material there were recorded the elastic modulus, the maximum compressive strength and maximum compressive force.

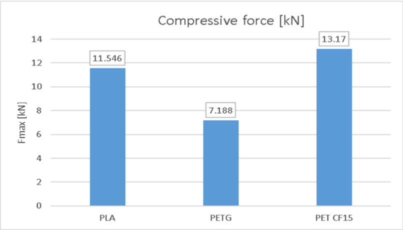
Results, expressed as average, showed that the composite material, the PET CF15 had the highest compressive strength (97.8 MPa) and a compressive force of (13.17kN) followed by PLA with 92.6 MPa and 11.546 kN (Fig. 6.).



a) Elastic modulus of the cylindrical samples



b) Compressive strength of the cylindrical



c) Compressive force of the cylindrical

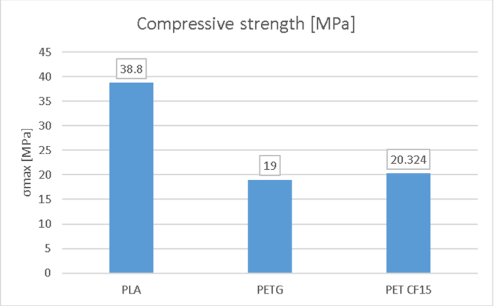
Fig.6. Results of the cylindrical specimens after testing

PLA recorded the highest elastic modulus of 2.582 GPa, indicating superior stiffness, and the PETG material demonstrated the lowest mechanical performance. These results serve as a comparison for the Willow structures.

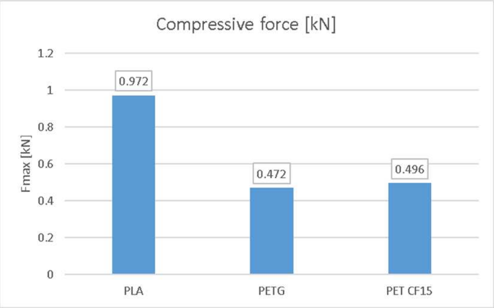
3.2 Results from Willow structures

Six Willow structures were fabricated on the BCN3D Sigma R19 3D printer using the same three materials that were used on the standardized samples. Five of them were tested, while one was used for preliminary microscopic inspection. All the samples were fabricated with a 0.6 mm nozzle diameter. The PLA structures showed superior performance in terms of rigidity and maximum force, followed by PET CF15 and PETG. After the compressive test of the cylindrical specimens, it was assumed that the PET CF15 Willow structure will perform better. The PET CF15 Willow structure showed a decline in effectiveness, likely due to the behavior of carbon fibers in thin-walled prints. Without sufficient structural support (like another wall) the fibers contributed less to stiffness and started to slip when axial force was present, this finding was described before [7], [17].

PLA had a maximum compressive strength of 38.8 MPa and a force of 0.972 kN, PETG showed weaker performance with a force of 0.472 kN and 19 MPa compressive strength. The PET CF15 material had a compressive force of 0.496 kN and 20.32 MPa compressive strength (Fig. 7.).



a) Compressive strength of the Willow



b) Compressive force of the Willow

Fig.7. Results of the Willow structures after

The results revealed a performance inversion, while PET CF15 outperformed in standard specimens, PLA demonstrated superior behavior in thin-walled geometries. This shift suggests that interlayer bonding and material continuity greatly influence these geometries, which traditional tests neglected.

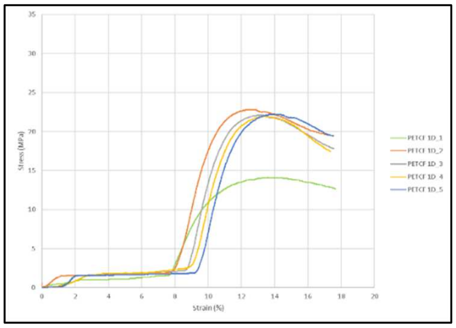


Fig.8. PET CF15 Willow structures stress-strain

3.3 Microscopic Analysis

To better understand the deformation behavior of the Willow structures, a microscopic analysis was carried out using the Leica Emspira 3 system. Samples before and after testing were checked. With the visual inspection is identified the manufacturing defects and how they influence the mechanical performance of the Willow structures. For the PET CF15 samples, fibers of carbon could already be observed protruding between layers before testing (Fig. 9.), along with a lack of continuity between the deposited layers.

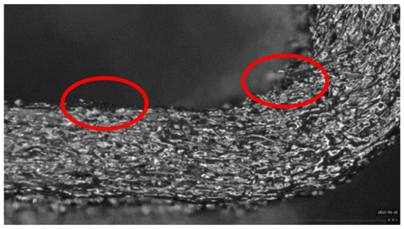


Fig.9. Carbon fibers out of the polymer matrix

As it was specified in previous research [7], [12] regarding this material, due to the adding of the fibers in the polymer matrix or due to the production process, presence of voids or interruptions in the structure will be found. After testing, a noticeable sliding of the upper layer toward the interior was observed (Fig. 10.), particularly in the top region, indicating the delamination effect that was supposed to be to blame for the poor mechanical performance results. In contrast, the PLA and PETG showed a more homogeneous appearance before testing and a uniform deformation after deformation, without signs of layer separation. These findings support the idea that, in thin-walled structures, like the Willow structure, the distribution and the orientation of the material play a critical role in mechanical performance.

4. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

The results obtained from both standardized cylindrical specimens and Willow structures revealed a significant difference between the mechanical behavior of materials in standardized form versus thin-walled geometries. PET CF15, which had the best mechanical properties in the D695 tests was outperformed by PLA in the Willow configuration, suggesting a degradation of structural efficiency in single wall applications. It was assumed that this was caused by the interlayer slippage observed in other research [7], [15] and it was confirmed by microscopic analysis.

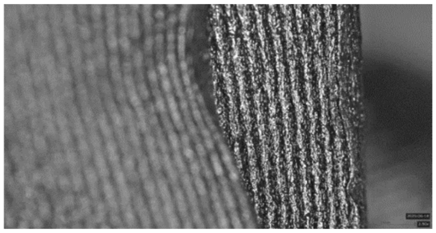


Fig.10. Material sliding in the upper region of the Willow structure from PET CF15

Several limitations should be mentioned. First, Willow geometry is susceptible to parameter variations, making results difficult to evaluate without practical verification. Changing design parameters could affect mechanical performance. If the design parameters are the same but the printing equipment is different, the same geometry might produce various results. Second, the Willow structure's curved walls and twisted form distribute evenly the axial compressive loading.

The geometry deforms smoothly and absorbs energy efficiently under vertical compression, but it reacts differently when loaded laterally or off-axis.

Based on these findings, future research will focus on a systematic study of wall thickness influence by fabricating and testing Willow structures with different thickness of walls. This will show the relationship between compressive strength, stiffness, and structural integrity as well as the validation of the hypothesis that increased thickness will minimize the delamination effect. Additionally, further work will investigate the implementation of the Willow geometry as an infill structure within actual remanufactured components, components that are prone to compressive loadings. Doing this will assess the feasibility of the structure in real-world industrial applications.

These directions aim to enhance the understanding of the interaction between geometry, material properties and additive manufacturing constraints.

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Cercetări privind comportamentul la compresiune al unei structuri Willow fabricată utilizând procedeul FDM

În contextul refabricării produselor industriale, structurile interne pot fi optimizate dincolo de cele generate automat de software-ul de slicing prin introducerea unor geometrii inovative. Acest studiu investighează comportamentul la compresiune al unei structuri de tip Willow, propusă de Snapp și echipa sa, care a dezvoltat un coeficient de eficiență a absorbției energiei mecanice Ks = 75,2%. Pentru a evalua riguros potențialul acestei geometrii ca infill în aplicații ce necesită capacitate mare de absorbție a energiei și greutate redusă, este esențial să se analizeze influența materialului asupra performanței structurii Willow. Structura a fost realizată prin tehnologia FFF/FDM cu duză de 0.6 mm, folosind trei materiale diferite: PLA, PETG și PET CF15 (armat cu 15% fibră de carbon). Scopul lucrării este de a oferi cititorilor un studiu comparativ asupra comportamentului global al structurii Willow fabricată prin tehnologii FFF/FDM și al materialelor selectate. Testele standardizate pe epruvetele cilindrice, conform ASTM D695, au evidențiat performanța superioară a materialului PET CF15. Totuși, în cazul structurii Willow cu pereți subțiri, ierarhia materialelor s-a schimbat din cauza tendinței straturilor de PET CF15 de a aluneca și a se delamina sub sarcină, acest lucru producându-se din cauza orientării aleatorie a fibrelor de carbon. Epruvetele au fost analizate microscopic înainte și după testarea la compresiune pentru a identifica defectele de material și modurile de cedare. Studiul evidențiază influența fibrelor de carbon asupra performanței structurilor Willow și propune direcții de cercetare viitoare.

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