THE INTEGRITY AND DURABILITY OF 3D PRINTED COMPONENTS

PhD Thesis – Abstract

for obtaining the scientific title of Doctor at
Polytechnic University of Timișoara
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This PhD thesis deals with the integrity and durability of PLA (Polylactic Acid) components manufactured by FDM (Fused Deposition Modeling) technology. The present work was conceived and carried out with the aim of investigating the physical (dimensional and mass accuracy, printing time) and mechanical (elastic and strength properties, characteristic deformations, energy absorption performance, etc.) characteristics of mechanically stressed PLA parts (tensile, compression, brittle fracture, impact and fatigue).

Additive manufacturing (AM), as the name suggests, adds the required material layer by layer to achieve a three-dimensional (3D) product. Rapid prototyping, 3D printing, additive layer manufacturing, additive manufacturing, layered manufacturing, additive processes and free-form manufacturing are other known names for AM in the scientific community [1]. In the AM process, the transformation is made from a 3D solid computer model (computer-aided design - CAD <Computer-Aided Design>) to a finished product with satisfactory geometric accuracy, without using additional devices or cutting tools such as conventional manufacturing processes [2, 3], although in some cases post-processing is required. Thus, in this sense, AM has a better ability to handle raw materials, as there is less material loss, and opens up the possibility of forming more complex geometric components [3].

Figure 1 shows the steps involved in the AM process to transform the digital world item into the real world object.

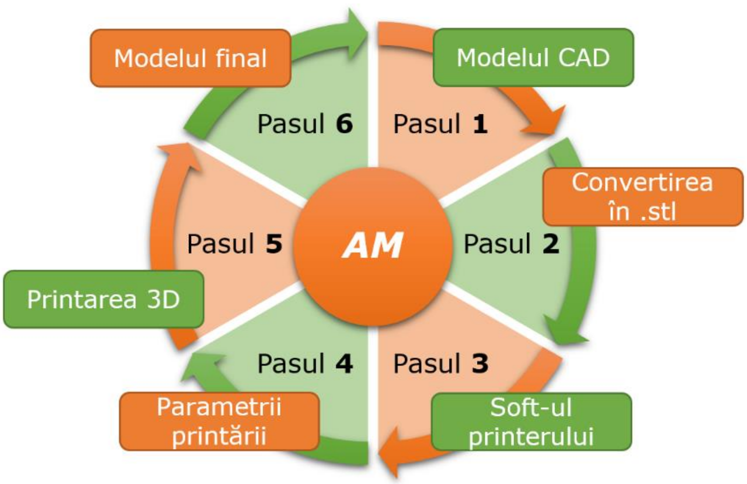


Fig. 1. Representative schematic of the additive manufacturing process

This paper is structured in 7 chapters, 6 of which are content chapters and one of which is a conclusion and personal contributions.

Chapter 1, entitled "**Introduction**", deals with general notions of additive manufacturing and beyond, focusing finally on the fused deposition printing (FDM) process. This technology is also used for all investigations in the present work.

Figure 2 shows the basic process of FDM printing.

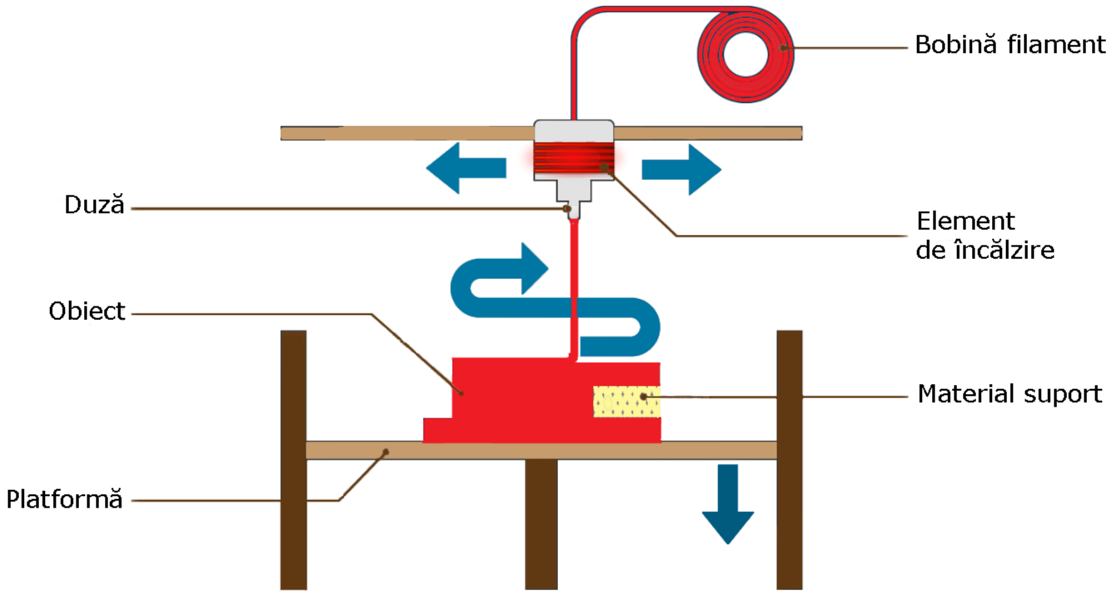


Fig. 2. Basic FDM printing process

3D printers that work with FDM technology consist of the printer platform, a nozzle (also called a printer head) and the raw material in the form of filament.

The printer platform (or bed) is usually made of metal, ceramic or hard plastic, and each successive layer is deposited on this platform.

The nozzle of FDM printers is attached to a mechanical chassis that uses belt systems and/or lead screws to move it. The entire extrusion assembly is allowed to move in X, Y and Z dimensions by a motorized system. A fourth motor, called a stepper motor, is used to advance the thermoplastic material into the nozzle. All movements of the head and the raw material are controlled by a computer.

The raw material is usually the thermoplastic of production, although sometimes metal is also used. The thermoplastic can be repeatedly melted when exposed to heat, and re-solidified when the heat is removed. The thermoplastic filament or metal wire is wound onto a mounted spool. It is then fed through the printer nozzle. The better class of FDM 3D printers allows the temperature of the nozzle to be maintained even close to the glass transition temperature of the material being extruded. This allows the material to be extruded in a semi-liquid state, but return to a solid state immediately. This results in better dimensional accuracy.

The most investigated process parameters in FDM technology include air gaps, print orientation, extrusion temperature, infill density, infill pattern, layer thickness, raster width, raster angle and print speed; these have substantial effects on filament bonding (inter-layer and intra-layer) and thus influence the mechanical performance of printed components [4]. In addition, interactions of these parameters play a significant role from the perspective of mechanical properties [5, 6].

Chapter 2, entitled "**Tensile Behaviour**", investigates the multiple effect of process parameters (infill density-DU, infill pattern-MU, print orientation-OP, layer thickness-GS, print speed-VP, nozzle temperature-TD and number of outer layers-NSE) on the tensile behaviour of 3D printed specimens.

The mechanical characterization of PLA-based components fabricated by different additive manufacturing techniques is of great interest among researchers, since their properties and the influence of printing parameters are still ambiguous. Moreover, the FDM process, is far from maturity level and is in continuous update/development, requiring a deeper understanding of the mechanical behaviour of different materials and structural components. For example, work [7-12] reports that the highest stretching properties are obtained for 0° printing orientation, while work [13, 14] claims that 90° printing orientation gives the best properties. Furthermore, References [9, 10, 13-15] report that maximum property values are obtained for small layer thicknesses, and References [11, 16] point out that large layer thicknesses lead to maximum properties. On the other hand, Birosz et al. [17] state that the Honeycomb filling model is more appropriate, while Rao et al. [15] state that the Cubic model. And, of course, the examples can continue for the other process parameters mentioned above. Therefore, as can be seen in the literature, there are still contradictions about the effect of certain process parameters on the mechanical properties of 3D printed parts.

This chapter experimentally investigates the quasi-static tensile properties of PLA specimens obtained by FDM technology. The study focuses on the multiple effect of process parameters on the tensile behaviour of 3D printed specimens.

The parameters investigated are as follows:

- Infill pattern (Grid, Triangular and Honeycomb);
- Infill density (40, 70 and 100%);
- Orientation of specimens in the plane (0, 45 and 90°);
- Layer thickness (0.10; 0.15 and 0.20 mm);
- Print speed (20, 40 and 60 mm/s);
- Nozzle temperature (200, 210 and 220°C);
- Number of outer layers (1, 2 and 3).

The strength properties and their related deformations and the fracture energy were investigated. After investigating the mentioned process parameters, optimized specimens were printed and tested. The optimized results are compared with literature data of PLA specimens obtained by both printing and injection molding processes.

In addition, the relative errors for thickness and width of 3D printed specimens were investigated from a dimensional perspective.

PLA filament was used as the printing material (see Figure 3).

Fig. 3. PLA filament used in the evaluation of tensile properties: characteristics (a) and packaging-use process (b)

Due to its property of being printed at a lower temperature, PLA is a very popular thermoplastic in 3D printing. It is suitable for almost all types of 3D printers and is easy to process (no heated print bed required).

The shape and dimensions of the test specimens used were according to ISO 527-2 [18], which regulates tensile testing of plastics.

The experimental phase included a series of quasi-static tensile tests performed on "double-T" or "dog-bone" specimens of different configurations, following the ISO 527-2 standard [18]. The experimental tests were carried out at room temperature on the Zwick Roell 005 5 kN universal testing machine.

The initial and optimized tensile strength values for PLA obtained by FDM technology are in good agreement with those reported in the literature for the same material. In most cases, especially the optimised results, they are clearly superior to those in the literature. Moreover, the results obtained are within the range of those injected, with a preponderance in the middle-upper region.

Chapter 3, entitled "**Compression behaviour**", presents a compression optimisation study of PLA specimens manufactured by FDM technology. The optimisation takes into account the influence of three process parameters (infill density, infill pattern and specimen shape) on the main compression properties (elastic and strength properties as well as energy absorption performance).

Analysis of the compressive properties studied by other researchers has shown that they focus entirely on two categories of properties: elastic and strength. However, given that rapid prototyping offers a wide range of process parameters, the mechanical behaviour of 3D printed components can also be addressed in terms of energy absorption capabilities.

Cubic specimens were used to determine the compression behaviour. Initially, the 3D printed cubic specimens were subjected to quality control from a constructional and dimensional point of view. The values of the three dimensions (height and in-plane widths of the specimens) resulting from the 3D printing process were statistically processed and validated before testing. Subsequently, specimens considered non-compliant (with errors greater than ±5%) were replaced.

The experimental program included a series of compression tests performed on cubic specimens. Mechanical tests were performed at room temperature on the 100 kN LBG TC100 test machine (Figure 4).

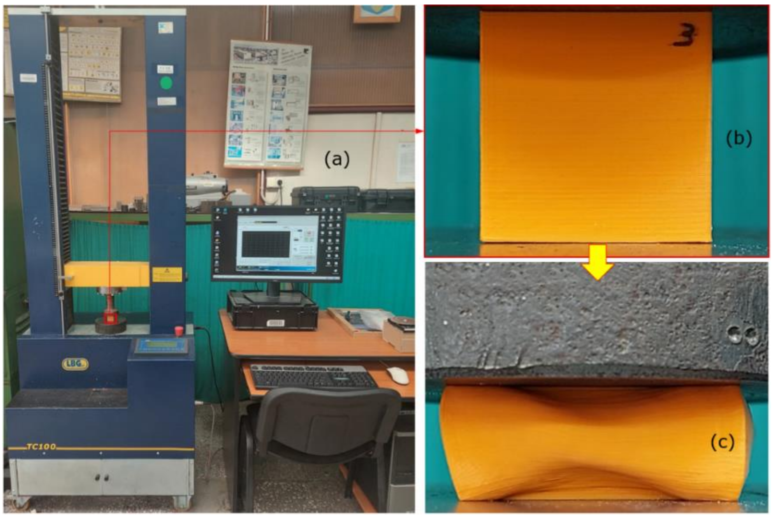


Fig. 4. LBG TC100 100 kN universal testing machine

Compression tests were performed in displacement control with a loading speed of 10 mm/min. In order to obtain reproducibility of results, four specimens were tested for each configuration.

The optimization study presented in Chapter 3 highlights the optimal parameters to be used to achieve maximum properties of the FDM printed PLA specimens, namely: infill density: 30%, infill pattern: STAR and specimen geometry: CUB.

Chapter 4, entitled "**Brittle fracture behaviour**", is devoted to the influence of process parameters (layer thickness, specimen thickness, printing direction, notch type and printer type) on the fracture behaviour (in pure load Mode I and II) of PLA specimens manufactured by FDM technology. To determine the fracture properties (fracture toughness, fracture energy and crack propagation mode in fracture Modes I and II) the specimen with a lateral notch was used (see Figure 5).

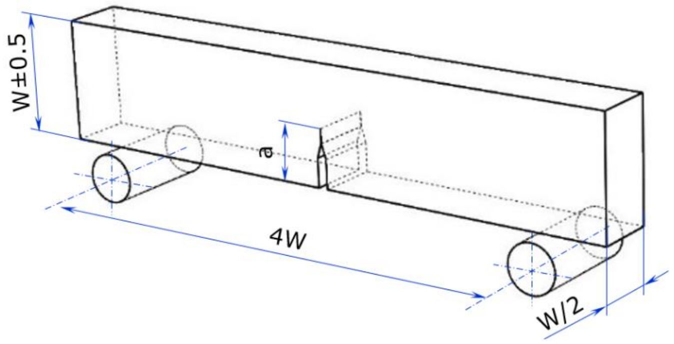
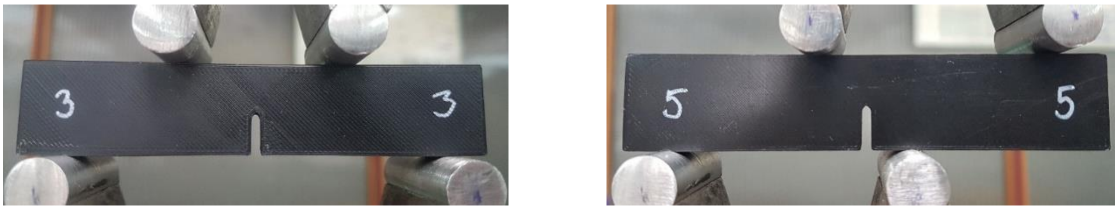


Fig. 5. Geometry and dimensions of the 3D printed SENB specimen

A symmetrical loading of the specimen was used to obtain Mode I, whereas Mode II failure was obtained by an asymmetrical loading (see Figure 6).



(a) (b)

Fig. 6. Positioning of the SENB specimen on the Walter+bay 10 kN machine clamp: mode I (a) and mode II (b) of loading

In practical applications different loading conditions are encountered, so the possibility of crack initiation and propagation in 3D printed components is very high. However, the literature reports only a few results for Mode II fracture toughness of PLA parts. Most data are reported on ABS specimens printed by FDM technology or on PA specimens obtained by SLS technology.

Mode I fracture toughness, K_{IC}, was determined using a Symmetric Four Point Bending (SFPB) configuration (Figure 6a), while for Mode II fracture toughness, K_{IIC}, specimens loaded asymmetrically at four-point bending (Asymmetric Four Point Bending-AFPB) were considered (Figure 6b).

The K_{IC} and K_{IIC} values were determined using the maximum force, P_{max}, recorded during the bending tests, according to equations in the literature.

According to the experimental results, the fracture toughness of specimens printed with different orientations is strongly dependent on the manufacturing parameters. In this scenario, specimens printed with 45° orientation are characterized by a lower K_{IC} value, while higher values were obtained for specimens printed with 0 and 90° orientations. This behaviour can be explained by a clear understanding of the effect of the angle effect between the notch of the specimens and the raster lines. This angle is equal to ±45°, 0°/90° and ±45° for SENB specimens printed with 0, 45 and 90° construction orientations. Given Mode I loading for 0 and 90° orientations, if the crack attempts to propagate along the bisecting line, it should break two sets of fibers inclined at angles of ±45°. On the other hand, if the crack propagates along the 45° direction, there is only one set of fibers (half the number of strong fibers) that prevents the crack from growing. This may be the reason for crack propagation at 45° for specimens printed at 0° and 90° and at 0° for specimens printed at 45° respectively.

Regarding the loading condition in Mode II, the major difference in the tested cases is the displacement at failure/breakage, while K_{IIC} showed smaller variations between the different cases. According to the Maximum Tangential Stress (MTS) criterion, the crack initiation angle for an isotropic material is approximately 70.5° [19]. Using the same argument as in the case of Mode I loading, in the samples where the angle between the maximum tangential stress and the raster angles is smaller, the crack resistance is expected to be lower. Considering an angle of 70.5° for the maximum tangential stress, this angle would be equal to 19.5° for specimens printed at 45° and 25.5° for those printed at 0 and 90°, resulting in a slightly lower K_{IIC} value for specimens obtained at 45°.

Chapter 5, entitled "**Impact behaviour**", focuses on the single and multiple impact behaviour of PLA samples printed by FDM technology.

The literature reports some studies on the impact behaviour of 3D printed specimens. However, the studies focus either on different test configurations or on different materials (ABS, PEEK, TPE, PC, PETG, HIPS) or AM technologies (FDM, SLS, DLP). Therefore, the current investigations report first results on single and multiple impact behaviour of printed PLA specimens.

Different types of impactors (10 mm diameter hemispherical, 20 mm diameter hemispherical and truncated cone) and different impact energies (5, 10, 20, 30 and 40 J) were used to evaluate the mechanical impact behaviour. For comparative analysis the strength properties and energy absorption performance were determined. The properties of interest were energy absorption (total energy absorption and specific energy absorption) and structural integrity (maximum forces supported by the specimens).

Finally, the specimens were subjected to radiographic inspection after each test performed. These results allow the generation of a large database that can be used by designers of rapidly prototyped components and guide future research into the fracture behaviour of PLA materials printed using FDM technology.

The PLA filament is the material used for 3D printing of the investigated impact specimens. Its characteristics are shown in Figure 3.

Figure 7 shows an overview of the 3D printed specimens along with their manufacturing process.

Fig. 7. 3D printed specimens used for impact testing: overview (a) and manufacturing process (b)

For the manufacture of the specimens, the optimization study carried out in Chapter 3 was taken into account. Therefore, the specimens used for the determination of the impact behaviour had the following characteristics:

- Infill density: 30%;
- Infill pattern: STAR;
- Specimen shape: CUB.

The first phase of the impact tests focused on identifying the energy level required for complete specimen failure, i.e. the energy value at which the impact mass penetrates the tested specimens. Therefore, tests were carried out at different impact energies (between 5-40 J) following a trial and error approach.

The second phase aimed to evaluate the response to multiple impacts of increasing energy for each indenter shape. Therefore, repeated impact tests were carried out starting with an energy of 5 J and increasing it up to 20 J, with a step of 5 J for each indenter type.

Finally, the specimens were subjected to radiographic analysis to identify failure modes. The analysis was carried out both according to the impactor type and the impact energy used. Radiographic inspection is the process of assessing the material using X-ray or gamma-ray technology. It is one of the most thorough non-destructive testing methods that is used to evaluate components for signs of defects that could interfere with functionality.

Figure 8 shows X-ray images of the specimens tested by impactor type (H10) and impact energy (20 and 30 J).

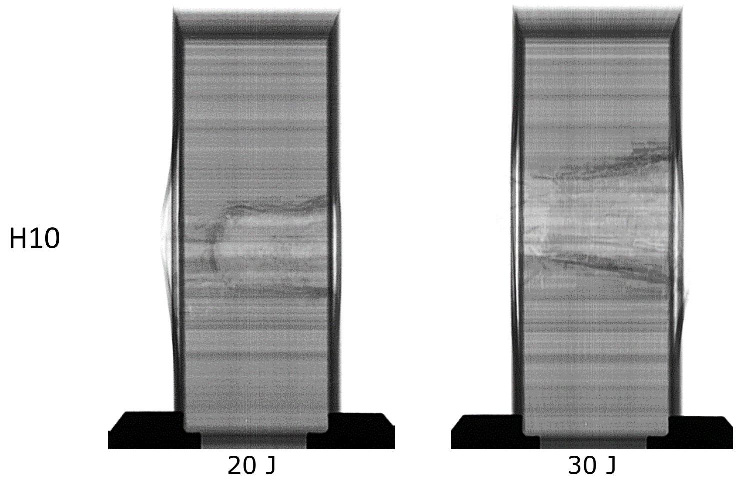


Fig. 8. X-ray images of the tested specimens as a function of impact energy

Chapter 6, entitled "**Fatigue behaviour**", aims to determine the fatigue behaviour of PLA specimens by performing compression-compression fatigue tests.

The fatigue studies in the literature, performed on PLA components printed by FDM technology, are mostly based on tensile - tensile loading conditions. Thus, the researchers used typical tensile test specimens. The aim of the current investigations was to determine the fatigue behaviour of PLA specimens by performing compression-compression fatigue tests. For this purpose, cubic specimens were used and typical fatigue characteristics such as life limit and failure mechanisms were determined. The process parameters of the tested specimens were obtained after an extensive optimization process presented in detail in Chapter 3.

The fundamentals of specimen geometry, modelling, processing and fabrication were presented in Chapter 3. Figure 9 shows an overview of 3D printed specimens using FDM technology, together with a detail of their internal structure.

Fig. 9. 3D printed specimens for fatigue tests: overview (a) and internal structure (b)

To determine the yield strength of the printed specimens, preliminary quasi-static compression tests were performed. The tests were performed on PLA cubic specimens using the 100 kN LBG TC100 universal testing machine (Figure 4). The experimental tests were performed in displacement control with a loading speed of 10 mm/min. To ensure reproducibility of the results, the compression tests were repeated on a number of four specimens according to ASTM D1621-16 [20] and ISO 844:2021 [21].

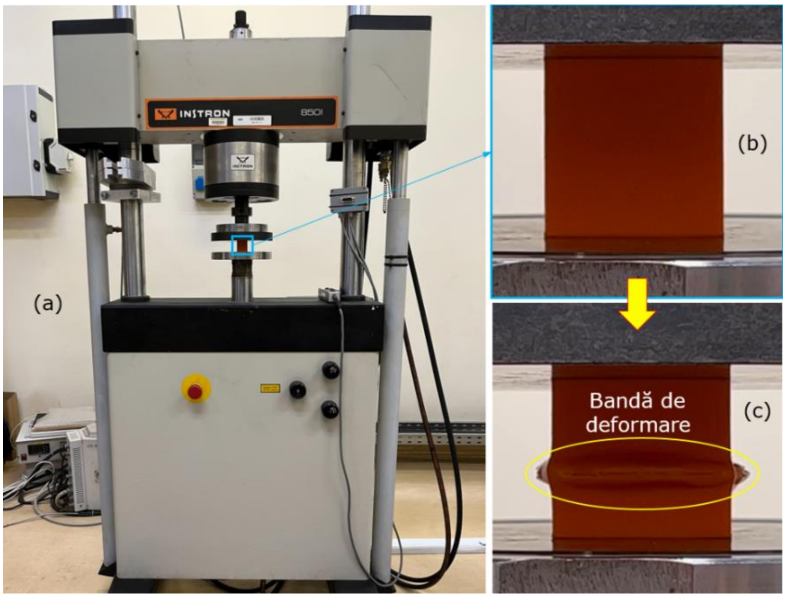


Fig. 10. Experimental setup: 100 kN Instron 8501 universal machine (a), specimen fixture in the test machine fixture (b) and specimen under test (c)

Following oligocycle fatigue tests, specimen breakage occurred abruptly. It was observed that the appearance of a deformation band across the full width of the specimens, normal to the loading direction, resulted in increased deformation (Figure 10). Thus, the appearance of the horizontal band was identified as the main failure mechanism of fatigue stressed specimens. Finally, with the obtained fatigue results, the Wöhler curve was plotted together with the confidence limits.

Chapter 7, entitled "**Conclusions and personal contributions. New research directions**", presents structured all the results of the investigations in the PhD thesis.

It also highlights the author's personal contributions, among which the following can be mentioned:

- Elaboration of an extensive literature survey on rapid prototyping, additive manufacturing technologies, as well as the defining characteristics (process parameters, filament materials, properties, areas of use, advantages and disadvantages) of components obtained using the fused deposition modelling process.
- Design and conduct a tensile optimisation study on the effect of seven process parameters (infill pattern, infill density, printing orientation, layer thickness, print speed,

nozzle temperature and number of outer layers) on the main tensile properties (dimensional accuracy, characteristic stresses and strains, breaking energy) of 3D printed components.

- Presentation of a diagram on the percentage influence of the seven investigated process parameters on tensile strength, strain corresponding to tensile strength and breaking energy.
- Integrating for the first time, within 3D printed components, energy absorption diagrams (associated with cellular materials - especially polymer foams) in order to identify the optimal filling density.
- First application of the Decision Matrix (Pugh Matrix or Grid Analysis) in 3D printed components to correctly identify the optimal filling pattern of specimens.
- Determination of fracture mechanics properties, on parallelepipedic specimens with a lateral notch, through symmetric (Mode I) and asymmetric (Mode II) four-point bending tests.
- First-time reporting of energy absorption (total energy absorption and specific energy absorption) and structure integrity (maximum loads borne by specimens) properties for low-speed impact tests.
- Determination of the number of cycles to failure as a function of the load level applied to the specimen.
- Plotting the Wöhler durability curve together with confidence limits.

Chapter 7 concludes with a presentation of the main research directions the author is considering.

The thesis is very well anchored in the current state of research in additive manufacturing. The whole work is based on more than 350 bibliographic titles, most of them of recent date and wide international visibility.

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