Doctoral Dissertation
Doctoral Program in Aerospace Enginering (33.rd cycle)

# Experimental, numerical and analytical methods for aerospace structures produced via additive manufacturing

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## Summary

Additive Manufacturing (AM) technologies received increasing attention in these years. They differ from the conventional machining because they shape components by adding material instead of removing or deforming it. This aspect results in flexibility and efficiency; it allows simplifying manufacturing, especially with complex geometries, increasing production performance and efficiency. AM, 3D printing, rapid prototyping are all definitions commonly used, in parallel, to describe the same concept; however, they hide very different processes, tools, and technologies. Many common materials can be employed; this directs the specific technology and process. AM does not innovate in terms of materials but in terms of their processing. Fused Filament Fabrication (FFF) stands out among polymeric-processing technologies thanks to its ease of use and the accessibility of materials and technology. It also expanded beyond fabrication facilities to the consumer market. FFF is at the core of this dissertation, together with the application polymer, the Polylactic Acid (PLA).

Choosing a material directs towards mechanical properties of a particular order of magnitude; however, any process affects them. Any technology guarantees a shift towards functional components if compliance with the performance criteria of the item is verified; this means understanding its structural behavior. From the mechanical response perspective, this translates into the structural analysis, requiring (among the others) a constitutive model. The long-term goal of this research path is an ad-hoc tool dedicated to structural analysis and optimization of 3D-printed components. It is a very ambitious result: considering the thermal, hygrometric, and mechanical boundary conditions, the feedstock material properties, and the component geometry, the output would be an optimized printing strategy and the mechanical response even when the printing parameters have already been selected. This work traces this path by proposing and validating a simplified approach to this problem. The polymeric isotropy vanishes in the transition to a finished object; it is speculated that a specific printing strategy trace anisotropy to orthotropy, which is easier to evaluate and manage. In this context, the thesis draws a parallel (initially only geometric) with composite materials and derives some analysis methodologies. The main *goal* of the research activity is to open up the possibility of standardizing the characterization and analysis processes.

The dissertation is organized into three main areas: theoretical, numerical, and experimental. A necessary introduction on FFF precedes those three aspects to discuss its operating principles and main process parameters, together with the scientific background on the mechanical performance of 3D-printed components. This introduction also establishes a technical vocabulary related to the printing process.

From a theoretical perspective, the first part outlines the approach to FFF-components to determine a constitutive model. It discusses a parallel with uni-directional composite laminae, emphasizing the appropriate distinctions. This suggests that a single FFF layer may exhibit an orthotropic behavior; this *hypothesis* guides in defining mechanical characterization tests. This setup is not trivial, as none of them are standardized. An intermediate and simplifying step is introduced, speculating that this parallel allows extending the Classical Lamination Theory (CLT) to this context. The theory is presented, and its simplifying hypotheses discussed. From the perspective of an ad-hoc tool for structural assessment, the starting point is a reliable solution for stress analysis, and a layer-wise evaluation of the problem is crucial. To this end, the last part of the dissertation discusses a comprehensive formulation for hygrothermal mechanical analysis of multilayered structures exploiting the exponential matrix method to handle the differential equations.

From an experimental point of view, the *methodology* introduced in the dissertation aims to define new standardized approaches for mechanical characterization. The feedstock polymer is characterized to assess its datasheet and provide a benchmark. No standardized test methods exist; two set-ups are proposed for tensile strength and modulus quantification. Then, assuming an orthotropic behavior for finished parts and relying on the CLT approach, tensile and shear tests are designed, drawing inspiration from the standard test methods for composites. In standardized tensile and shear tests for composite materials, the load introduction into the specimen is facilitated by a set of bonded tabs. Their optimal shape for FFF specimens is determined through a Design of Experiment (DoE) approach. The 2D orthotropic mechanical properties are defined: the non-isotropy and the degradation over the transition from the filament to the finished part are confirmed. A speculative research on the compression behavior shows an asymmetric behavior between compression and tension along the same load application direction and allows an experimental approach to buckling. External strain monitoring is conducted through Digital Image Correlation (DIC), as in-contact instruments proved to affect the mechanical response of polymeric specimens.

The numerical perspective is introduced with a set of tests designed to validate the approach. A three-point bending, a simple bending, and a bending torsion test are simulated through finite element models tuned with a CLT constitutive model. Several set-ups accentuate the non-isotropic response of the FFF-processed PLA. The mechanical response prediction is excellent when the model considers the orthotropic behavior hypothesis. Retaining the feedstock material properties leads to more significant discrepancies; this validates the approach. Buckling prediction is also reasonable, if the model considers the actual compressive behavior. The dissertation discusses an aeronautical application example, considering an Unmanned Aerial Vehicle (UAV) with an FFF-printed frame. A structural validation is proposed, limiting the study to the mechanical response of some specific components.

The main findings of the dissertation can be summarized as follows:

- The displacement ad strain monitoring on polymeric samples can be successfully accomplished with a non-contact system, the Digital Image Correlation. Compared to traditional contact systems, this avoids any mutual influence between the specimen and the transducer. Contact instruments locally alter the field of deformations in components with a low stiffness modulus. In the PLA case, this effect is confirmed, despite limited, but it would increase its importance in less rigid configurations.
- Parts produced via FFF have an anisotropic behavior; this behavior can be traced back to a simpler and mild orthotropy if the print features a linear and 100 % infill. Along the filament deposition direction (direction 1), the stiffness modulus is slightly lower than the one observed in the feedstock filament. In the two directions perpendicular to it (direction 2, in the printing plane, and direction 3 outside the printing plane), a slight decrease in the stiffness modulus is observed.
- Of considerable importance is the variability found in the tensile strengths. The difference found with the feedstock filament values is minimal in direction 1. However, it considerably increases when considering direction 2 and becomes critical when considering direction 3.
- The mechanical response prediction of thin components, predominantly arranged in the 1-2 plane, is excellent when FE models are tuned with 2D orthotropic mechanical properties following the CLT approach. More significant inconsistencies arise if an isotropic constitutive model is considered. If the feedstock filament determines the isotropic properties, the errors can be considered as acceptable. The filament datasheet properties must always be verified to establish that they reflect the filament and not its precursors.
- The mechanical properties in compression can differ from those in tension; this has been experimentally verified for direction 3. In this context, the difference is considerable and must be considered, especially when dealing with bucking phenomena. A reasonable estimate of the critical loads can be obtained using isotropic constitutive models. Still, these must reflect the mechanical properties in compression to return consistent results.
- In the perspective of an ad-hoc tool for structural assessment of polymeric 3D-printed components, the effects of thermal and hygrometric loads must be evaluated because they play a significant role due to the limited mechanical performances of polymers. The hygrothermal mechanical analysis of multilayered shells and plates can be accomplished by exploiting the exponential matrix method to handle the differential equations and analytically solve them. The ability to manage different ways of calculating temperature and moisture content profiles allows the following consideration: significant differences arise in the mechanical performance with simplified and not explicitly calculated profiles, as temperature and moisture content act as field loads.