Development of next generation multifunctional composite structures for CubeSats, pico- and nanosatellites

Current CubeSats usually exhibit a low structural mass efficiency and a low internal volume for their payloads. The present work is aimed at proposing an advanced structural architecture for CubeSats that addresses the issues of low structural mass efficiency and payload volume. The starting concept is the smart tiles architecture for satellites, developed for the ARAMIS (an italian acronym for highly modular architecture for satellite infrastructures) CubeSat project. By introducing multifunctional structures and lightweight, composite materials in the design of smart tiles, the volumetric and structural mass efficiency of the entire CubeSat are enhanced. A 1U battery tile design is selected to investigate the multifunctional structures design aspects in the project of space structures. A battery tile prototype is designed, produced and tested.

The first chapter demonstrates the advantages of multifunctional, composite material smart tiles from the point of view of satellite lifecycle cost, volumetric efficiency and amplitude of the payload design space. The second chapter shows the design and construction of the battery tile prototype. Miniaturized, ultrathin and ultralight Carbon Fiber-Reinforced Polymers (CFRP) components are produced with the traditional autoclave curing of commercial prepregs. The tile includes commercial batteries to comply with the low-cost CubeSat requirement. Then the Finite Element Method (FEM) mechanical model of the tile components and of the entire tile is developed and validated with an experimental modal test campaign. A specific procedure is set up for the modal testing of ultrathin and ultralight CubeSat components, with a minimum thickness of 0.23 mm and a minimum mass of 3.0 g. The tile prototype modal behaviour is shown to be compatible with the Vega launch vehicle requirements. Being the batteries tightly integrated with the structure, the thermal loads due to their operation must be taken into account in the modal behaviour of the system. This aspect is investigated in the third chapter, where a thermomechanical model of the tile is developed. The electrical behaviour of the embedded, commercial batteries is modeled with equivalent Randles circuits, whose parameters are determined experimentally with HHPC (Hybrid Pulse Power Characterization) tests. The parameters are introduced in a LS-DYNA electromechanical model of the embedded battery tile. The thermal loads due to the nominal and failure functioning of the batteries are kept in account in the temperature field. The results show that the nominal functioning of the batteries does not produce temperature overloads in the tile components and does not change significantly the tile modal behaviour. The fourth chapter describes a numerical thermal simulation of a typical ARAMIS configuration, with embedded battery tiles installed, in a typical Low Earth Orbit (LEO) thermal environment. The influence of passive thermal system components thermal properties on the satellite temperature field is investigated and a selection of components is proposed. Due to the multifunctional nature of the tile prototype, the embedded batteries are more exposed to the thermal environment with respect to traditional CubeSat architectures. For this reason, the batteries are shown to need an active thermal control system (i.e. heaters) to keep their temperature within the prescribed range.

The CubeSat volumetric increment, related to the volumetric efficiency, is shown to reach a maximum of 37%, i.e. the internal volume available to the payload can be increased of the 37% in the best case. The CubeSat structural mass ratio (i.e. the ratio of structural mass to total satellite mass) can reach 16.7%, while for a value of 30% a structural optimization is considered necessary.