Design methods for lightweight cellular structures produced via additive manufacturing

Antonio Coluccia
Supervisor: Prof. Giorgio De Pasquale, Politecnico di Torino
Doctoral Examination Committee: Prof. Sara Bagherifard, Politecnico di Milano; Prof. Franco Concli, Libera Università di Bolzano.

Summary

Architected cellular materials have been gaining an increasing attention from several research and industrial fields, given their excellent mechanical and functional properties. Lattice structures, considered as particular class of these materials, consisting of artificial truss or shell repetitive unit cells structures, have been benefiting from the advancing of innovative production techniques, in particular additive manufacturing.

Main argument of this thesis is the development of models aiming at the description of the structural behavior of the aforementioned materials, with a special focus on metal lattices.

First presented model has the objective of enhancing the energy absorption properties of lattices investigated; given their porous nature, these materials are excellent absorbers, often used for the design of crash boxes. Prior to the development of the model itself, a set of pre-defined lattice topologies has been selected and studied, on the basis of their different characteristics. Implicit and explicit finite element modelling has been employed for the investigation. Once the behavior of such structures under compressive load from the point of view of energy absorption has been established, such topologies have been subjected to a topology modification routine, aiming at limiting stress concentrations while enhancing properties such as volumetric and specific energy absorption. The process consists of a functional grading, based on the initial stress configuration of the considered samples before the application of the process itself. The model development and presentation has been enriched with an experimental campaign, where additively manufactured samples have been tested under compression load. Both computational and experimental validation of the grading process show how the model developed helps the lattices investigated achieving higher energy absorption performances.

Given the high employability of lattice structures, in particular for sectors such as the aeronautical and space ones, particular attention must be paid to certain phenomena: first of all, fatigue. A fatigue analysis methodology, specifically designed for lattice structures, has been developed and proposed in this thesis. The method makes use of different techniques: homogenization, often employed for metamaterials and in general multi-phase composites, has been essential in making the model lighter and more computationally efficient. In order to detect the critical point of the lattice component analysed, a strain-based criterion has been used, aiming at the identification the lattice cell where the failure is supposed to start. The analysis is thus focused on a single representative volume element. Finally, though de-homogenization, the original stress state of the single critical lattice cell is retrieved, allowing for a comparison with data from literature. The described methodology has been applied to two different case studies, comprehensive of experimental tests: the cantilever beam and the 4-point-bending test, both for fully reversed load conditions ($R = -1$). Achieved results reveal

how the methodology is valid for the identification of the point where the failure originates. Moreover, the generalization of the model has been made possible, generating a relationship between metal lattice structures fatigue properties and the ones of the original bulk metal.

Analysis methodologies typically used for lattice structures have been revealed as valid alternatives for studying different structures as well. It is the case of multi-material metal-CFRP joints, based on metal pins array penetrating the composite. Homogenization can be considered as the key factor of the developed analysis model, with the repetitive volume element containing the three layers that the joint is composed of: metal, metal anchor plus surrounding CFRP and CFRP alone. This helped developing a third material medium between the two joints' ends, generating an accurate yet efficient analysis tool. Results obtained with the developed model have been compared to the ones from two previously developed simplified models and experiments.

A spin-off investigation has been also conducted on the benefits of the introduction of a substrate placed under the metal pins made of lattice structures. Such feature would help relieving the stresses originating due to the different thermal expansion behaviours of the two materials in contact.

Different developed models, aimed at describing the structural behavior of lattices and repetitive unit structures, have been proving valid tools for analyses concerning energy absorption, fatigue and mechanical properties of multi-material joints. In the optic of enhancing mechanical properties of investigated structures, with the final objective of making them suitable for advanced primary load-bearing structural purposes, the proposed methods and relative applicative cases serve as a valid example.