Mechanical and structural characterization of composite plates: from beams to TPMS

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Advanced engineering demands materials that are stronger, tougher, and lighter, exceeding the capabilities of conventional materials. This has led to the exploration of innovative design approaches, particularly through the use of cellular solids. These materials achieve a desirable balance of strength and lightness through intricate lattice designs composed of solid struts forming the edges or faces of individual cells. Lattice structure, a prominent subset of cellular solids, feature repeating and interconnected structures which can be inspired by the strategic porosity found in biological materials. This engineered porosity significantly enhances their mechanical properties. A key application of lattice structure, relevant to this research, is in tissue engineering scaffolds, where open-cell lattice structures promote cell infiltration and migration, crucial for effective tissue regeneration.

The advancement of additive manufacturing techniques, such as PolyJet 3D printing, has enabled the creation of architectured materials. These materials integrate individual constituents with varying mechanical properties at the mesoscale into spatial arrangements optimized for mechanical performance. Drawing inspiration from the evolutionary design principles found in biological tissue, these architectured structures often exhibit superior properties compared to their individual components.

In this study, we utilize multimaterial PolyJet 3D printing to fabricate cellular solids with beams featuring a hybrid sandwich-like design to enhance mechanical efficiency and, more specifically, energy absorption. We investigate the flexural behavior of these struts in two configurations: core-shell (C-S) and core-interface-shell (C-I-S), using 3-point bending tests combined with Digital Image Correlation (DIC). The core is composed of a rubbery material (Shore95, Young's modulus $\sim$ 100 [MPa]), while the faces are made from a rigid glassy material (VeroWhitePlus, Young's modulus $\sim$ 2 [GPa]), and the interface are made of a softer material (TangoBlackPlus, Young's modulus $\sim$ 1 [MPa]). Additionally, we examine how the printing orientation influences the behavior of the composites due to differences in the interface connecting two materials: when printed horizontally bimaterial interfaces are sharp (i.e. less than 20 μm in width), whereas printed vertically, internal interfaces are rather blurred (i.e. around 150 μm in width).

Our findings indicate a 30% increase in energy absorption for small core-to-strut thickness ratios compared to monolithic beams. Different core-to-strut thickness ratios result in varying failure modes, including complete brittle failure or delamination. The addition of an interface slightly decreases performance, except at an intermediate ratio of c/t = 0.2, where blurred interfaces reduce delamination and enhance flexural strength. For thicker soft layers, a blurred interface achieved by vertical printing is advantageous, while for thinner layers, a sharp interface achieved by horizontal printing is preferable.

The study further explores the energy absorption capacity of 3D-printed triply periodic minimal surface (TPMS) gyroid lattices with composite cell walls, designed based on results of the first part of the thesis, under in-plane compression. Results reveal that the composite TPMS gyroid retains the performance characteristics of its individual stiff material but also demonstrates improved deformation recovery compared to the individual stiff consitutent.

Keywords: Cellular Solids, Tissue Engineering Scaffolds, Additive Manufacturing, PolyJet 3D printing, Architectured Materials, Hybrid Sandwich Design, Energy Absorption, Flexural Behavior. Digital Image Correlation, Triply Periodic Minimal Surface (TPMS).