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3D Printed Optimally Graded Cellular Beams

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ABSTRACT

Structures made out of periodic cellular materials can demonstrate enhanced stiffness-to-weight ratios. This enhancement relies on the architecture of their underlying unit cells. In this study, we, first, investigate how the distribution of the relative density of unit cells affects the bending stiffness of an architected cellular beam. Next, we present the idea of improving the specific bending stiffness of the cellular beam without increasing its weight by optimizing the relative density distribution, that is, by optimally grading through the length and/or across the thickness of the cellular beams. We define a general optimization problem to maximize the bending stiffness with relative density of unit cells as design variables and with a strict optimization bound based on limitations of the stereolithography (SLA) 3D printing as the adopted fabrication process. To evaluate the bending performance of the graded cellular beam, we use a hybrid-homogenized model, the results of which are also validated by detailed finite element analysis (FEA) and experimental bending tests on 3D printed cellular beam samples. The hybrid-homogenized model is highly beneficial in terms of expediting the computational evaluation and facilitating transformation of the general optimization problem into a shape optimization process. We employ the teaching-learning-based optimization (TLBO) algorithm to solve the optimization problem and obtain the optimum relative density distribution that maximizes the bending stiffness. The optimization results reveal substantial increase as high as 43%, 155%, and 182% in bending stiffness for a cellular beam graded through the length, across the thickness, and in both directions, respectively. The optimization findings are corroborated by detailed FEA and experimental bending tests carried out on 3D printed optimally graded cellular beam samples. A further investigation into the cell architecture also sheds light on the fact that optimally graded cellular design can potentially outperform uniform cellular beams made out of ideal unit cells (defined as a unit cell that satisfies Voigt upper bound for elastic properties, with elastic modulus linearly proportional to the relative density) by reaching bending stiffness-to-density ratios greater than one. This is of significant importance in applications that require stiffness-driven design such as airplane wings, and load-bearing structural elements such as joist, girder, beam, and slab. We believe that these results, together with advances in additive manufacturing, open a new avenue for design and fabrication of the next generation of optimized lightweight structures.