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A Modular Topology Optimization Framework for Additive Manufacturing Enabling Stiffness Adaptation

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Abstract

In structural design for additive manufacturing, topology optimization is widely used to maximize stiffness (minimize compliance) under prescribed loads and boundary conditions. Although it can generate highly efficient geometries, the optimized topology is often tightly coupled to a single loading scenario. When service conditions change, a full redesign is typically required, increasing engineering effort and creating many bespoke part variants that each require build preparation and qualification. A complementary paradigm is to achieve multiple stiffness performances by rearranging a limited set of reusable modules that can be additively manufactured as standardized parts. If stiffness adaptation is obtained mainly through layout changes rather than repeated geometry redesign, the same printed module library can support multiple applications and enable reconfigurable mechanical components. In this study, we investigate such a modular workflow by extending the Layout-Enhanced Topology Optimization (LETO) framework, originally introduced for thermal conductivity optimization, to stiffness-driven structural problems. The proposed framework separates the design task into two interacting scales. At the module scale, a small number of module geometries are optimized using topology optimization techniques. At the structural scale, these optimized modules are assembled into different layouts to address multiple load cases. By varying only the placement and rotation of a shared module set, different global stiffness responses can be obtained without generating a fully tailored topology for each use case. This hierarchical formulation supports part reuse while preserving system-level adaptability, consistent with a print-and-assemble workflow. Structural performance is evaluated using standard finite element analysis, and stiffness is quantified through compliance under a prescribed material-usage constraint. The design process combines continuous optimization of module shapes with discrete selection among candidate layouts for each loading scenario. Rather than emphasizing algorithmic novelty, this paper provides a baseline assessment of the feasibility and limitations of modular stiffness optimization using LETO. Additive-manufacturing constraints (e.g., overhang limits, minimum feature size, and build-orientation effects) are not enforced in this baseline study; however, the modular formulation is compatible with such constraints and can reduce manufacturing overhead by limiting the number of distinct geometries and enabling batch production of identical modules. Numerical examples are presented under several representative loading scenarios that emulate varying service conditions. The results show that competitive stiffness performance can be achieved by reconfiguring a limited set of shared modules, although some performance loss relative to fully customized, load-specific designs is observed in certain cases. The resulting layouts exhibit physically intuitive features, such as material alignment with dominant load paths, indicating that the modular approach can capture essential structural mechanics with a restricted part set. Overall, the study demonstrates the applicability of LETO to stiffness-driven topology optimization in a modular setting relevant to additive manufacturing and clarifies trade-offs between stiffness performance, design flexibility, and module reuse. The findings suggest a viable pathway for reducing redesign cycles and part-variant proliferation in additively manufactured structural systems.

Keywords:

Topology Optimization Additive Manufacturing Modular Design Stiffness Optimization Layout Optimization