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Material-informed topology optimization for Wire-and-Arc Additive Manufacturing

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Abstract

Wire-and-Arc Additive Manufacturing (WAAM) is a metal 3d printing technique that allows fabricating elements ranging from simple geometry to extremely complex shapes. “Layer-by-layer” manufacturing produces a printed material with significant elastic anisotropy, whereas “dot-by-dot” printing may be used to fabricate funicular geometries in which the mechanical properties of the single bars are affected by the printing process. The design of WAAM components is addressed by formulating problems of structural optimizations that account for the peculiar features of the printed alloy. Topology optimization by distribution of anisotropic material is exploited to find optimal shapes in layer-by-layer manufacturing. Two-dimensional specimens are addressed along with I-beams. In the latter case it is assumed that a web plate and two flanges are printed and subsequently welded to assemble the structural component. A constrained force density method is proposed for the design of grid shells in dot-by-dot printing, formulating local enforcements to govern the magnitude of the axial force in each branch of the network. In both formulations, the arising multi-constrained problem is efficiently tackled through methods of sequential convex programming. Lightweight solutions for layer-by-layer and dot-by-dot manufacturing are found for given printing directions. Extensions of the proposed numerical tools are highlighted to endow the optimization problems with additional set of material-related constraints.

Keywords: topology optimization, form finding, additive manufacturing, metal 3d printing, mathematical programming.

1 Introduction

Wire-and-Arc Additive Manufacturing is a metal 3d printing technique that allows fabricating elements ranging from simple geometry to extremely complex shapes [1]. The WAAM process exploits an off-the-shelf welding equipment mounted on top of a numerically controlled robotic arm. Previous studies confirm that WAAM-produced metals differ both in the microstructure and in the mechanical response with respect to those that are traditionally manufactured, see e.g. [2,3].

Two techniques of WAAM are addressed herein. "Layer-by-layer" manufacturing produces thin plates of printed material that exhibit significant elastic anisotropy. Indeed, experimental tests show that yielding and tensile strength values are comparable to those commonly adopted for stainless steel members, whereas values of the apparent Young's modulus are highly affected by the orientation of the specimen with respect to the deposition layer. "Dot-by-dot" manufacturing produces bars of printed material whose mechanical properties are affected by the printing orientation, both in tension and in compression.

In this contribution, the design of WAAM components is addressed by formulating problems of structural optimization that account for the peculiar features of the printing process. In both cases, the arising multi-constrained optimization problem may be efficiently tackled through methods of mathematical programming [4].

Displacement-constrained topology optimization [5] by distribution of anisotropic material is herein considered to find optimal shapes in layer-by-layer manufacturing, depending on the selected printed orientation for the single plate [6]. Also, the design of I-beams is addressed, assuming that a web plate and two flanges are printed and subsequently welded to assemble the structural component.

Grid shells take their strength from their double curvature, being constructed from members that mainly undergo axial forces [7]. A numerical approach based on funicular analysis, see e.g. [8], is proposed to cope with the design of spatial truss networks fabricated by dot-by-dot WAAM. The equilibrium of funicular networks is handled through the force density method [9], such that they can also play as unknowns of the optimization problem [10,11]. Local enforcements are formulated to prescribe lower and upper bounds for the vertical coordinates of the nodes, and to control the force densities in the branches. This allows for a straightforward control of the length, inclination, and maximum force in each branch.

Lightweight solutions are shown both for layer-by-layer and dot-by-dot manufacturing, for prescribed printing direction.

2 Methods

In a classical topology optimization problem [12], isotropic material is distributed to minimize an objective function, given a set of constraints. Topology optimization by distribution of orthotropic material is herein considered, based on the material model for layer-by-layer WAAM presented in [3]. Indeed, the elastic constants of the printed alloy depend on the prescribed building orientation. Instead of working with a conventional volume-constrained minimum compliance problem, a displacement-constrained minimum volume problem is formulated, to control pointwise the displacement field also in case of distributed loads and loads with multiple point of applications. The proposed approach may be applied both to single plates and to I-beams. The latter class of structures may be preliminary addressed by using a simplified two-dimensional modelling. Two-node truss elements are combined with four-node finite elements to account for the axial forces in the flanges along with a plane stress state in the web. In this case, the optimization problem is written in terms of the material density in the web and of the cross-sectional area of the two flanges. Sequential convex programming is employed to solve the arising multi-constrained problem resorting to the Methods of Moving Asymptotes [4]. The adjoint method is exploited to compute derivatives of the objective function and constraints with respect to the optimization unknowns.

Concerning dot-by-dot WAAM, the method of funicular analysis originally presented in [11] is herein implemented and extended. The equilibrium of funicular networks is tackled through the force density method [9], i.e. by writing the problem in terms of the ratio of force to length in each branch of the network. As investigated in the literature, independent sets of branches can be detected for networks with fixed plan geometry [10]. The minimization of the horizontal thrusts in such kind of networks can be stated in terms of any independent subset of the force densities. Local enforcements are formulated to prescribe lower and upper bounds for the vertical coordinates of the nodes, and to govern the force densities in the branches. This allows also for a straightforward control of the length, inclination, and maximum force magnitude in each branch. Different limits can be considered in tension and compression to prevent yielding and local buckling, respectively. Constraints are such that sequential convex programming can be conveniently exploited to handle grids with general topology and boundary conditions. Hence, the same algorithm used for topology optimization in layer-by-layer WAAM is used for grid shells design employing dot-by-dot printing.

3 Results

A numerical example is considered addressing a cantilever I-beam to be printed using layer-by-layer WAAM. The cantilever is fully clamped along one end and is subjected to a point load acting vertically at the opposite end. It may be either a fixed load applied at the tip, or a moving load applied at any point of the lower edge of the specimen. Optimal layouts achieved through the proposed procedure of topology optimization for orthotropic material are shown in Figure 1. Experimental results show that the maximum value of the apparent Young's modulus is found at an orientation of approximately 45° with respect to the direction of the printed layers. To maximize the stiffness of the bars modelling the flanges, it is assumed that they are printed such that their axes are oriented of 45° with respect to the printed layers. Similarly, since the web plate is well known to be mainly acted upon by shear stresses that can be effectively tackled by inclined bracing members, a 45° orientation is assumed to print this plate. In both pictures of Figure 1, variations in shape of the flanges agree with the diagram of the bending moment of the I-beam, whereas a truss structure arise in the shear-dominated web, as expected. However, the adoption of a single load case (fixed point force), or several load cases (each one referring to a different location of a moving force) lead to different results.

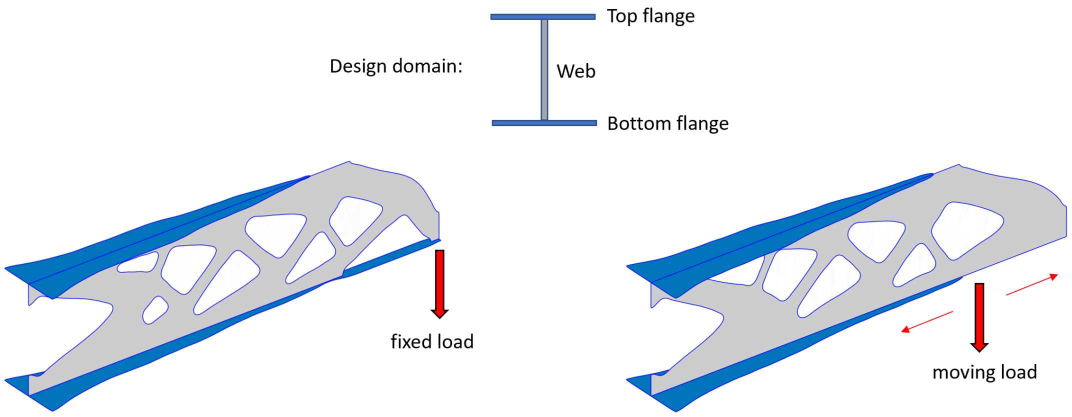

Figure 1: Optimal design of I-beams for layer-by-layer WAAM considering a fixed load (left) and a moving load (right).

Another numerical example concerns a grid shell subject to vertical loads, to be printed using dot-by-dot WAAM. Five nodes are restrained along the three directions, whereas partial restraints apply at the boundaries of the bay to enforce symmetry with four adjacent bays. In Figure 2, the optimal design found when considering constraints on the heigh of each node, while searching for the minimum overall thrust, is presented. Crosses and circles stand for points at the upper and lower bound of the design domain, respectively. The picture concerns an example of optimization that is endowed with geometrical constraints only. However, since vertical coordinates of the nodes and force densities in the bars may be simultaneously controlled, any constraint related to overhang or strength can be easily implemented. For instance, this is the case of a set of force limits to prevent yielding and local buckling. Failure criteria depending on the printing process used to fabricate the bars may be accounted for, as well.

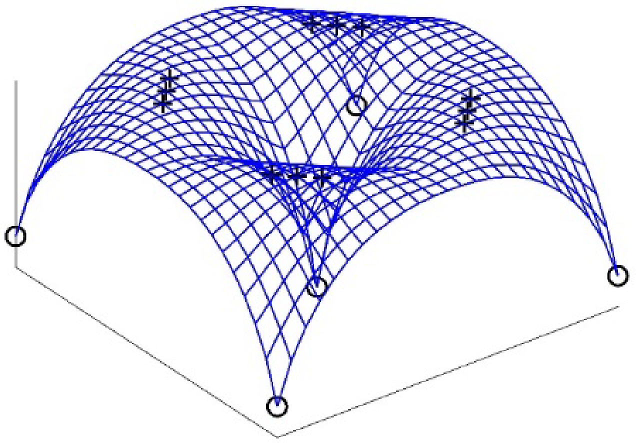

Figure 2: Optimal design of grid shells for dot-by-dot WAAM considering constraints on the node height.

4 Conclusions and Contributions

In this contribution, layer-by-layer and dot-by-dot Wire-and-Arc Additive Manufacturing (WAAM) have been addressed, with the aim of formulating problems of structural optimizations that take into account the peculiar features of the printing process.

Layer-by-layer manufacturing produces a printed material with significant elastic anisotropy, whereas dot-by-dot printing requires funicular geometries with control of the material strength (both in tension and in compression).

Topology optimization by distribution of anisotropic material has been exploited to find optimal shapes in layer-by-layer manufacturing under the effect of multiple displacement constraints. A simplified approach has been presented to extend the two-dimensional formulation to the preliminary design of I-beams.

A constrained force density method has been proposed for the design of grid shell produced through dot-by-dot printing. By governing the vertical coordinates of the nodes and the force density in each bar, local enforcements concerning the geometry and the strength of the branches of the spatial network may be accounted for.

In both cases, the arising multi-constrained formulation may be efficiently tackled through methods of mathematical programming.

Preliminary results have been shown in view of the extension of the tested algorithms to the design of structural components at a larger scale. Indeed, the proposed formulations may be conveniently extended by including other set of constraints. Among the others, buckling constraints for the (web-) plates, in layer-by-layer manufacturing, and at the global level, for dot-by-dot printing.

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