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Investigation on the influence of the cross-sectional geometry on the mechanical response of lattice steel systems produced with Wire-and-Arc Additive Manufacturing

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Abstract

Metal Additive Manufacturing (AM), and in particular Wire-and-Arc Additive Manufacturing (WAAM), offers a promising solution to realize new sustainable and optimized steel structures. Lattice structures are characterized by high efficiency (in terms of high stiffness and minimized material use), however their application at the scale of the single element ("meso-scale"), such as beams and columns, is still hampered by the issue of the connection at nodes (in terms of geometry complexity, assembly and production cost). The ambition of this work is to propose a new class of efficient structural elements by exploiting the efficiency of lattice structures at the meso-scale through the adoption of WAAM production technology. The increased efficiency of lattice structures is provided by their high structural performances and reduced environmental impact, through the adoption of digital fabrication and optimization techniques for construction. The present work proposes an investigation on the computational design and fabrication of a new class of lattice steel structural elements fabricated with WAAM technology with different geometrical features. The geometry is varied in terms of cross-section (i.e. number of points in the lattice for the base cross-section) and relative local slenderness (i.e. maximum distance of the intersecting points of the lattice). The study investigates in particular the mechanical behavior of the different geometries of lattice columns under compressive action. In detail, the influence of the different geometries on the secondary bending moments coming from the outward thrust due to the absence of horizontal hoops at the control sections is quantified through experimental tests and numerical simulations. The optimal geometries are considered as the ones having the lowest value of secondary bending moment.

Keywords: Additive Manufacturing; Steel structures; Lattice structures; Computational design; Mechanical properties.

1. Introduction

The adoption of digital solutions for construction has proved to increase work safety and support the Circular Economy, by reducing the material waste and simplifying the resource recapture [1,2]. Additive Manufacturing (AM, or 3D printing) processes have the great advantage of flexibility in the geometry of the outcome. This aspect appears to be most suitable for the realization of efficient forms which are difficult to realize with conventional manufacturing techniques, but result in a severe reduction in the material use. Such forms could be achieved with the use of novel Algorithm-Aided Design (AAD) tools, already commonly used in other industrial sectors, such as automotive and aerospace.

The application of both AM solutions and computational design tools for steel structures have always been limited to few pioneering cases. Recent developments of AM process in construction have seen the application of these techniques to realize a new generation of structures in concrete, polymers and metals [3,4]. Regarding applications in steel structures, the most developed metal AM technology (Powder-Bed Fusion, PBF) has often limited the maximum dimension of the printed outcomes. Thus, it has been adopted to realize ad-hoc connections parametrically designed either for structural optimization purposes [5] or to create free-form gridshells [6]. However, due to the intrinsic geometrical constraints of the printer environment (enclosed in a box of typically 250-mm side), the application of PBF process is limited to the realization of small-size connections and structural details [7]. More recently, Directed-Energy Deposition (DED) techniques such as Wire-and-Arc Additive Manufacturing (WAAM) allowed to increase the dimension of the printed outcomes up to several meters of span, thus increasing the potential use of digital fabrication in steel construction [8]. The first application of this technique is the MX3D Bridge, the world's first steel 3D printed footbridge, currently located in Amsterdam city center [9]. Recent research effort has been devoted to assess the structural behavior of WAAM-produced steel parts, such as tubular elements [10,11], gridshell columns [12], beams [13–16] and connections [17,18].

The computational design freedom of creating new structural forms was limited to the traditional building production which does not allow for such freedom. Hence, the application of computational design tools for free-form design was often limited to few explorations in pioneering architectural applications. With the advent of AM process in construction, the use of structural optimization could potentially allow to realize a new generation of optimized structures [19]. Current research effort is paid to combine AM with optimization tools to solve issues related to manufacturing processes (such as overhang, see e.g.[20]) or exploit the material anisotropy to find new optimal solutions (see e.g. [15,21]).

2. WAAM for lattice structural elements

WAAM-produced outcomes may be realized by adopting one of the currently known printing deposition strategies: (i) "continuous" printing, a layer-by-layer deposition, suitable to realize planar geometries, (ii) "dot-by-dot" printing, consisting in a droplet's deposition, suitable to realize rod-like elements, constituting the basic units of grid and lattice structures.

Currently, the interest in the "dot-by-dot" strategy is growing, allowing the realization of structural elements, such as free-form gridshells, lattice structures and application of steel rods as reinforcement for innovative 3D-printed concrete structures [12,22] (Figure 1). Therefore, there is an increasing need in the assessment of the mechanical properties of WAAM-produced steel rods, which may differ with respect to those of WAAM-produced "continuous" specimens.

The design of steel lattice structures requires de-tailed knowledge of the mechanical response of WAAM-produced steel rods, taking into account various aspects, such as (1) the inherent geometrical irregularities (such as surface roughness, lack of straightness, cross-section variation), (2) the influence of the inclination of the build angles (referring to the angle between the axis of the WAAM rod and the vertical axis, perpendicular to the base platform) and nozzle angles (referring to the inclination of the nozzle with respect to the printed rod), (3) the presence of the nodes in the connected rods.

Figure 1: Possible application of WAAM dot-by-dot process to fabricate lattice steel structural elements. Adapted from [23].

3. Experimental tests on WAAM lattice components

The present section provides an overview of the main result of the experimental investigation on single rods and crossed rods carried out at the structural testing lab of the University of Bologna. The aim is to study the mechanical response of "dot-by-dot" WAAM-produced stainless steel basic components of a WAAM lattice structure, e.g. inclined single rods and nodes (Figure 2). The influence of the build angle and nodal region on the mechanical response of the printed rods has been investigated by considering different build angles for both single and crossed rods, between the two limit cases of 0° and 30° build angles, corresponding to the limit conditions for printable structural applications. The mechanical response was studied under different loading conditions: tension, compression and bending [24]. The different experimental tests allow the assessment of the key mechanical properties of WAAM-produced lattice structures in construction applications. The mechanical tests were carried out on as-built rods, hence not subjected to post-processing milling treatments, to account for the influence of the surface roughness and other geometrical irregularities, as for the case of real applications in construction.

The tested WAAM-produced rods were manufactured adopting the specific values of the printing process parameters based on the know-how of the manufacturing company MX3D [25]. The wire used for the printing process was the commercially available standard stainless steel welding wire grade ER308LSi (1 mm diameter) supplied by Oerlikon.

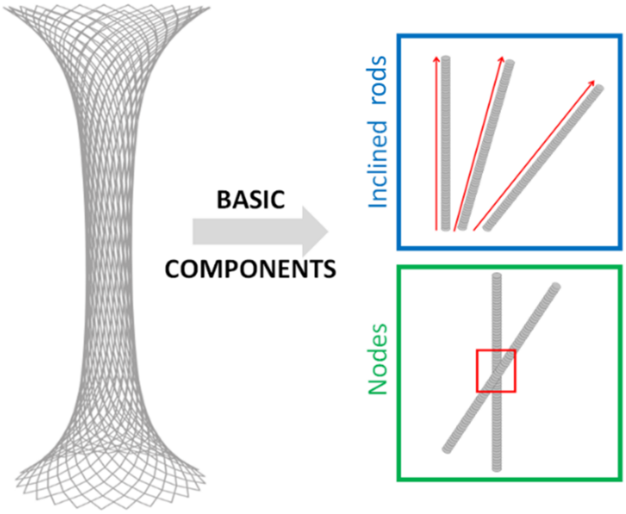

Figure 2: Basic components of WAAM lattice structural elements.

3.1. Single bars

The single bars were tested in tension considering four different build angles: 0°, 10°, 20° and 30°. The tensile tests were performed at the Structural Engineering lab of the University of Bologna. The experimental set-up consisted of a Universal testing machine of 500 kN load capacity. The rods were tested in displacement control with a velocity corresponding to a stress rate of 2MPa/s. The strains were measured through a linear deformometer with a nominal dimension of 50 mm to detect the linear deformation of the rod up to yielding.

Figure 3 reports the values of ultimate tensile force (F_u in kN) comparing the results for the different build angles. It is possible to appreciate both the mean values for each batch as well as their dispersions. Overall, there is not a clear detrimental effect of the increasing build angle in the mechanical properties, as evidenced on a previously-tested batch (see e.g. [26]).

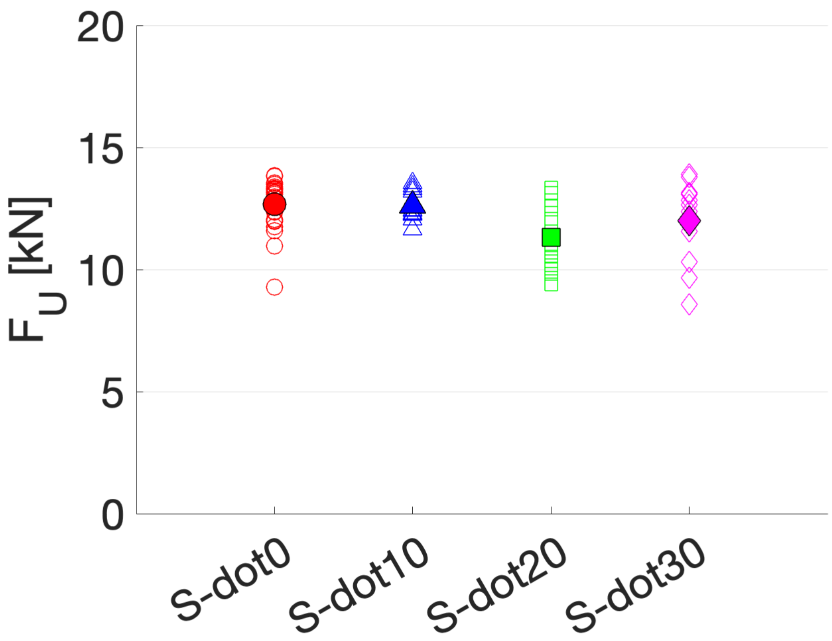

Figure 3: Tensile results for single bars.

3.2. Crossed bars

Crossed bars were produced with the same manufacturing set-up and process parameters as for the single bars, considering three different intersection angles (i.e. 10°, 20° and 30°). The aim of these tests is to investigate the detrimental effect of the presence of intersections, referred to as nodal regions, in the mechanical response under tensile loading.

The three batches of WAAM-produced crossed bars with three different build angles were tested in tension to assess the influence of the nodal area and intersection angle (e.g. the build angle of the inclined bar, B) on the tensile behavior. For this aim, the crossed bars were manufactured in order to have one vertical bar, printed with a build angle of 0°, referred to as bar A, and one inclined bar printed at a certain build angle based on the different batch, referred to as bar B, with angles respectively of 10°, 20° and 30°.

The three batches are referred to as X10, X20, and X30. For some specimens of each batch, a first series of tensile tests were performed by applying the tensile force on type-A bars, while a second series of tensile tests were performed on type-B bars.

A total number of 43 WAAM-produced specimens were manufactured, 15 of type X10, 15 of type X20 and 13 of type X30. The tensile tests were performed using the same testing machine and the same loading condition of the single rods presented in Section 3.1.

Figure 4 reports the bar chart related to the ultimate tensile force (F_u) derived from the tensile tests performed on bars A and B of the three batches. The chart shows that, on average, the ultimate strength of both bars A and B decreases for increasing values of build angles, from an average value of 12.11 kN of bar A-X10 up to 8.40 kN of bar B-X30.

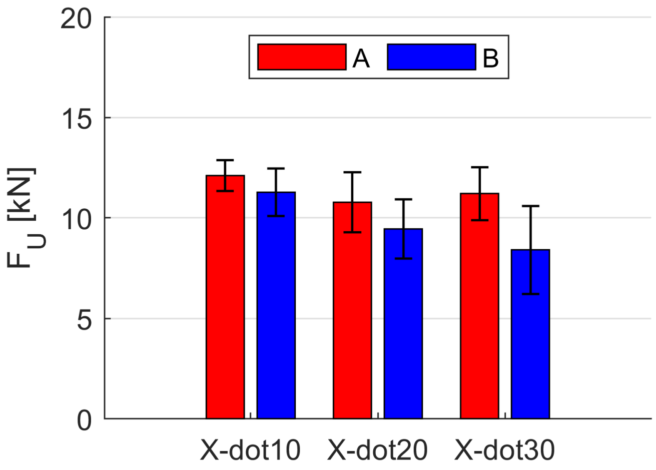

Figure 4: Tensile results for crossed bars.

4. Computational design of WAAM lattice structural elements

From the mechanical performances of the basic components (single bars and intersections) forming the WAAM lattice elements, it is possible to design a new class of steel structural elements by making use of computational design procedures and digital fabrication techniques. The final goal is to realize a new generation of green structural elements to reduce the environmental footprint of steel structures.

4.1. The "blended" approach

With the aim of integrating the capabilities of optimization procedures in terms of new structural shapes with the current limitations of WAAM technology (i.e. manufacturing constraints, printing precision and material properties) together with the robustness and reliability of structural design verifications, a so-called "blended" structural optimization approach was proposed (see [14]). Indeed, the approach is intended to "blend" a stiffness-based topology optimization approach (suitably tailored for WAAM stainless steel, see e.g. [21]) with basic principles of structural design in terms of conceptual design and structural solutions to conceive an initial design, together with concepts of robustness and reliability to guide the designer from the purely mathematically optimized solutions towards the final design. A "blended" structural optimization approach may be conveniently used to investigate effective solutions in an efficient way. The fundamental aspects of the blended design approach are the basic principles, the manufacturing constraints, the algorithms for topology optimization, the numerical simulations to verify the structural performances. Detailed information on the approach can be found in [14].

4.2. WAAM lattice elements

The integration of computational design and fabrication is adopted for the realization of WAAM lattice elements (Figure 5).

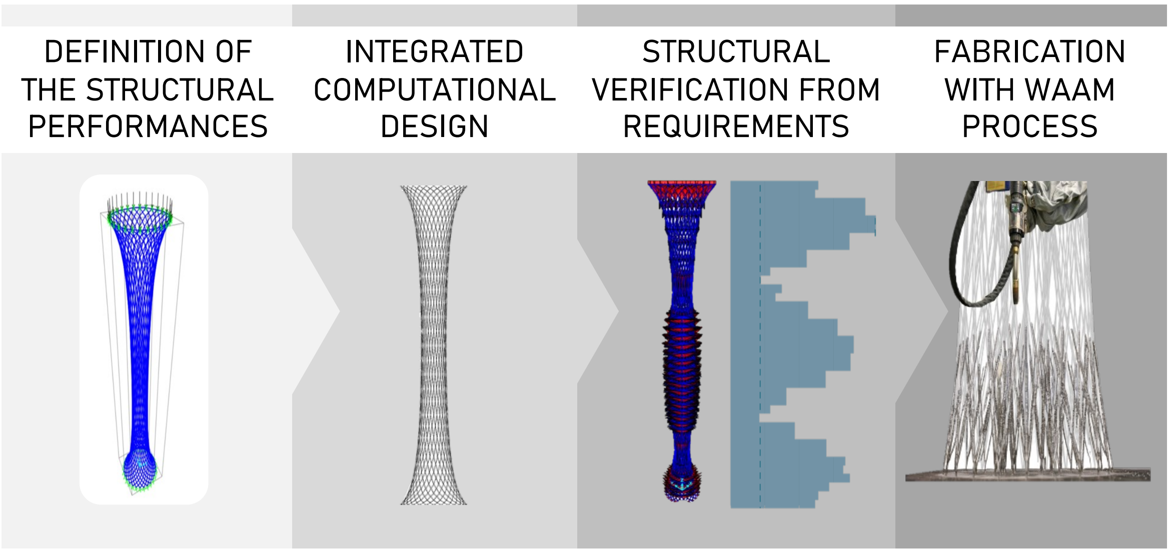

Figure 5: The "blended" approach for WAAM lattice elements.

The first applications of WAAM lattice structural elements are specifically intended for vertical elements under either compressive loading or self-loading only, such as columns, pillars and poles. Various applications in Architecture, Engineering and Construction (AEC) are envisaged, among which: (i) aluminum pole systems for street lighting, (ii) stainless steel pillars for high architectural appealing buildings, (iii) carbon steel reinforcement grid for shotcrete 3D printed (SC3DP) free-form concrete systems (see e.g. [22]), (iv) carbon steel grid as retrofitting system for existing members (see e.g.[16]) .

In order to adopt algorithm-aided design techniques for WAAM and integrate structural design requirements for the construction industry, a new computational design protocol for WAAM lattice structural elements was developed. The computational design protocol combines: (i) specific features proper of WAAM process (such as manufacturing constraints, specific mechanical properties and geometrical tolerances), (ii) structural design requirements from Eurocodes based on the specific applications in Architecture, Engineering and Construction (AEC), and (iii) topology optimization algorithms for efficient designs. The protocol is based on new analytical derivation of efficient lattice poles based on slenderness and inertia equivalency currently under patent protection.

The first study was based on four different configurations of lattice vertical elements varying the distribution of outer diameter and the control section spacings according to a sinusoidal and hyperbolic analytical formulation (Figure 6):

- Type 1: lattice vertical element with constant outer diameter and constant control section spacing.
- Type 2: lattice vertical element with constant outer diameter and varying control section spacing.
- Type 3: lattice vertical element with varying outer diameter and constant control section spacing.
- Type 4: lattice vertical element with varying outer diameter and varying control section spacing.

The design was based on the analytical formulation proposed by the authors and under patent protection in Italy (deposit number: IT102021000032411) to generate lattice poles from conventional ones, based on inertia equivalency. The designs are governed by the parameter α that determines the ratio between outer diameter and volume reduction: by increasing the outer diameter of the lattice element, a reduced volume is required to maintain the same inertia request. Figure 6 displays the volume reduction for the four design types based on different values of α.

The different designs proposed for the lattice elements were also verified under compression loading in terms of their structural performances. The interested reader could refer to [23] for further details.

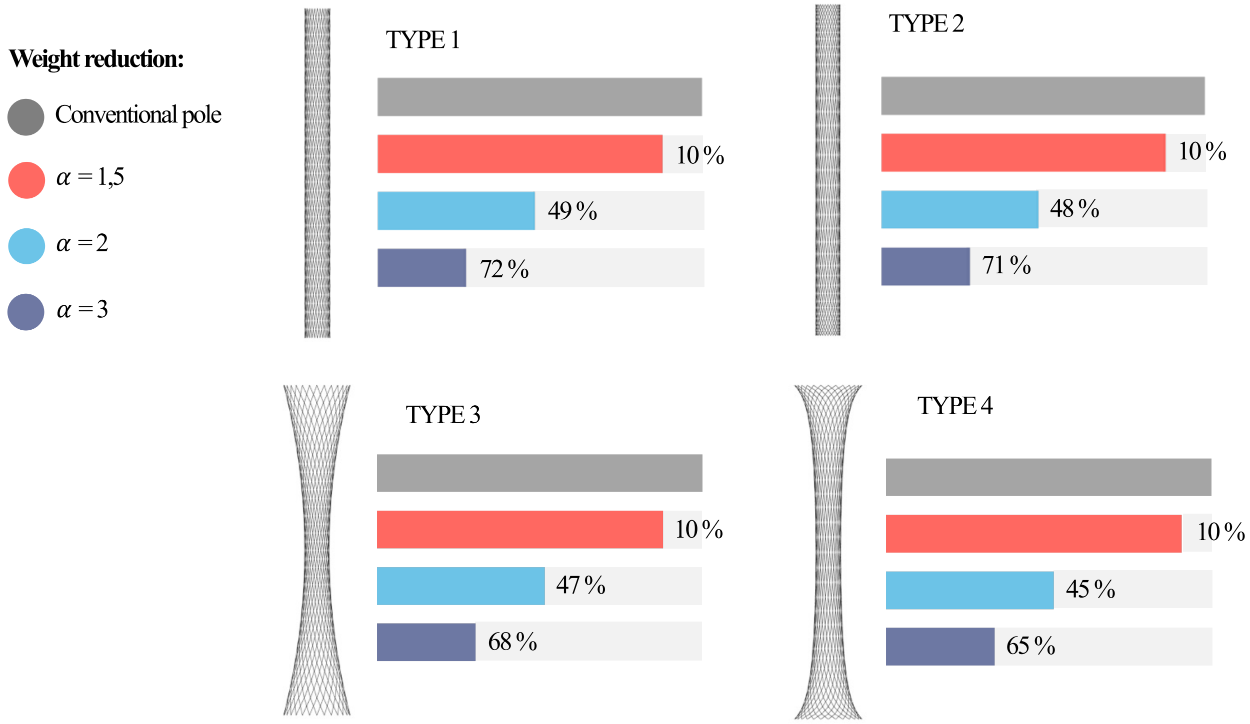

Figure 6: Examples of WAAM lattice elements and their weight reduction compared to conventional elements.

5. Conclusions

The application of metal Additive Manufacturing (AM) techniques for construction, and especially Wire-and-Arc Additive Manufacturing (WAAM), has proved to be a good solution towards a new generation of efficient and sustainable structural systems.

Current research work has been focused on the application of WAAM to few pioneering projects, which also highlighted the need of proper design for manufacturing solutions to account for both the fabrication constraints and the specific mechanical behavior of the printed outcomes.

The present study aims at providing an integrated design approach to combine computational design with fabrication properties for a new class of resource-efficient WAAM elements. The approach is applied to new steel structural members which can be adopted as either columns or slender elements and fabricated with WAAM dot-by-dot process.

The solution is aimed at developing a new generation of resource-efficient structural elements, able to guarantee good structural performances while reducing the material use. Further considerations will be developed to assess the environmental and economic impact of WAAM production in construction.

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