TOWARDS A NEW GENERATION OF LATTICE STEEL STRUCTURES FABRICATED WITH WIRE-ARC ADDITIVE MANUFACTURING

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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 experimental tests were carried out on the single components of lattice elements: the single bars at different inclinations, the intersected bars and the elementary cells.

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, such as rolling, casting, or milling, 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 for AM processes 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 [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 processes 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]).

WAAM FOR LATTICE STRUCTURES

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 bar-like elements, constituting the basic units of grid and lattice structures.

Currently, the interest in the "dot-by-dot" strategy is growing, allowing for the realization of structural elements, such as free-form gridshells, lattice structures and application of steel bars as reinforcement for innovative 3D-printed concrete structures [12,22]. Therefore, there is an increasing need in the assessment of the mechanical properties of WAAM-produced steel bars, which may differ from the typical behavior of conventionally-manufactured steel bars.

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.

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]) (Figure 1).

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.

EXPERIMENTAL TESTS ON WAAM LATTICE COMPONENTS

The present section provides an overview of the main results of the experimental investigations carried out at 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: (i) single bars at different inclinations, (ii) intersected bars and (iii) elementary cells (Figure 3). The influence of the build angle and nodal region on the mechanical response of the printed bars has been investigated by considering different build angles for both single and crossed bars, 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 elementary cells were studied under compression loading by comparing different geometrical configurations, obtaining varying the cross-sectional geometry of the cell. 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 specimens, hence not subjected to

Figure 1: Conceptual render of possible application of WAAM lattice columns [credits: Matilde Barchi, Sofia Capelli, Wessal Akrar].

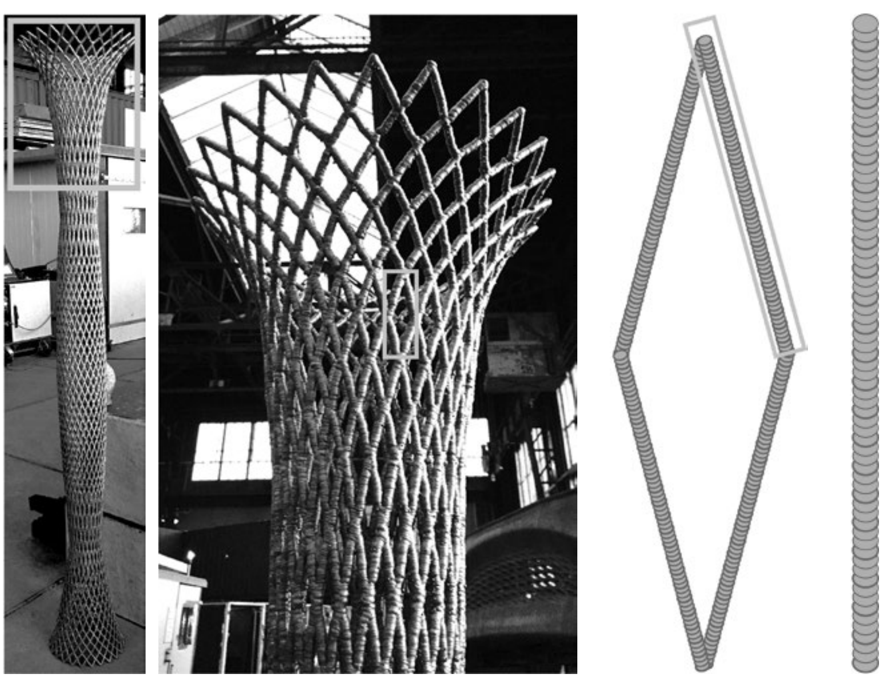

Figure 2: From the lattice column to the single bar.

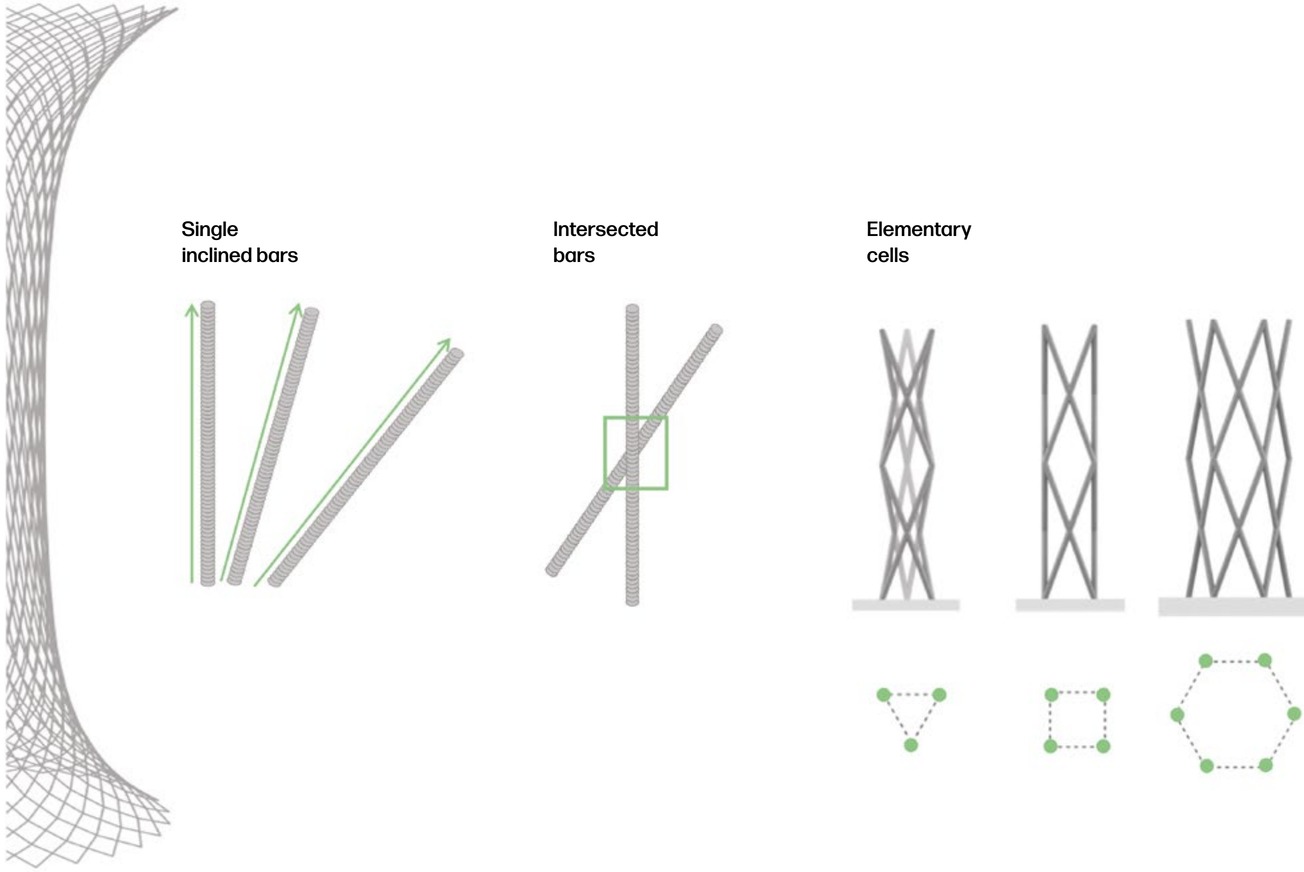

Figure 3: The basic components of WAAM lattice columns.

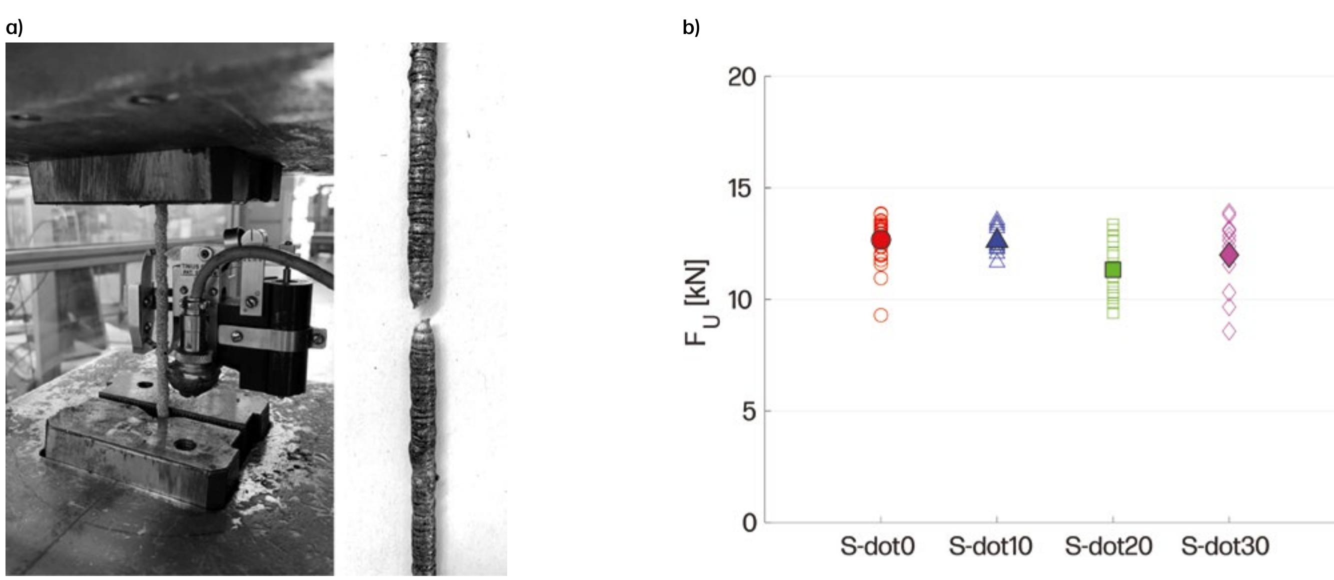

Figure 4: Tensile tests on single bars: (a) experimental set-up; (b) experimental results on single bars printed at different inclinations (from 0° to 30° build angle).

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.

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 bars 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 4 reports the values of ultimate tensile force (Fu 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 previously-tested batches (see e.g. [26]).

INTERSECTED 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, referring to crossed bars B printed at 10°, 20° and 30° build angle, respectively. 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 bars presented above.

Figure 5 reports the bar chart related to the ultimate tensile force (Fu) 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.

ELEMENTARY CELLS

The first studies on elementary cells were carried out in terms of numerical simulations to assess their overall behavior under compression loading.

Figure 6 presents the results from Finite Element Analysis (FEA) carried out through SAP2000 software on three different elementary cells, i.e. a triangular-based, a squared-based and an hexagonal-based cell respectively. The results confirm that the critical part of the elementary cells under compression loading is at the central nodes, while the whole behavior is mainly governed by bending moment.

These first outcomes suggest the need for further investigations on the influence of the geometrical configurations, in terms of both cross-sectional geometry and external shape, of WAAM lattice columns under various loading conditions. In particular, detailed analyses on the influence of the ideal vs real printed geometry of the lattice elements should be carried out, to calibrate the effective structural behavior of this new class of elements.

CONCLUSION

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 either as columns or slender elements fabricated with WAAM dot-by-dot process. The presented approach aims for developing

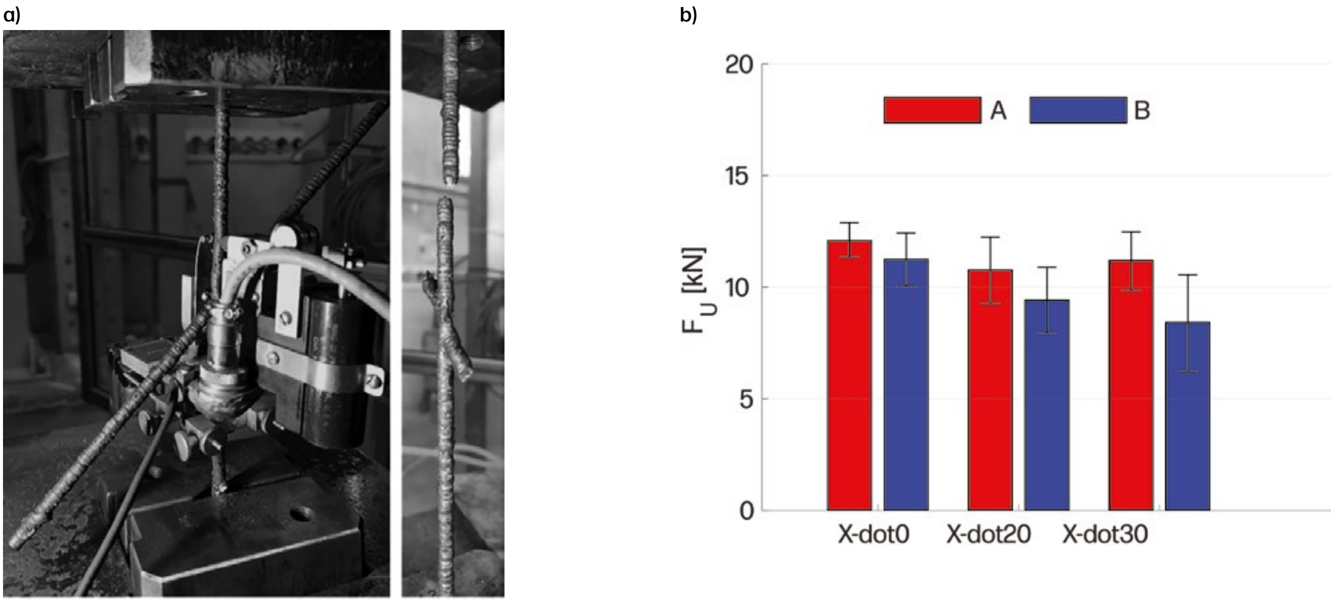

Figure 5: Tensile tests on intersected bars: (a) test set-up; (b) experimental results on intersected bars printed at different inclinations (from 10° to 30° build angle).

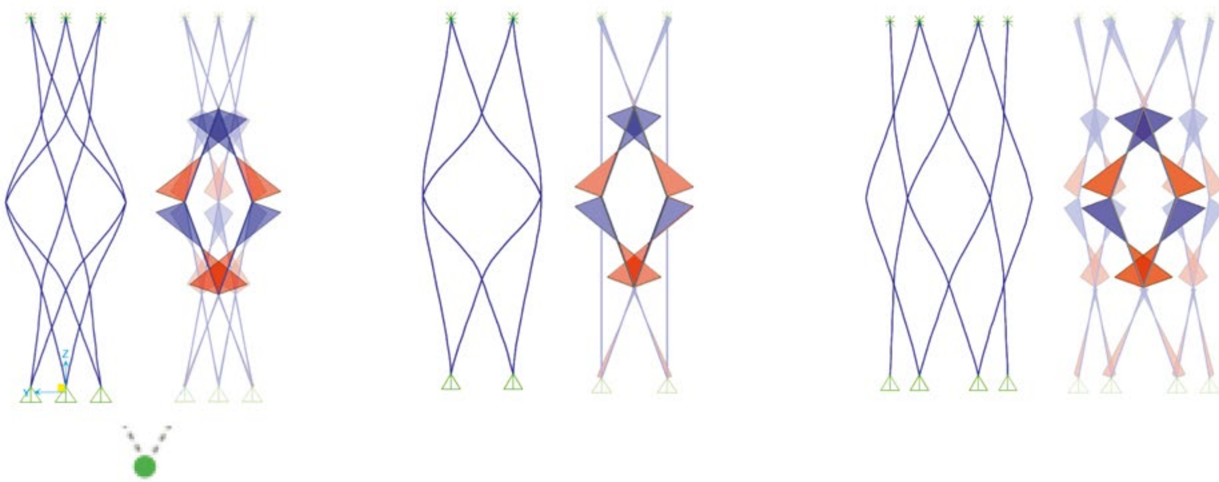

Figure 6: FEA results on the compression behavior of three elementary cells.

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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