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Explorations of efficient design solutions for Wire-and-Arc Additive manufacturing in construction

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ABSTRACT

The digitalization of the construction sector could potentially produce more efficient structures, reduce material waste and increase work safety. Current strategies for the realization of automated steel constructions see the application of metal Additive Manufacturing processes (and in particular Wire-and-Arc Additive Manufacturing, WAAM) as an opportunity to build a new generation of efficient steel structures with reduced material use. This, though, requires advanced multidisciplinary knowledge in manufacturing, metallurgy, structural engineering and computational design. Recent effort has been made in order to combine computational design with current digital fabrication procedures to realize resource-efficient steel structures for the future. The present work aims at providing an integrated design approach to develop resource-efficient structural elements combining computational design algorithms with considerations on the WAAM fabrication process, structural considerations and verifications. The idea comes from the preliminary results achieved in terms of new structural optimization theories, fabrication of large-scale elements with WAAM and structural verification of first prototypes. The approach is applied to two classes of structural elements (beam and column). The results aim at increasing the application of metal Additive Manufacturing in construction, through the development a new generation of resource-efficient structural members.

1. Introduction

The adoption of digital solutions for construction has proved to increase work safety and support the Circular Economy, by reducing 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]. 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 [7]. The first application of this technique is the MX3D Bridge, the world’s first steel 3D printed footbridge, currently located in Amsterdam city center [8]. Recent research effort has been devoted to assess the structural behavior of WAAM-produced steel parts, such as tubular elements [9,10],

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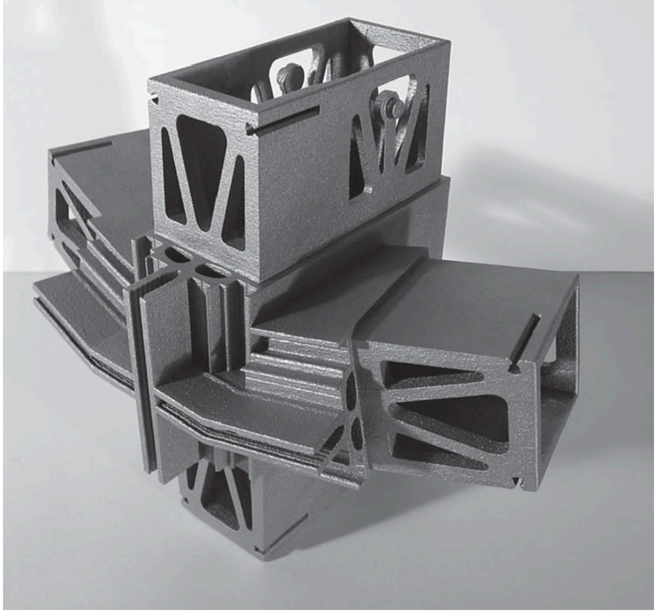

Fig. 1. Full-size aluminum prototype Nematox façade node [21].

gridshell columns [11], beams [12–15] and connections [16,17].

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 [18]. Current research effort is paid to combine AM with optimization tools to solve issues related to manufacturing processes (such as overhang, see e.g.[19]) or exploit the material anisotropy to find new optimal solutions (see e.g. [14,20]).

The present work aims at exploring the recent applications of metal AM solutions in construction. First, the attention is paid to recent studies made in pioneering applications (Section 2). Then, different computational design approaches are presented in brief with specific applications of metal AM in construction (Section 3). Section 4 reports possible solutions to combine design and fabrication to realize new efficient structural members in WAAM, with additional considerations on the sustainability aspect of the solutions proposed (Section 5). The aim is to draw attention to the current and perspective solutions to efficiently use metal AM towards a new generation of efficient and sustainable steel structures.

2. Recent studies on metal AM in construction

2.1. First applications

Early uses of metal AM in construction have primarily featured modest-scale components such as façade nodes and connections [3]. One example of an AM-produced façade node is the Nematox façade node [21], developed to show how additive manufacturing process could be used to allow more optimized geometries. A full-size prototype (Fig. 1) was built using PBF with aluminum powder.

A tensegrity structure lighting node was redesigned by Arup to take advantage of the opportunities presented by AM combined with topology optimization. The design has been first optimized according to the boundary conditions prescribed, and then rationalized for manufacture, i.e. reducing the amount of material used, minimize cost and speed up manufacture (Fig. 2). The final design has been realized using PBF with ultra-high strength steel powder. Although it was noted in 2014 that the final node costed roughly three times that of a conventionally produced node, it was expected to become cheaper through manufacturing development within five years.

More recently, metal AM nodes were adopted to create an ultra-light pavilion held in Singapore and developed by AirLab at Singapore

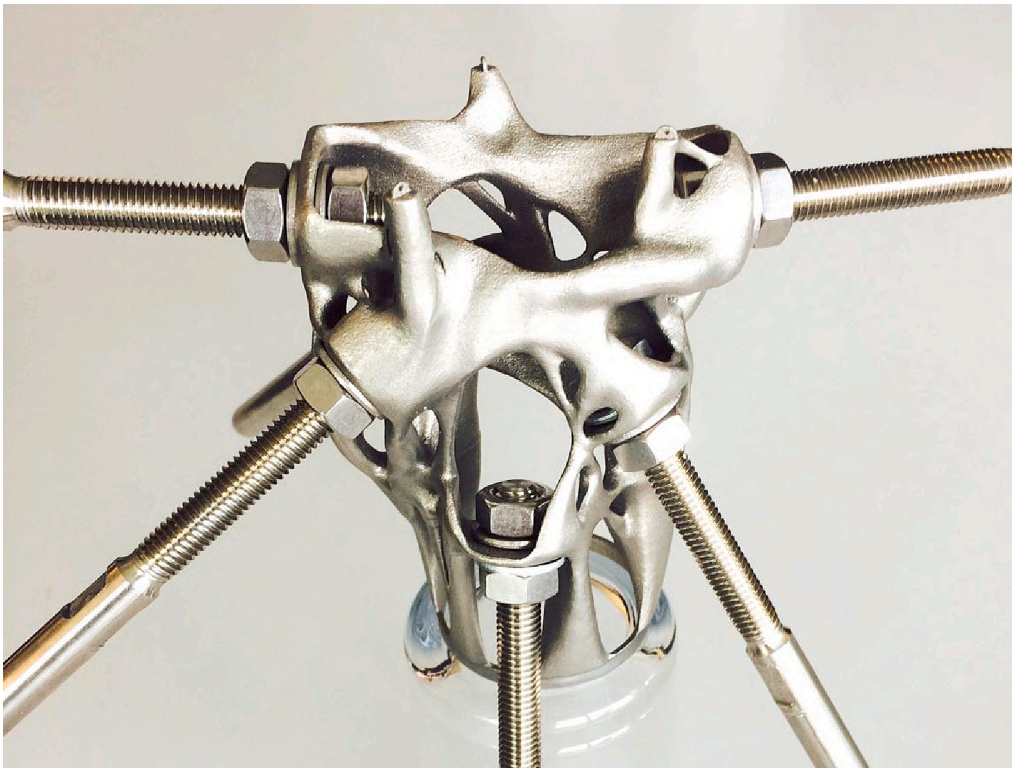

Fig. 2. Arup lighting node [22,23].

Fig. 3. AirMesh Pavilion [24].

Fig. 4. MX3D Bridge [25].

University of Technology and Design [24]. Geometric optimization processes based on force distributions have been applied to design the 54 unique nodes realized using PBF with stainless steel powder (Fig. 3).

2.2. *Wire-and-Arc Additive manufacturing (WAAM)*

Among different AM processes, Wire-and-Arc Additive Manufacturing (WAAM) technology consists of a combination of an electric arc as heat source and wire as feedstock. It currently uses off-the-shelf welding equipment, such as welding power source, torches and wire feeding system, while motion is provided by either a robotic arm or computer numerically-controlled gantries. Such flexible building set-up allows for the realization of elements without theoretically any dimensional constraint. Thus, it appears more suitable for structural engineering applications, for which the outputs requested are of the order of several meters (typically 3 to 5 m long). In order to obtain pieces of large dimensions, higher printing velocities are required, resulting in larger geometrical imperfections with respect to the digital model. Therefore, much effort is needed for a proper assessment of both the geometrical and mechanical characterization of the outputs from WAAM process.

Fig. 5. MX3D Takenaka Connector [26].

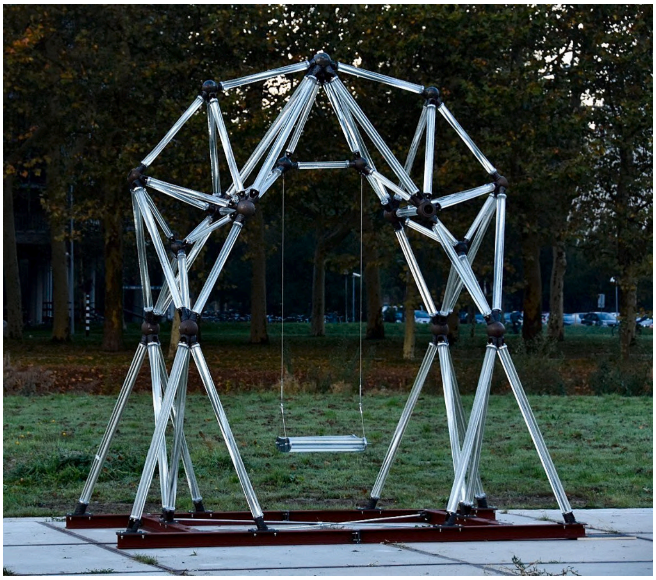

Fig. 6. The Glass Swing realized at TU Delft in collaboration with the Dutch company RAMLAB [28].

The first application of WAAM in construction is the MX3D Bridge, the first full-size pedestrian bridge ever realized in metal AM and currently located in Amsterdam city center (Fig. 4) [8].

Recently, MX3D partnered with Takenaka to produce a structural steel connector [26] (Fig. 5). The connector is designed by MX3D and Takenaka engineers with the help of topology optimization program, to show the progress in the production of highly customized and engineered steel connectors using WAAM. The connector is realized with WAAM process using Duplex stainless steel.

Another example on the application of structural optimization and WAAM technique has been proposed by a research group from TU Delft (Fig. 6). The Glass Swing has been realized in structural glass and WAAM-produced steel nodes by the Dutch company RAMLAB [27]. The non-standard form of the swing was developed through ad-hoc optimization procedure for vector active glass structures [28].

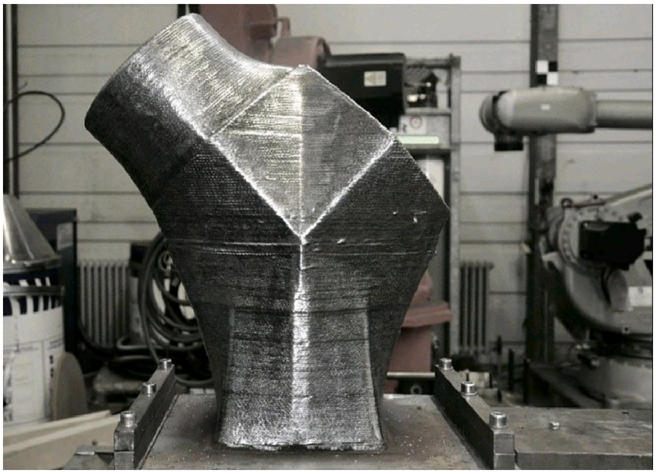

Fig. 7. WAAM node connector realized by TU Darmstadt [29].

Very recently, the research group from TU Darmstadt presented the potentials of production and post-processing of steel node connections realized in WAAM (Fig. 7) [29].

3. Computational design approaches

3.1. Recent approaches

Recently, a paradigm shift has occurred in the structural design workflow thanks to the computational design concept, that fully entails the use of computation for the exploration of structural solutions and the development of novel design ideas.

Within computational design framework, different approaches have been proposed so far. Cascone et al. recently proposed a so-called “structural grammar approach” for the generative design of diagrid-like structures [30]. A similar concept was also adopted to realize a

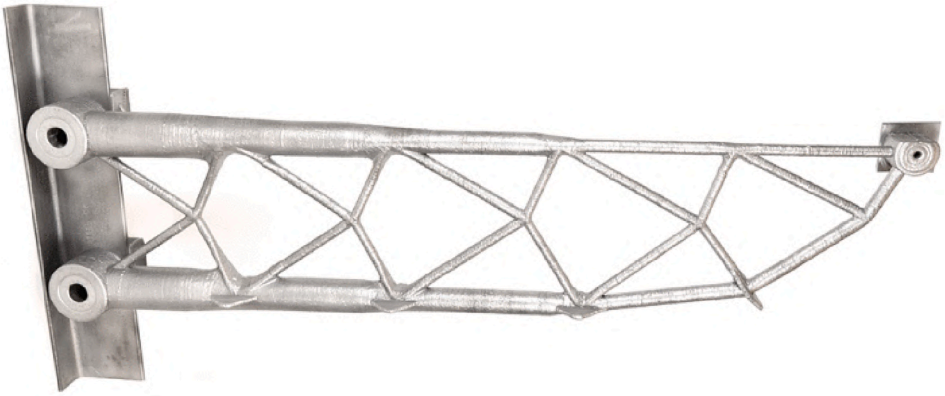

Fig. 8. WAAM optimized member [37].

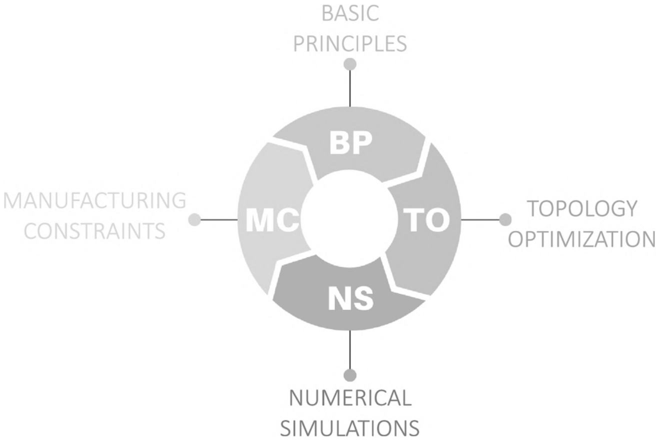

Fig. 9. Conceptual workflow of the blended optimization approach. Adapted from [13]

WAAM diagrid column [11]. Generative design has also been used by Wang et al. in an integrated method to create joints for tree-like columns to be realized in AM [31].

Topology optimization results to be a good strategy to design resource-efficient structural elements. Nonetheless, proper considerations regarding structural performances and manufacturing constraints should be implemented in the algorithm in order to develop suitable design solutions for construction. In this direction the research group of Prof. Mike Xie at RMIT University has been working on developing structural optimization algorithms able to embed structural verifications within the design process (see. e.g. [32]). Kanyilmaz et al. proposed a series of innovative steel tubular joints designed by making use of topology optimization and metal AM techniques by mimicking features present in nature [33]. A new formulation to implement manufacturing constraints and printing orientation in topology optimization algorithms has also been proposed to realize a new generation of WAAM-produced planar elements. In detail, a displacement-constrained minimum weight formulation for WAAM stainless steel plates accounting for the orthotropic material model was developed. Numerical simulations revealed that the build orientation remarkably affects the shape and stiffness of the optimal layouts in case of single-plate specimens [20]. The same formulation has been extended to propose optimal design of WAAM-produced stainless steel I-beams [14]. Topology optimization algorithms have also been ad-hoc modified accounting for the specific anisotropy in both elastic and post-elastic regime proper of WAAM-produced stainless steel plates (see e.g. [34–36]). Recently, an automated end-to-end framework for the generation of high-performance AM structures was implemented to integrate AM techniques into the construction of optimized members [37] (Fig. 8). It is worth noticing that none of the above-mentioned approaches have formulated an integrated computational design with fabrication constraints and manufacturing considerations in a unified workflow.

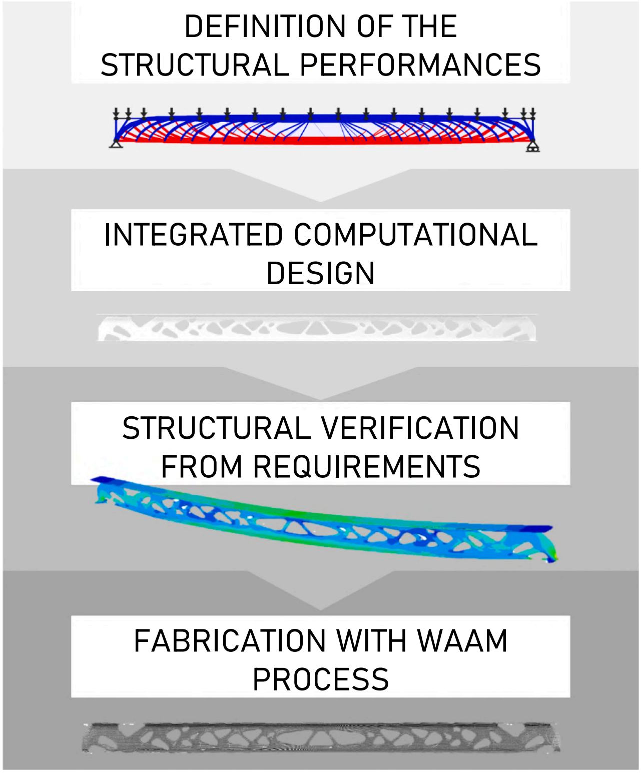

Fig. 10. Conceptual workflow for WAAM optimized beams.

3.2. 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

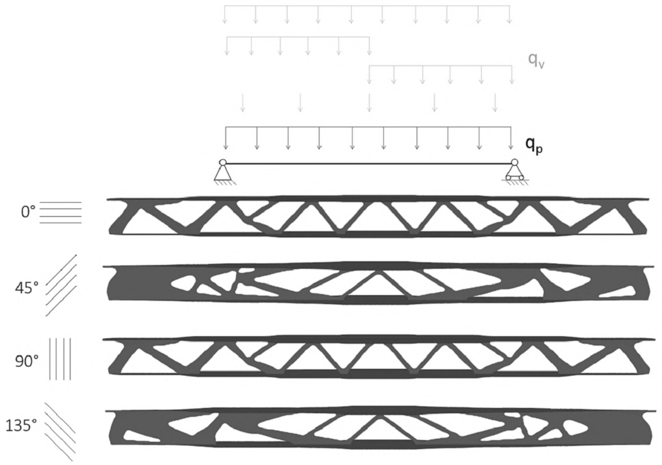

Fig. 11. Design optimization of the WAAM optimized beams.
Adapted from [13]

structural design verifications, a so-called "blended" structural optimization approach was proposed (see [13]). Indeed, the approach is intended to "blend" a stiffness-based topology optimization approach (suitably tailored for WAAM stainless steel, see e.g. [20]) 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 (Fig. 9). Detailed information on the approach can be found in [13].

4. Integrating computational design and fabrication for efficient structural elements produced with WAAM

4.1. Optimized beams

The first idea of an integrated computational design and fabrication framework was developed for the production of optimized I-type beam members through a series of conceptual steps (Fig. 10). The first application of this procedure was presented in [13] for the case of I-type beam to be inserted in a residential building.

4.1.1. Definition of the structural performances

The design process started from the definition of the initial design, i. e. the I-type steel beam. Then, target performances are formulated in terms of structural behavior, economic and functional requirements. Then, the modelling criteria for the optimization process are defined in terms of domain definition, material behavior and manufacturing constraints. Based on the predicted application, the boundary conditions are set in terms of support and load configurations.

4.1.2. Integrated computational design

The design phase was developed following an optimization process which was formulated in terms of a topology optimization algorithm seeking for lightweight solutions with prescribed stiffness. The topology optimization is performed through a tailored algorithm which accounts for the inherent anisotropic behavior of WAAM alloys (see e.g. [36,38]). The design process accounted for two different support conditions (hinge-roller and doubly-hinged) and four different load case scenarios common for structural engineering applications. The result is a "blend" of all optimal solutions found through the algorithm, in terms of both design geometry and printing direction, to maximize the stiffness while minimizing the material use (Fig. 11). In detail, the optimization algorithm was run under multiple loading conditions (e.g. distributed load, point load, asymmetric load) and by considering four different printing orientations. This latter aspect was included to highlight the elastic orthotropic behavior of WAAM-produced stainless steel (extensively studied in [36]), which induces different optimal geometries for different printing orientations. Among them, the design solution obtained for a 45°-printing inclination resulted to be the best in terms of structural performances and weight minimization. Further details can be found in [13].

4.1.3. Structural verification

The solution was then numerically verified in terms of its structural performances through numerical simulations. (Fig. 12). The results confirmed that the design follows the structural requirements for a structural steel beam in terms of strength and deflections. In particular, the maximum stresses reached for a serviceability loading condition (for typical residential use) was below the yielding point set at 400 MPa for WAAM stainless steel (see e.g. [39]). By considering the three main printing orientations at 0°, 45° and 90° (also referred to as L, T and D directions), a numerical comparison of the performances for the three

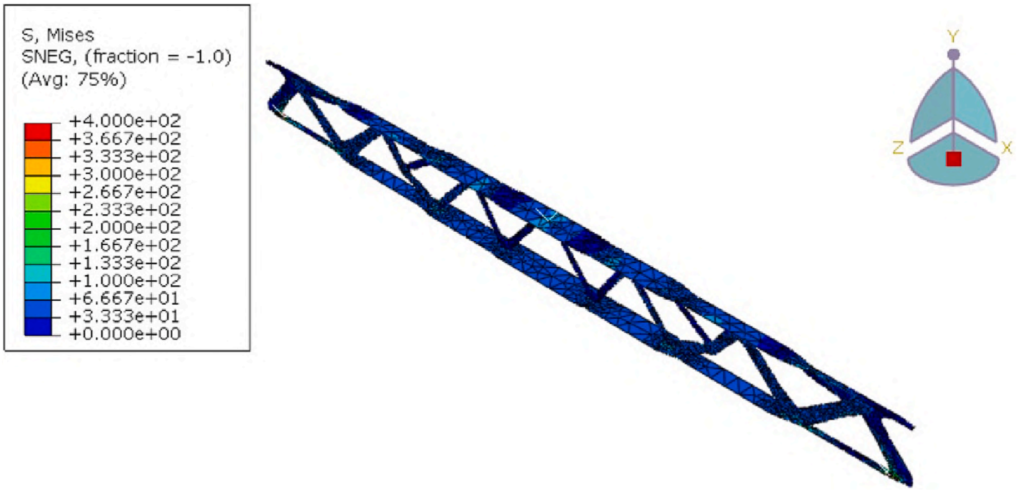

Fig. 12. Structural verification of WAAM optimized beam.
Adapted from [13]

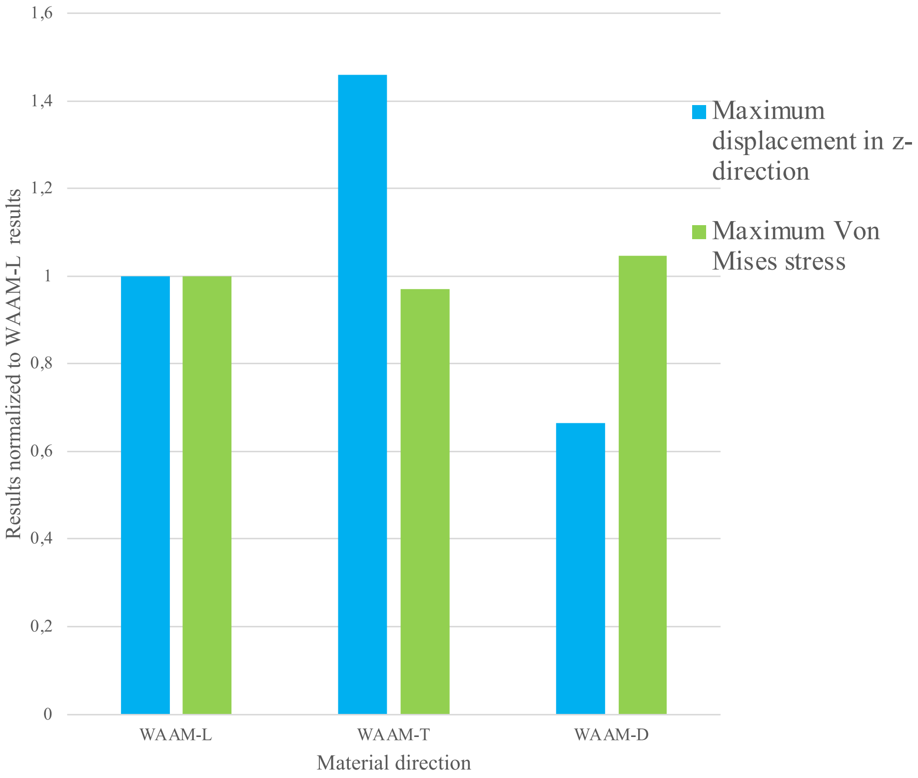

Fig. 13. Comparison of structural performances for different printing orientations: 0° (WAAM-T), 90° (WAAM-L), 45° (WAAM-D).

different printing solutions confirmed that the beam printed at 45° inclination (WAAM-D) results in having the best structural performances in terms of strength and deflection (Fig. 13).

4.1.4. *Fabrication*

The final step of the procedure is the fabrication of the optimized beams (Fig. 14). Based on the previous phases of activities, the optimized beam is required to be printed at 45° of inclination, hence additional rotational axes are needed to fabricate the part. Nonetheless, preliminary feasibility studies confirmed that the proposed design is suitable for fabrication with WAAM process mounted on multi-axis robotic system with tilting base plate.

4.2. *WAAM lattice elements*

The integration of computational design and fabrication was also proposed for the realization of lattice structural elements (Fig. 15). Indeed, a new generation of WAAM lattice elements were conceptualized through an integrated computational design process accounting for both fabrication and structural considerations.

4.2.1. *Definition of the structural performances*

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. [40]), (iv) carbon steel grid as retrofitting system for existing members (see e.g.[15]) (Fig. 16).

4.2.2. *Integrated computational design*

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 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 (Fig. 17):

- 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:

Fig. 14. Graphical representation of the WAAM optimized beams inserted on a residential building.

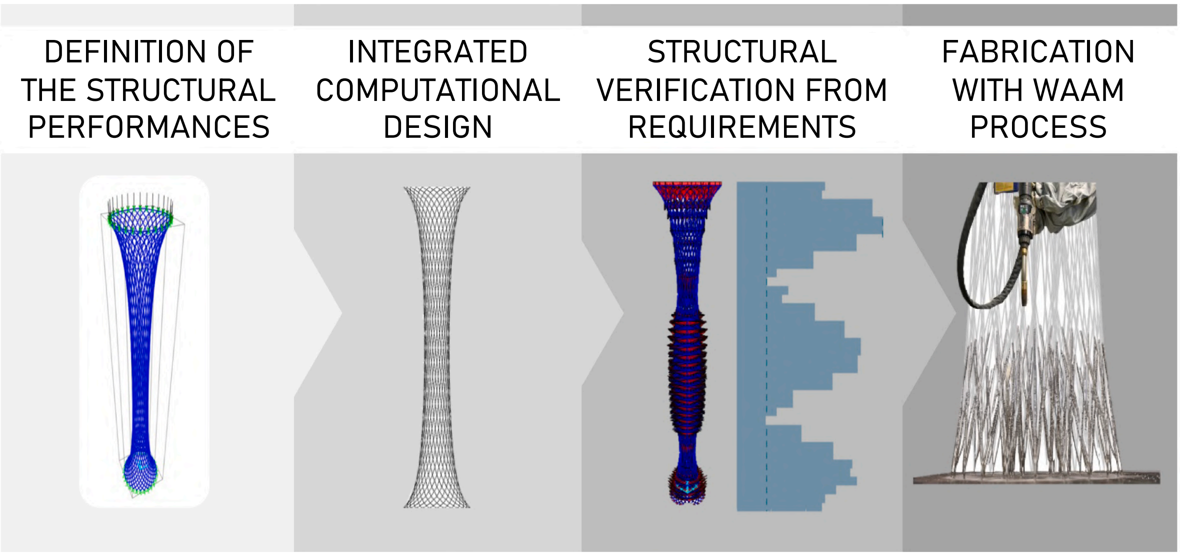

Fig. 15. Conceptual workflow for WAAM lattice elements.

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. Fig. 18 displays the volume reduction for the four design types based on different values of α.

4.2.3. Structural verification

The proposed designs were then verified in terms of their structural performances under serviceability compressive loading conditions. A non-linear static analysis was carried out for this purpose through the Finite Element program SAP2000 ([41]). Fig. 19 shows the distribution of utilization factor along the height of the four different design types. All of the proposed design solutions remain under the plastic limit during serviceability state, thus confirming the good structural performances of the proposed solution.

4.2.4. Fabrication

The last phase is the fabrication of the proposed design solutions. A very first demonstrator was fabricated at MX3D facilities in Amsterdam in 2018 (Fig. 20) [11]. The half-scaled diagrid column validated the proposed approach in predicting the manufacturing constraints of the element during the design stage.

More recently, a joint research collaboration with TU Braunschweig in Germany was assessed to study the fabrication process to realize large-scale lattice columns produced with WAAM. The final outcome resulted in the first 60-cm high fully infilled steel lattice column, representing the base of a 12-m high pillar (Fig. 21).

5. Considerations on the sustainability aspects

The digitalization of the construction sector could potentially produce more efficient structures, reduce material waste and increase work safety. In particular, the application of AM has proved to support the Circular Economy by (i) offering new raw material options, (ii) increasing the efficiency of the fabricated designs thus reducing the in-production waste and (iii) simplifying the resource recapture, hence supporting composting and recycling. Current strategies for the realization of automated steel constructions see the application of metal AM processes (and in particular WAAM) as an opportunity to build a new generation of resource-efficient steel structures with reduced material use [42]. The efficiency of these new members is obtained from the adoption of WAAM technique able to realize free-form geometries with high structural performances. The sustainability of these new solutions is obtained both from the economic and environmental points of view. For this aim, the following aspects should be studied in detail: (i) possibility to use recycled raw material for the fabrication process; (ii) design of optimized geometry with reduced material use; (iii) verification of high-efficiency structural performances; (iv) analysis of the economic and environmental advantages. From these, a systematic analysis on the economic and environmental impact of WAAM members should be developed. The economic impact can be assessed from a quantitative (in terms of reduction of raw material) and environmental points of view (in terms of transportation costs). For the analysis, production cost comparison and production organization models should also be developed.

Such future analysis will propose new metrics to quantify the advantages of these new construction solutions from the economic and environmental perspectives. These metrics will contribute to develop and foster the relationship with industries and companies that might exploit WAAM technologies in construction.

6. 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

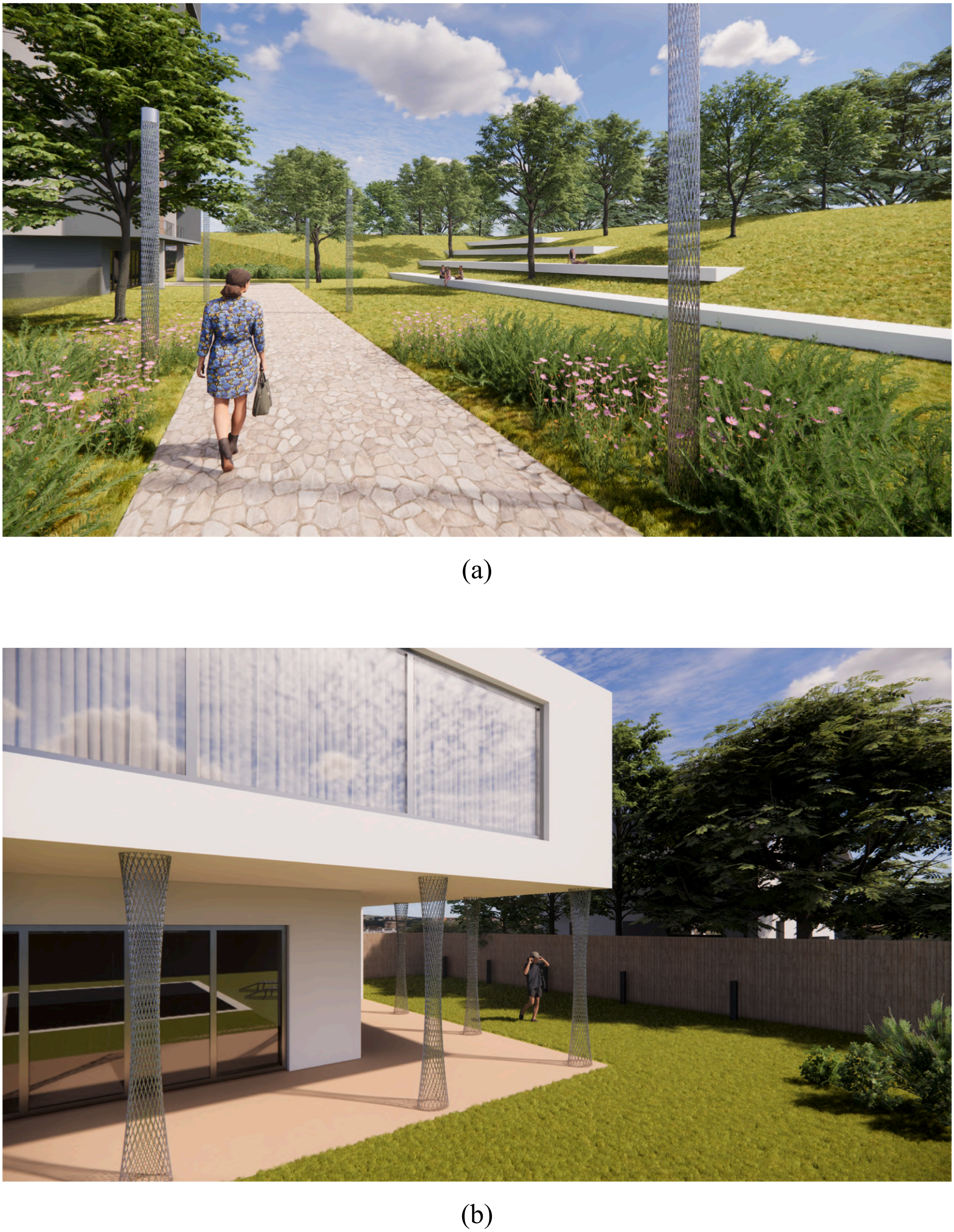

Fig. 16. Graphical representations of the WAAM lattice pole: (a) for urban lighting; (b) for structural applications on high-end architectural buildings.

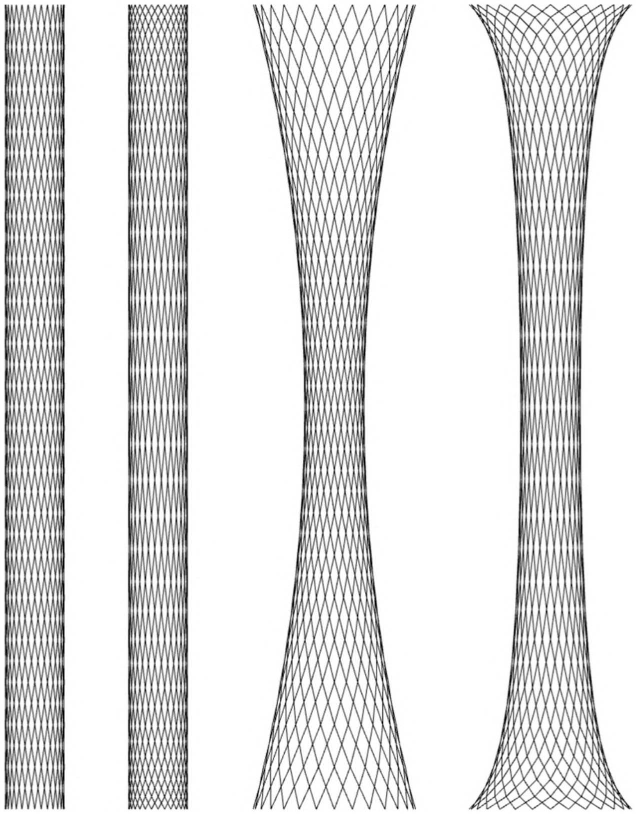

Fig. 17. Designs of WAAM lattice vertical elements.

class of resource-efficient WAAM elements. The approach is applied to two classes of steel structural members, i.e. beam and column, fabricated with two different printing strategies proper of WAAM process, i.e. layer-by-layer and dot-by-dot.

Both solutions are aimed to develop 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.

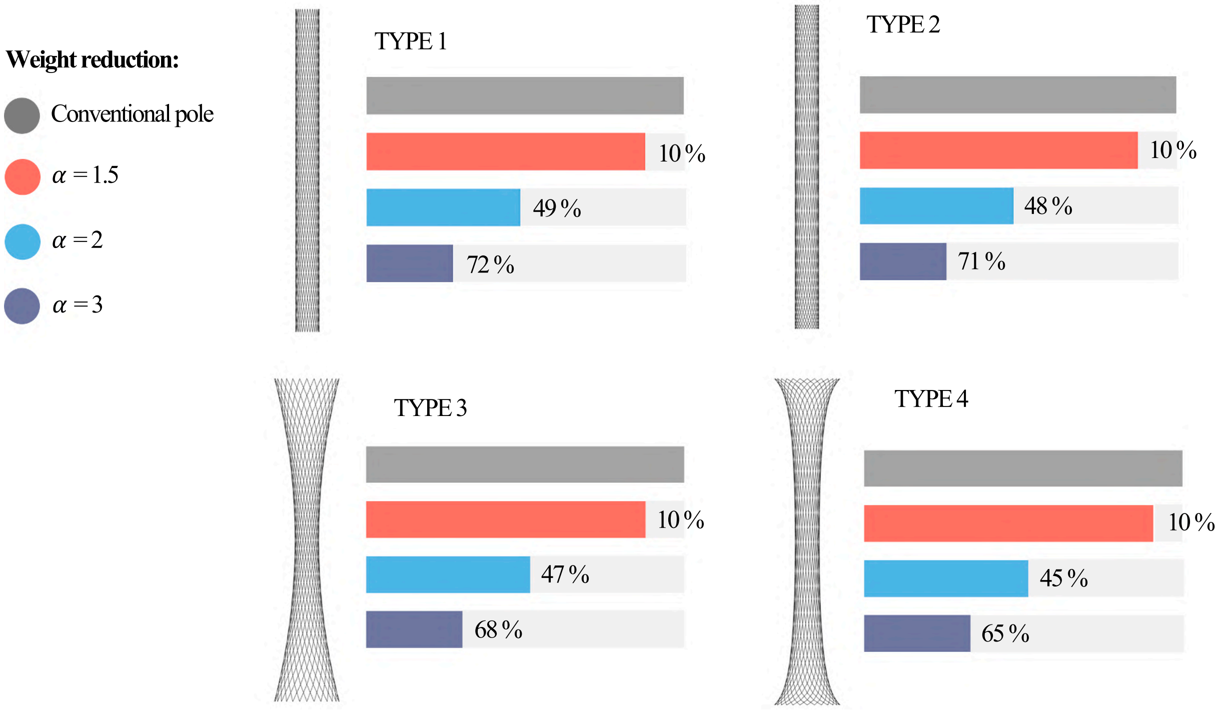

Fig. 18. Weight reduction of WAAM lattice vertical elements with respect to the conventional one.

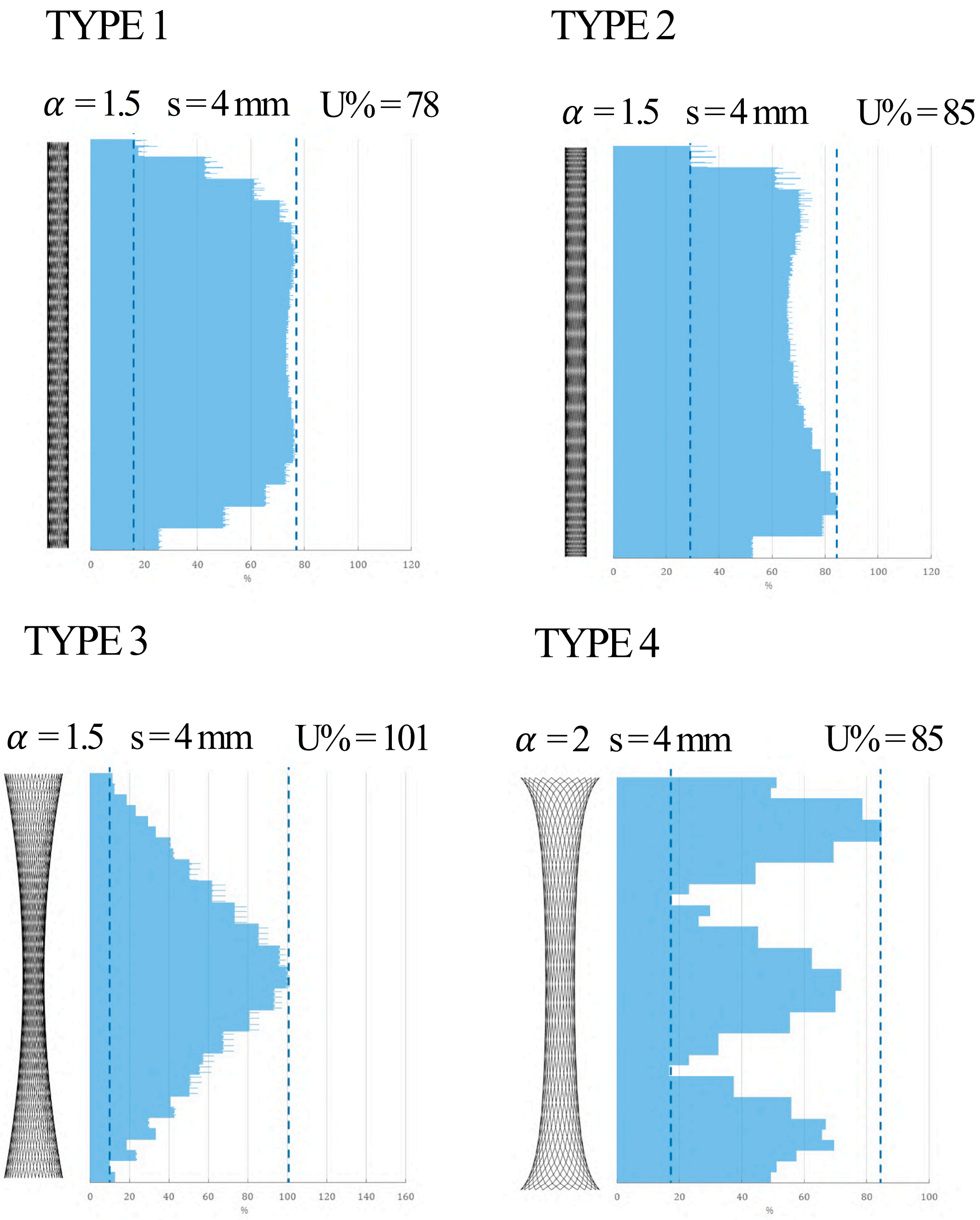

Fig. 19. Structural performances of WAAM lattice vertical elements.

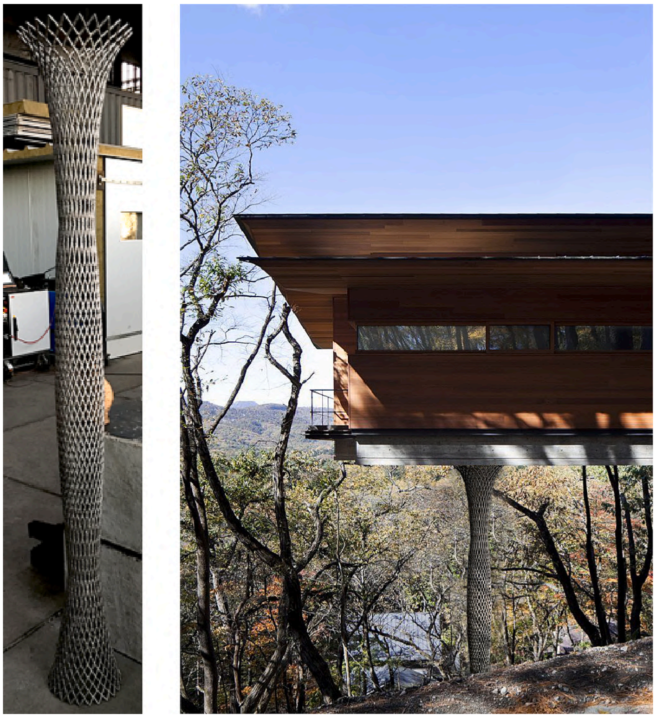

Fig. 20. WAAM diagrid column fabricated in 2018 at MX3D, Amsterdam [11].

Fig. 21. WAAM infilled diagrid pillar fabricated in 2021 at TU Braunschweig, Germany.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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