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THE APPLICATION OF WELD-BASED ADDITIVE MANUFACTURING STEEL TO STRUCTURAL ENGINEERING

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The present work aims at providing the first considerations upon the application of innovative manufacturing technology for civil engineering purposes. In particular, among the 3D printing processes currently available, Weld-Based Additive Manufacturing (WAM) results to be the most suitable technique for the realization of innovative structural forms in metal material. The great potential of taking the printing head "out of the box" allows for the construction of innovative shapes by adding layer upon layer of welded steel. In particular, the study is focused on the realization of the first 3D-printed steel footbridge by a Dutch company held in Amsterdam, called MX3D, and its Additive manufacturing process, which results in specific constraints and limitations to be taken into account for design purposes. First, the design issues are described, by considering the printing parameters to be adopted for the realization of large-dimensions structures, and then the implications in terms of specific geometrical and mechanical characteristics are studied. These first engineering evaluations are intended to pave the way towards the development of a ground-breaking technology for the fully-automated design and construction of novel 3D-printed building structures through innovative robotic manufacturing processes whose parameters are still not fully known.

Keywords: 3D printing, Mechanical characterization, Experimental tests, Stainless steel, Geometrical imperfections, Manufacturing techniques.

1 INTRODUCTION

Over the two last centuries, the progress in civil engineering always derived from advancements in technology and material science from the Industrial Revolution, which paved the way towards the realization of steel structures, to the studies of Hennebique at the beginning of XX century for the introduction of concrete in civil engineering. In the last decades, much attention has been brought to innovative manufacturing processes by means of Rapid Prototyping (RP), leading towards a new era for the construction field (Addis 2007).

The fundamental part of this process is the "digital turn" (Carpo 2013) in the design and planning process for civil engineering over the last 25 years, to emphasize the increasing influence of Computer-Aided Design (CAD) tools in the realization of innovative unexplored forms for architecture (i.e., complex, doubly-curved geometries, free-form design) (Schlaich and Schlaich 2000, Iwamoto 2013). Although many research efforts have been done since the 1950s on compressed and flux structures (Adriaenssens *et al.* 2014, Sasaki 2005), the construction technology at the time could not overcome the intrinsic issues related to the manufacturing process of such complex shapes. On the other hand, automation has been starting to prevail for the last decades in almost all production domains for aero-spatial, mechanical and biomedical fields, whereas for civil engineering it has still been a challenging task due to large dimensions of the products to be 3D-printed (Wong and Hernandez 2005).

Very recently, innovations in digital fabrication such as Additive Manufacturing (AM) processes present high potentials to be involved in the realization of structural elements without geometrical constraints, which would start a new trend towards automatic constructions.

2 WELD-BASED ADDITIVE MANUFACTURING PROCESS

The basic equipment of an Additive Manufacturing system consists of a motion part, a heat source and a feedstock (Williams *et al.* 2016). Several research activities aimed at providing appropriate terminology and classification among the widespread variation of technologies within this family (Sames *et al.* 2016), and a first distinction can be made based on the material adopted. In particular, for metal Additive Manufacturing processes, they can be divided into three main categories: (i) Powder-Based Fusion (PBF), (ii) Directed Energy Deposition (DED) and (iii) sheet delamination.

Although intense work has been done in the mechanical characterization of PBF metal outcomes (Buchanan *et al.* 2017, Song *et al.* 2015, Yap *et al.* 2015, Niendorf *et al.* 2013), this technology suffers from intrinsic dimensional constraints related to the volume of the box being part of the printing apparatus, therefore becoming highly challenging to realize real-dimension structural elements. Differently, among the DED processes, the so-called Wire-and-Arc Additive Manufacturing (WAAM), also referred to as simply Weld-based Additive Manufacturing (WAM), is able to provide larger outcomes due to the absence of the volume constriction and flexibility in the set up. In fact, the printing head is positioned on top of a robotic arm, literally taking 3D printing process “out of the box”. On the other hand, larger dimensions of the outputs require also higher printing velocities, and therefore less accuracy in the geometry of the element realized.

3 THE FIRST APPLICATION OF WAAM IN STRUCTURAL ENGINEERING

The present work focuses on the application of Weld-based Additive Manufacturing process in the structural engineering field.

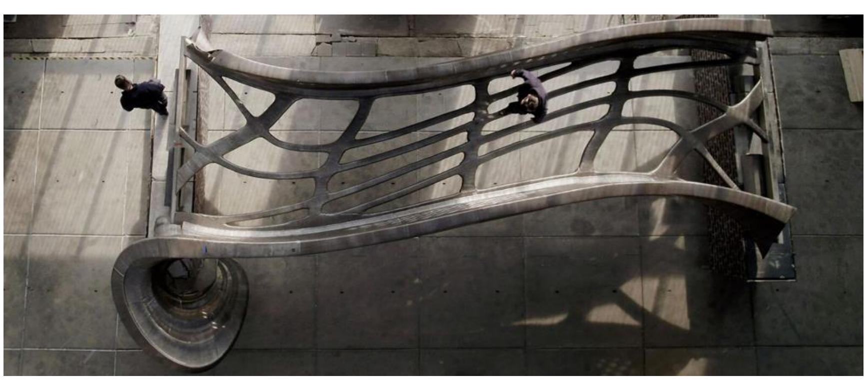

Figure 1. MX3D footbridge realized with the WAM process [courtesy of MX3D].

In particular, the first attempt to develop a new building trend has been done by MX3D (2019), a Dutch company based in Amsterdam which realized the first 3D-printed real-scale footbridge in Additive-Manufactured stainless steel (Figure 1).

The specifications of such manufacturing process in order to build a large-scale structure are crucial in the derivation of the structural response of the outcomes. First, the intrinsic lack of precision of the printing equipment has to be devoted to the higher velocities required to print large parts. Moreover, the welding process induces some non-negligible residual stresses due to heating, which might also alter the internal crystalized structure of stainless steel, to be objective of further research as well.

4 THE DESIGN ISSUES

In order to assess the design specification of a brand-new construction process, both geometrical and mechanical characterization should be performed, to properly quantify the peculiarities related to the WAAM process adopted in the realization of structural engineering parts.

4.1 Geometrical Imperfections

Figure 2 shows some of the crucial geometrical imperfections due to the manufacturing process: irregular cross-sectional area, surface roughness, and un-straightness.

Figure 2. The geometric issue of WAM tubular elements: irregular cross-section, un-straightness, surface roughness.

The cross-sectional area, of main importance to be considered in the derivation of the element structural response, is mainly affected by both surface roughness and un-straightness of the outcomes. In order to properly assess and quantify the external roughness and position of the longitudinal axis of the 3D-printed tubular elements studied, a high-resolution 3D scanning acquisition has been used to reproduce the surface by means of FE model, from which the irregularities have been studied and quantified.

The results from the geometrical characterization of Weld-based Additive Manufactured structural elements composing the MX3D's footbridge will be part of a more specific work. However, at first, it should be mentioned a discrepancy between the real and nominal cross-sectional areas, due to the irregular thickness of the welding portion, as well as the non-negligible roughness of the external surface. The same applies to the lack of straightness of some tubular elements, which alters their response in buckling under compressive load.

4.2 Mechanical Response

Regarding the structural response of Weld-based Additive Manufactured stainless-steel material, it is essential to perform some standard tests on scaled elements.

First, monotonic tensile and compressive tests are performed in order to assess the 0.2% proof stress, the ultimate stress, the Young modulus, and the ultimate deformation. Results of the first experimental campaign are briefly mentioned in recent work done by the authors (Laghi *et al.* 2018) and will be extensively described in a further study. Figure 3a shows the “dog-bone” shaped specimens used to derive the tensile strength, while Figure 3b shows the “stub columns” adopted for the compressive tests.

(a) (b)

Figure 3. (a) “dog bone” shaped specimens for tensile tests before and after the test; (b) “stub columns” specimens for compressive tests before and after the test.

The first experimental campaign shows some interesting results in terms of the mechanical properties of this innovatively processed material. As far as the 0.2% proof stress is concerned, the mean values resulting from both tensile and compressive tests are higher than the ones recommended for traditionally formed stainless steel (grade 316LSi), while for the ultimate stress the experimental results are on the lower side of the range requested by the EN 1993-1-4:2006+A1 (2015). The interesting parameter, which substantially differs from the traditional stainless-steel behavior is Young modulus, for which the first experimental tests show values around 100 GPa, corresponding to half the one commonly adopted for cold-formed stainless-steel material. This reduction might be due to several factors typical of the innovative manufacturing process adopted: some residual stresses coming from the heating treatment during the welding process, possible critical internal porosity or irregular crystalized microstructure, or else the geometric imperfections affecting the mechanical response of the element.

Further investigations on the overall structural response of WAM metal material will be the objective of some further specific work provided in a journal paper.

5 CONCLUSIONS

The advancements in digital fabrications have led over the last decade on the development of some innovative manufacturing processes for metal materials, which could be applied for civil engineering purposes. This new trend, paving the way towards a new era of construction technologies, has already been adopted in the realization of the first footbridge made by Weld-based Additive Manufactured stainless steel by a Dutch company, MX3D, held in Amsterdam.

The work focuses on the Weld-based Additive Manufacturing process adopted in the realization of the structure, and on its intrinsic design issues, concerning both the geometrical and the mechanical characterization of the 3D-printed steel structural elements.

From the studies conducted by means of 3D scanner acquisition models, both surface roughness and un-straightness are to be considered in the overall structural response of the 3D-printed structure. The results from tensile and compressive tests compared with EN 1993-1-4:2006+A1 (2015) for 316LSi stainless steel show a good match with respect to 0.2% proof stress and ultimate stress, while for the Young modulus a substantial discrepancy between the two manufacturing processes is visible. From these first considerations, further work is required to extensively characterize the WAM structural elements to be applied in the civil engineering field.

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