Experimental behaviour of Wire-and-Arc Additively Manufactured stainless steel rods

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Introduction

Recent developments of additive manufacturing (AM) process in construction have seen the application of 3D printing techniques to realize a new generation of structures in concrete, polymers and metals. In applications for steel structures, different metal AM processes can be distinguished: (i) Powder Bed Fusion (PBF); (ii) Directed Energy Deposition (DED) and (iii) sheet lamination [1–4].

Previous applications of metal AM in construction used PBF technology, limited to realize ad-hoc parametrically designed joints [5,6], due to the intrinsic geometrical constraints of the printer environment (enclosed in a box of typically 250-mm side) [7].

In order to realize real-scale structural elements without ideally any geometrical constraints either in size or shape, the most suitable manufacturing solution for metallic elements is a DED process referred to as Wire-and-Arc Additive Manufacturing (WAAM). It currently uses off-the-shelf welding equipment, while motion is usually provided by a robotic arm. Such flexible building set-up well suits the needs of structural engineering applications, for which the outputs requested are of the order of several meters. The main advantage of WAAM relies on the possibility to create new shapes and forms following the breakthrough design tools for modern architecture as algorithm-aided design [8,9]. On the other hand, additional considerations must be made when dealing with WAAM-produced elements: (i) the inherent surface roughness proper of WAAM process, which could influence the mechanical properties [10], (ii) the marked mechanical anisotropy, as also evidenced from the material microstructure [11], (iii) the influence of process parameters in the geometrical and mechanical response [12].

Wire-and-Arc Additive Manufacturing (WAAM)

2.1 WAAM process

Current WAAM technologies make use of two different printing strategies (i.e. printing deposition techniques): (i) the so-called “continuous” printing, consisting in the traditional layer-by-layer deposition strategy, suitable for planar and shell-like geometries; (ii) the so-called “dot-by-dot” printing, consisting in the traditional layer-by-layer deposition strategy, suitable for planar and shell-like geometries.
dot" printing, consisting in a spot-like deposition strategy, whose outcomes are metal rods suitable to realize gridshells and lattice structures (Fig.1). Although there is wide research interest in the study of the outcomes from the "continuous" printing [13–18], the dot-by-dot strategy is a quite innovative (and still almost unexplored) technique [19–21].

![Figure 1 WAAM-produced lattice structure: diagrid column designed at University of Bologna and fabricated at MX3D [8,9].](image)

The present work investigates rod-like straight specimens having constant nominal 6-mm diameter (as governed by the welding dot). The specimens have been manufactured by MX3D [22] using a commercially available standard stainless steel welding wire grade ER308LSi (1 mm diameter) supplied by Oerlikon. The printing parameters are listed in Table 1. Previous work on the chemical composition and microstructural analysis of WAAM-produced plates from the same wire resulted in a material characterized by the same properties as 304L austenitic stainless steel [11].

**Table 1 Printing process parameters.**

| Process parameters | Details            | Value*        |
|--------------------|--------------------|---------------|
| Deposition power   | Current            | 100-140 A     |
|                    | Arc voltage        | 18-21 V       |
| Speed              | Welding spot       | 0.5-1 s       |
|                    | Wire feed rate     | 2-4 m/min     |
| Distance and angle | Rod diameter       | 3-7 mm        |
|                    | Electrode to layer angle | 90°       |
| Shield gas         | Shield gas type    | 98% Ar, 2% CO₂ |
|                    | Shield gas flow rate | 10-20 L/min |

*Values are provided within typical ranges. For more specific information refer to MX3D [22].

2.2 Structural design approach for WAAM structures

The design issues proper of WAAM stainless steel (i.e. geometrical irregularities and different mechanical response with respect to the feedstock) evidenced the need of ad-hoc guidelines and standards to design structures realized with this technology.

For this aim, a novel design approach has been developed by the authors [23,24]. The design approach is grounded on the conventional design format established by EC0 based on the use of partial safety factors. Additional coefficients are then introduced to specifically account for the two main sources of uncertainties (i.e. the one related to the geometrical irregularities and the one proper of the inherent material behaviour). For instance, the mechanical properties of the printed elements are estimated in terms of their effective values, consisting in assuming an effective cross-sectional area, constant along the member length, so that the axial stress can be computed according to simple beam theory:

\[
\sigma_{\text{eff}} = \frac{F}{A_{\text{eff}}} \tag{1}
\]

where:
- \(A_{\text{eff}}\) is an effective cross-sectional area of the structural member
- \(F\) is the axial force.

The effective stress \(\sigma_{\text{eff}}\) depends on how \(A_{\text{eff}}\) has been computed, and specific attention should be devoted to its choice. Recent studies [10,15,23] considered the values of \(A_{\text{eff}}\) derived from volume measurements on as-built specimens. Fig.2 provides a qualitatively comparison of the nominal, the real and the effective cross-sections of a WAAM-produced rod.

![Figure 2 Nominal, real and effective cross-sections for WAAM-produced rods.](image)

In order to adopt this specific design approach, detailed investigations should be carried out in order to assess the key material properties and the possible influence of the geometrical irregularities on their values. As such, two sources on information should be studied and quantified:

1. Global information on the geometry from volume measurements (on the diameter and cross-sectional area) to evaluate the effective mechanical properties;
2. Detailed information on the geometrical irregularities from 3D scan (cross-section variability, lack of straightness) for advanced modelling.
Experimental characterization of WAAM-produced stainless steel rods

3.1 Geometrical characterization

In order to fully characterize the inherent geometrical irregularities of WAAM dot-by-dot rods, both global and detailed investigations have been performed through different types of measures.

A detailed investigation on the cross-sectional distribution and lack of straightness proper of dot-by-dot WAAM process has been carried out on one specific specimen using 3D scanning technique.

The instrument adopted for the 3D scan acquisition is a structured-light projection Artec Spider 3D scanner. The 3D model of the scanned rod specimen consists of around 40 million triangular elements, with a medium points spacing of about 0.10 mm. Figure 3 shows a view of the entire mesh (blue model) and a zoom of it. The mesh is compared with a uniform cylinder having the dimensions of the digital model used as input in the printing process (red model).

![Figure 3](image)

Figure 3 3D model of one dot-by-dot rod and a zoom of it.

From the 3D model, a total of 120 cross-sections along the length of the specimen have been extracted, from which information regarding cross section variations and centroid location has been obtained.

The global investigation was carried out on all rods tested both in tensile and compression. The effective cross-sectional area $A_{\text{eff}}$ of the specimens has been characterized by means of volume measurements, based on the Archimedes’ principle [15,23].

3.1.1 Cross-sectional distribution

Given the inherent geometrical variability of the WAAM-produced rods, high-precision 3D scanning acquisition was adopted to evaluate the distribution of cross-sections and discrepancies with respect to the digital input. Indeed, the rods were realized having a full circular cross-section of nominal diameter equal to 6 mm.

Figure 4 shows the distribution of the diameter in terms of cumulative frequency (Figure 4a) and frequency distribution (Figure 4b) as evaluated on 120 cross-sections of the 3D-scan model (in terms of relative frequency scaled to have a unitary bars’ area). Both Gaussian Normal and Lognormal distributions seem to fit well the empirical distribution of the diameters measured.

![Figure 4](image)

Figure 4 (a) Empirical cumulative distribution and (b) frequency distribution of diameters of a WAAM-produced rod.

The average diameter from the analysis of the 3D scan acquisition is equal to 5.81 mm, resulting in a discrepancy with respect to the nominal value of 3%. The standard deviation results equal to 0.28 (corresponding to a coefficient of variation of around 0.05).

In order to correctly interpret the results of the mechanical tests, a volume-equivalent effective cross-section has been considered as the resistant effective area adopted to compute the effective stresses from tensile tests, according to the procedure adopted also in [10,25]. The values of the effective cross-sectional area have been taken from volume measurements according to Archimedes’ principle. The average value of the effective diameter taken over the 40 specimens is 5.80 ± 0.27 mm, substantially equal to the average diameter obtained from 3D scan acquisition. The relative difference between the effective diameter and the nominal one is of the order of 3% of the nominal value, among all rods tested.

3.1.2 Lack-of-straightness

From the 120 cross-sections taken on the 3D model, information regarding the lack of straightness of WAAM-produced rods has been investigated as well. In detail, from each cross-section, the coordinates of the centroid have been extracted both on Cartesian coordinate system (x, y, ...
z) and cylindrical coordinate system \((r, \theta, z)\). Figure 5 compares the piece-wise line connecting the centroids (blue line) with the longitudinal axis of the nominal ideal cylinder (black line). A maximum discrepancy of 1.10 mm has been registered on one cross-section, although on average the variation of straightness is of 0.46 mm, corresponding to 0.18% of the total length \(L\) of the rod (18/1000 \(L\)).

### 3.2 Mechanical characterization

Both tensile and compressive tests have been performed on a Universal testing machine of 500 kN load capacity at the Structural Engineering labs of University of Bologna.

The tensile tests have been performed in displacement-control with a velocity of 2 MPa/sec. Two types of monitoring systems have been utilized to evaluate the strains: a linear deformometer of nominal dimension of 50 mm, to detect the linear deformation of the specimens up to yielding, and an optical-based system referred to as Digital Image Correlation (DIC), to acquire the full strain field during the whole test until failure (Figure 6a).

The compression tests have been performed in displacement-control with an initial velocity of 0.2 mm/min, with an unloading after 6-mm displacement at 0.2 mm/min and re-loading at 0.2 mm/min until 12-mm displacement. The rods were constrained in order to obtain a hinge-clamped configuration. Since the purpose of the compression tests is to evaluate the buckling strength at different slenderness values, no additional monitoring systems were adopted (Figure 6c).

### 3.2.1 Tensile tests

The tensile tests were performed on 10 specimens having 250-mm length. Figure 7 presents the engineering stress-strain curve of WAAM-produced rods tested under monotonic tensile action.

![Figure 6](image6.png)

![Figure 7](image7.png)

Table 2 collects the main mechanical parameters (mean values +/- one standard deviation) in terms of Young’s modulus \(E\), 0.2% proof stress \(R_{p,0.2}\), ultimate tensile strength \(UTS\), elongation at rupture \(A\%\) and yield to tensile strength ratio \(R_{p,0.2}/UTS\).

|          | \(E\) [GPa] | \(R_{p,0.2}\) [MPa] | \(UTS\) [MPa] | \(A\%\) | \(R_{p,0.2}/UTS\) |
|----------|-------------|-------------------|----------------|--------|------------------|
|          | 133 ± 27    | 243 ± 20          | 524 ± 56       | 35 ± 14| 0.47 ± 0.03      |

In general, the results present a high variability (coefficients of variations between 0.06 and 0.4), especially in terms of elongation at rupture (as visible from Fig.7). Comparing the experimental values with traditionally-manufactured 304L stainless steel, the main discrepancy is evidenced in the Young’s modulus, for which almost 40% of reduction is registered. This reduction, however, is in line with the findings obtained on specimens extracted from WAAM stainless steel plates printed with the “continuous” strategy [10,11,15]. It is also important to notice the low values (on average 0.47) of the strength ratio \(R_{p,0.2}/UTS\), which evidences a significant hardening behaviour of the WAAM-produced rods, possibly related to the microstructure resulting from the dot-by-dot deposition process. Indeed, previous work on WAAM-produced plates using the same wire resulted in higher values of strength ratios, thus indicating lower strain hardening compared to the rods [10].

### 3.2.2 Compression tests

Compression tests have been performed on 14 rod specimens, with different lengths \(L\) (corresponding to slenderness ratios \(\lambda = i/L_{eff}\) from 0.30 to 1.70, with \(i\) equal to the cross-section radius of gyration and \(L_{eff} = kL\).
than their corresponding mean plastic force. As expected, the specimens with lowest slenderness ratio (i.e. stub rods) tested: (1) 4 specimens of \( L=45 \text{ mm} \) (corresponding to \( \lambda = 0.30 \), e.g. very stub), (2) 4 specimens of \( L=130 \text{ mm} \) (corresponding to \( \lambda = 0.85 \), e.g. stub), (3) 1 specimen of \( L=190 \text{ mm} \) (corresponding to \( t \lambda = 1.35 \), e.g. slender), (4) 5 specimens of \( L=250 \text{ mm} \) (corresponding to \( t \lambda = 1.70 \), e.g. very slender).

The values of the plastic capacity \( N_p \) and the critical Eulerian buckling load \( N_{cr} \) have been evaluated as:

\[
N_p = A_{eff} f_y
\]

\[
N_{cr} = \frac{\pi^2 E I}{L^2}
\]

The plastic capacity \( N_p \) has been evaluated considering the effective cross-sectional area \( A_{eff} \) taken from volume-based measurements (and also used for the tensile tests). The average 0.2% proof stress value from tensile tests has been considered as \( f_y \). Table 3 collects the main results in terms of average plastic capacity \( N_{p,av} \) and average ultimate capacity in compression \( N_{u,av} \) for the four main groups of specimens. The results are also reported in Figure 8.

Table 3 Results from compression tests on WAAM-produced stainless steel rods.

| Slenderness | \( L_{e} \) \([\text{mm}]\) | \( N_{p,av} \) \([\text{kN}]\) | \( N_{u,av} \) \([\text{kN}]\) | \( N_{p,av}/N_{cr} \) \([-\text{]}\) | \( N_{u,av}/N_{cr} \) \([-\text{]}\) | \( N_{p,av}/N_{u,av} \) \([-\text{]}\) |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Very stub   | 43 (0.28)     | 8.83           | 83.99          | 6.83           | 0.11           | 1.29           |
| Stub        | 128 (0.87)    | 4.57           | 8.66           | 6.49           | 0.53           | 0.70           |
| Slender     | 192 (1.38)    | 2.79           | 3.07           | 5.82           | 0.91           | 0.48           |
| Very slender| 255 (1.67)    | 1.50           | 2.53           | 7.01           | 0.59           | 0.21           |

Figure 7 Compression results for WAAM-produced stainless steel rods.

As expected, the specimens with lowest slenderness ratio (i.e. stub rods of \( \lambda = 0.28 \)) registered the highest ultimate force values \( (N_u) \), even higher than their corresponding mean plastic force \( N_p \). This result might be associated with the significant post-yielding hardening before failure, as evidenced from tensile tests. This aspect suggests the need of further investigations on the buckling behavior of WAAM-produced rods, with sophisticated advanced modelling tools able to account for both geometrical and mechanical features.

4 Current studies on buckling behaviour of WAAM-produced stainless steel rods

Current research is devoted to extend the results here presented in terms of (i) additional experimental tests conducted on rods with different end constraints (ii) development of numerical studies in order to explore the influence of the main parameters on the buckling behaviour and calibrate ad-hoc buckling curves for WAAM-produced rods. As such, two different sets of analyses are envisaged:

- Parametric studies on the buckling behaviour of WAAM-produced rods: specific numerical investigations on the influence of different geometrical (cross-sectional variation, lack of straightness) and mechanical (inhomogeneous stress field) parameters are developed. The results will be used to improve the knowledge from experiments on the buckling behaviour of the rods, towards the calibration of specific buckling curves for structural design and verification of WAAM-produced slender elements.

- Advanced Finite Element Modelling on “digital twins”: from 3D scan acquisition, detailed information on the geometrical irregularities is used to simulate the buckling behaviour of WAAM-produced rods. Specific material models will be calibrated from experiments on tensile tests to account for the mechanical properties of the printed rods.

The results from parametric and numerical investigations will be compared with the experimental results to draw first design guidelines for WAAM-produced stainless steel structures subjected to compression.

5 Conclusions

From the experimental characterization of WAAM-produced stainless steel rod-like elements, the following key findings can be summarized:

- In order to geometrically characterize the rods, detailed measurements on the diameter distribution (influenced by the surface roughness of the as-built specimens) are necessary. The specific results on the tested rods indicate a small discrepancy (3%) between the effective and the nominal diameter. A Non-negligible lack of straightness is also evidenced resulting in the order of 0.18% of the total length of the rod.

- From the tensile tests, it appeared that the mechanical behavior of dot-by-dot printed specimens is remarkably different with respect to the feedstock. In detail, the WAAM-produced rods are characterized by values of Young’s modulus of around 130 GPa, far less than the traditionally-manufactured stainless steel, although in line with the values estimated in literature for WAAM-produced plates. Moreover, a marked hardening behavior is registered, with strength ratio lower than 0.50.
The compression capacity of rods of different lengths has been obtained from the compression tests. The first results evidence the need for further studies on both the mechanical parameters in compression and the influence of the geometrical irregularities in the compression response of the printed rods.

On-going research is devoted to develop further experimental tests and numerical studies devoted to draw new buckling curves for WAAM-produced slender elements (through parametric studies which take into account both geometrical and mechanical parameters affecting the buckling behavior).

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