Performance under tensile loading of point-by-point wire and arc additively manufactured steel bars for structural components

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1. Introduction

Nowadays, digital design and fabrication are expanding the limits of architecture and structural engineering. In particular, additive manufacturing (AM) shows a large potential to produce high-performance structures by precisely controlling the placement of material only where it is required. Yet, AM technologies in construction face challenges on scalability since most suitable materials have limitations in terms of speed, cost and/or performance. New developments on steel AM exhibit a good trade-off in this regard. High strength material can be precisely deposited with the technology of point-by-point wire and arc additive manufacturing (WAAM) to produce custom structural components. Furthermore, by combining the degrees of freedom of a robotic arm and sensing techniques in the printing process, point-by-point WAAM can be used to design on-demand parts to fit varying or uncertain building conditions. Pushing this concept further, in this research, WAAM/AM is used as a joining technique particularly where adaptation, geometric complexity, and/or material minimization are needed.

The resulting in-place adaptive connections are considered especially advantageous in structures where complex fitting strategies are necessary for fixing neighbouring elements, as it is the case in freeform grid shells or spatial trusses. A simplification of the manufacturing requirements of steel parts, by reducing cutting operations and post-processing, would be possible by an adaptive joining with point-by-point WAAM.

A specific challenge of the application of point-by-point WAAM is that the printing of connections between existing elements requires flexibility on the orientation of the printing tool to avoid collisions, as can be observed from the examples in Fig. 1. This results in a large variety of printing conditions. Therefore, there is a need for understanding the implications of these geometric variations in the properties of the resulting material. This paper contributes with significant investigations related to the variety of printing conditions for understanding various properties (geometry, strength and stiffness, simulation possibilities) of the innovative application of steel and welding technology to produce...
in-place connections between steel elements for non-standard spa-
tral structures.

2. State-of-the-art review

General reviews on additive manufacturing applications in con-
struction show the potential and recent development of such pro-
duction technologies for different materials, including steel (see 
Buchanan & Gardner [1] and Paolini et al. [2]). WAAM is a metal 
additive manufacturing technology based on arc welding where a 
metal wire is melted to create three-dimensional parts layer-by-
layer (see Williams et al. [3]). The wire is fed, heated, melted, 
and transferred to the substrate with a certain motion to create a 
fused seam. Depending on the length of the deposited seam, the 
technique can be classified as continuous or discrete (also known 
as point-by-point or dot-by-dot) according to [4–7]. There are dif-
ter types of feeding, heating, transfer, and motion systems 
available, which depend on the given requirements, the part char-
acteristics and the metals used (see Wu et al. [8] and Frazier [9]). 
WAAM offers flexibility in the setup requisites, such as the possi-
bility to use low-cost conventional welding setups in non-
controlled environments while providing high deposition rates 
for the creation of small to large size parts according to Jin et al. 
[10]. This flexibility in the setup complexity and part size accompa-
nied by relatively fast deposition times has made WAAM a compet-
itive candidate for producing high-precision (Assunção et al. [11], 
complex (Ya & Hamilton [12]) or non-standard structurally-
sound AM steel components (Lange et al. [13]) and structures 
(Gardner et al. [14]). Most published research on WAAM is investi-
gating the applicability of this method to optimize the production 
and material distribution of structural elements or components. 
Examples for this are nodes in which several structural elements 
intersect at various angles (see examples in Buchanan & Gardner 
[1], Delgado Camacho et al. [15], Lange et al. [13] and Strauss 
et al. [16]) or more extreme cases like whole small pedestrian 
bridges such as the MX3D bridge in Amsterdam (see Gardner 
et al. [14]) or the on-site printed bridge in Darmstadt (see Lange 
et al. [13]).

As opposed to continuously depositing layers in the form of 
solid walls, discrete WAAM is performed point-by-point with 
intermediate cooling times to allow solidification between layers. 
This cooling technique allows building self-supporting bars that 
can be used as linear elements for reinforcement of concrete struc-
tures ([17–19]), in stand-alone networks ([17,20–23]), or lattice 
structures [24]. In the present study, the discrete self-supporting 
bars are used as a bridging strategy for joining non-touching parts 
during the assembly of steel elements as described by Ariza et al. in 
[5]. Further research was recently carried out to control the process 
parameters and path-planning strategies by Abe & Sasahara [24] 
and Heimig et al. [25] and to characterize the material of the dis-
crete bars built with different building directions by Müller et al. 
[17] and by Joosten [26]. However, the in-place joining method 
also requires a certain flexibility in the torch orientation to avoid 
collisions with the existing elements. This is provided by the high 
degrees of freedom of the robotic arm that supports the welding 
torch. While the manufacturing strategy has been described in 
Yu et al. [20] and Radel et al. [21], the potential effects of variable 
building directions combined with variable orientations of the 
torch on geometric variations and mechanical properties of the 
bars were not addressed before and require further investigations.

Geometrical measurements of components or specimens pro-
duced by WAAM are essential for understanding the actual geom-
etry and being able to consider it in later modelling and structural 
design of such elements. Generally, 3D scanning with professional 
instruments and subsequent evaluation of surface topology and 
cross-section variations is applied, as described for example by 
van Bolderen [4], Müller et al. [17], Joosten [26] or Laghi et al. 
[29,30]. For determining the mechanical properties of metals in 
general, the most common test is the uniaxial tensile test. For this 
type of tests on specimens produced by WAAM, two main different 
sample types can be found in the literature. In most past projects 
dealing with 3D-printing technologies for metals, flat samples are 
used, which are cut out of wall-type printed structures, either lon-
gitudinal to the layering direction or perpendicular to it (see for 
example Lange et al. [13], van Bolderen [4], Gu et al. [31], Qiu 
et al. [32], Buchanan et al. [33], Haden et al. [34] and Feldmann 
et al. [35], Kyvelou et al. [36]). Fewer projects investigate finger-
type samples produced by depositing the material point-by-point 
(see Müller et al. [17] or Joosten [26]).

Although investigating different materials (unalloyed steel and 
stainless steel), both Müller et al. [17] and Joosten [26] tested as-
printed WAAM-bars to evaluate their overall structural perfor-
mane as well as locally milled bars to assess mechanical tensile 
properties of the material without the effects of the imperfect 
geometry. The diameters of the as-printed bars were 5 to 8 mm, 
while the diameter of the milled bars was 4 mm. In terms of sim-
ulation of WAAM-printed components, available research results 
are very limited. However, existing pioneering projects are consist-
ent regarding the importance of considering the actual geometry 
and are aiming at introducing effective thicknesses for wall-type 
components (see Kühne et al. [28]) or effective diameters for bar-
type components (see Lozanovski et al. [27]).
A further challenge to date is the lack of a comprehensive modelling technique of process parameters for discrete WAAM that can predict deformations due to heat and gravity. Therefore, due to the variations in the build direction and torch orientation, the volume and shape of each deposited drop are, to a certain extent, unknown. To overcome this uncertainty, ongoing research investigates strategies to adaptively control the layer height (see Yu et al. [20]) and the location of subsequent drops (see Mechthechine et al. [18], Radel et al. [21] and Heimig et al. [25]). The present study employs a touch-sensing process after a certain printing length to determine the position of the last deposited drop and to re-adjust the location for the drops to follow. This is expected to affect the characteristics of the printed material due to a different cooling time at the measured interface and therefore needs a proper examination of this effect in the mechanical properties of the bars.

3. Materials and methods

Various methods ranging from 3D geometry scans to uniaxial tensile tests and finite element simulations were applied to characterize from different points of view the properties of the novel additively printed steel bars. Table 1 presents an overview of the performed test series, the number of investigated test specimens and the used nomenclature. In the following subsections, the printing of the WAAM-bars, the test specimens and the applied methodology are described.

3.1. Printing of the WAAM-bars

The experimental robotic welding setup was comprised of an ABB IRB 4600/40 robot, a Fronius TPS 500i Pulse power source, and a Fronius 60i Robacta Drive Cold Metal Transfer (CMT) torch with a 22° neck as shown in Fig. 2a. The substrate of the printed bars was 230 × 50 × 5 mm and was fixed to a stationary welding table of the size of a pallet (see Fig. 2).

The CMT standard process was used in all series. As shown by Müller et al. [17], this process allows for more precise control of the point-by-point deposition compared to GMAW thanks to the low heat input and current-free transfer.

The discrete point-by-point process consists of the deposition of a droplet of material on top of an already solidified droplet. Each iteration includes the following steps: (i) the robot moves to the target centre point of the droplet; (ii) a gas pre-flow is started; (iii) the arc process starts; (iv) while the arc process is on, the robot moves upwards at a certain welding speed in the build direction vector for a certain distance or seam height; (v) the arc process ends; (vi) a gas post-flow protects the weld as it solidifies, and (vii) an idle time lets the droplet to solidify. The process is repeated a certain number of iterations with a fixed layer height until a target height is reached.

The specimen bars were produced in groups of four to six specimens to use the cooling time between depositions for the production time of the next bar. The experimental setup does not record thermal changes, therefore the cooling time was set empirically, and as such, was not optimized to its minimum. This lack of control of the thermal state of the build led to a significant number of tests until the cooling time and the process parameters were set for the target diameter of ~8 mm for each of the series. The minimum cooling time per deposition is defined by the addition of the operation time for each of the following processes: the approach motion for each drop (2.5 s), the travel time between bars (1–1.5 s), the gas pre and post flow for each droplet (3.5 s), and the welding time per droplet (1 s), multiplied by the number of bars produced at once. As the mass of the build and the distance to the cooling plate increases, and consequently, the heat transfer speed changes over time, the cooling time needs to adapt layer by layer. This challenge was resolved by a fixed increase of the cooling time per layer of 0.15 s for all series. The minimum and maximum idle cooling time per droplet for each series are provided in Table 2.

The CMT standard setup allows controlling a large number of process parameters (see [38]). In the current study, the following welding process parameters were taken into account: wire diameter, wire feed speed (Wfs), current (I), voltage (U), arc-length correction, inclining value, start, slope and end current, and gas pre and post flow. Table 2 shows the welding parameters adapted for each of the series to meet a constant target diameter for all specimens. As the input and output values for current, voltage and wire-speed differ, Table 2 includes both the input parameter, the value defined in the job setting, and the output parameter, the recorded value during the experiment, for each of the series. The rest of the welding, geometric and motion parameters that were constant for all the series are shown in Table 3.

For specimens TS13 and TS14, the touch-sensing process was used at half of the length of the bar. The process consists of searching the coordinates of the top of the column with the steel wire used as a probe. During the search procedure, the wire is electrically charged, and the robot moves in a search path where the column is expected to be found. Once the wire touches the column, the electrical circuit is closed, the robot receives a stop signal, and the coordinates of the points where the top of the column is located are stored. The path is then adapted to fit the updated coordinates. The overall operation of measuring, adapting, and continuing printing took approximately four times longer than the idle time between depositions for the previous layer, and therefore it is expected to affect the properties at the interface.

Table 1 Overview of the performed uniaxial tensile test series.

| Test series | TS01a | TS02a | TS03a | TS04a | TS05a | TS06a | TS07a | TS08a | TS09a | TS10a | TS11a | TS12a | TS13a | TS14a |
|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Nozzle angle | 0°    | 0°    | 22.5° | 22.5° | 45°   | 45°   | 0°    | 0°    | 22.5° | 22.5° | 45°   | 45°   | 45°   | 0°    | 0°    |
| Build angle  | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    | 0°    |
| Surface type | as-printed | as-milled | as-printed | as-milled | as-printed | as-milled | as-printed | as-milled | as-printed | as-milled | as-printed | as-milled | as-printed | as-milled |
| Touch-sensing Number | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Geometry scan | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes | yes |
| Specimen nomenclature | TS01a | TS02a | TS03a | TS04a | TS05a | TS06a | TS07a | TS08a | TS09a | TS10a | TS11a | TS12a | TS13a | TS14a |

* The nozzle angle is the angle between the axis of the WAAM printing nozzle and the axis of the WAAM-bar (see also descriptive sketch in Section 3.2, Fig. 4).
* The build angle is the angle between a vertical axis (gravity) and the axis of the WAAM-bar (see also descriptive sketch in Section 3.2, Fig. 4).
* For these test series, additional tests to evaluate the corrosion resistance (wetting and drying cycles and local electrochemical mapping) and microscopic metallography analyses were carried out on bars printed with the same parameters. The results of these investigations can be found in Michel et al. [37].
For the point-by-point additively manufactured bars, the material Union SG 2-H was used. According to the datasheet [39], this is a solid wire for gas metal arc welding (GMAW) of unalloyed and low alloy steels. As for the shielding gas, a mixture of 20% carbon dioxide (CO₂) in pure argon (Ar), also known as M21, was applied with a constant flow of 16 L/m.

### 3.2. Description of the test specimens

The standards EN ISO 6892–1 [40] and DIN 50125 [41], as well as previously used test specimens for tensile tests on 3D printed steel bars from literature (e.g. Müller et al. [17] and Joosten [26]), were considered for the design of the test specimens. The test specimen of Type A according to DIN 50125 [41] was used as an orientation. As results of the uniaxial tensile tests, on the one hand, the evaluation of the mechanical behaviour for the as-printed bars with an irregular surface was of interest. On the other hand, for determining mechanical properties like Young’s modulus or yield and ultimate strength, a specimen exhibiting a constant cross-section area along a predefined bar length was necessary. This resulted into two different specimen types:

(i) **as-printed** WAAM-bars welded by robot to cylinders made of structural steel S355 with a diameter of 30 mm and

(ii) **locally milled** WAAM-bars without any cylinders. These types of specimens were determined as the result of preliminary tests. In this way, the risk for failure outside the desired area was minimized and the required effort for manufacturing the specimens was reduced. Fig. 3 illustrates the geometry and dimensions of the tensile test specimens. For all as-printed bars, a target diameter of 8 mm was aimed, while for all milled bars the cross-section was reduced to a constant diameter of 5.5 mm over a length of 35 mm. Furthermore, the cylinders used for the as-printed bars were milled on two sides, over a length of 40 mm, to a width of 20 mm to fit the clamping jaws of the testing machine.

### Table 2

| Series     | Number of bars printed as a group | Minimum idle cooling time per droplet (first layer) [s] | Maximum idle cooling time per droplet (last layer) [s] | Input process parameters | Output process parameters |
|------------|----------------------------------|--------------------------------------------------------|-------------------------------------------------------|---------------------------|--------------------------|
| TS01–TS02 | 5                                | 41                                                     | 66.5                                                  | Current I [A] | Voltage U [V] | Wfs [m/min] | Welding time [s] | Current I [A] | I median [A] | Voltage U [V] | U median [V] | Wfs median [m/min] |
| TS03–TS04 | 6                                | 49                                                     | 74.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.2              | 87–120       | 116          | 11–15  | 12.7          | 2.4              |
| TS05–TS06 | 4                                | 33                                                     | 58.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.3              | 109–138      | 127          | 11–15  | 13.1          | 2.4              |
| TS07–TS08 | 4                                | 33                                                     | 58.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.2              | 85–118       | 106          | 11–14  | 12.5          | 2.0              |
| TS09–TS10 | 4                                | 33                                                     | 58.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.2              | 81–114       | 104          | 11–14  | 12.5          | 2.0              |
| TS11–TS12 | 4                                | 33                                                     | 58.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.3              | 100–123      | 115          | 11–14  | 12.7          | 2.4              |
| TS13–TS14 | 4                                | 33                                                     | 58.5                                                  | 129                                      | 13.9                  | 3.5               | 1.1–1.2              | 84–119       | 108          | 11–14  | 12.4          | 1.8              |

**Table 3**

| Wire diameter [mm] | Layer height [mm] | Seam height [mm] | Welding speed [mm/s] | Arc-length correction | Inching value [m/min] | Starting current [%] | Start current time [s] | Slope 1 and 2 [s] | End current [%] | Gas pre flow [s] | Gas post flow [s] |
|--------------------|-------------------|------------------|----------------------|-----------------------|-----------------------|----------------------|----------------------|------------------|----------------|------------------|------------------|
| 1.2                | 1.0               | 1.0              | 1.0                  | -4                    | 3.0                   | 135                  | 0.2                  | 1.0              | 50             | 0.5              | 3                |

For the point-by-point additively manufactured bars, the material Union SG 2-H was used. According to the datasheet [39], this is a solid wire for gas metal arc welding (GMAW) of unalloyed and low alloy steels. As for the shielding gas, a mixture of 20% carbon dioxide (CO₂) in pure argon (Ar), also known as M21, was applied with a constant flow of 16 L/m.
For the envisioned applications presented in the introduction, the nozzle angle and the build angle (see descriptive sketches in Fig. 4) will most certainly vary depending mainly on accessibility to the parts to be connected. Therefore, the influence of these parameters on the geometry and the mechanical performance of the bars was assessed by including (i) test series with a nozzle angle of 22.5° and 45° additional to 0° as well as (ii) test series with a build angle of 45° additional to that of 0°. For all of these series, both as-printed specimens and milled specimens were tested (see overview in Table 1).

For the WAAM printing process, a target layer thickness has to be defined. Several input parameters influence how much the real layer thickness varies from the defined target value. In the case of longer bars and especially in the case of build angles differing from 0°, deviations from the target layer thickness require including so-called touch-sensing steps in the printing process (see Section 3.1). However, such a touch-sensing step means an interruption of the printing process and might have an influence on the properties of the material within the touch-sensing layers. To analyse this influence, two additional test series were added (TS13 and TS14 in Table 1), for which a touch-sensing step was included approximately in the middle of the assumed original gauge length of the bars.

3.3. Applied methodology

3.3.1. Geometry measurements

The point-by-point WAAM-bars exhibit, due to the manufacturing process, strongly irregular surfaces and implicitly varying cross-section areas along their length. To characterize this geometry and to be able to relate failure patterns from the tensile tests to it, a 3-dimensional (3D) measurement resulting in a 3D mesh or a 3D point cloud is necessary. The optical 3D scanner ATOS Core from GOM with the corresponding scan software was used for the measurements within the current investigations. Only the as-printed test specimens were measured, since for the milled specimens the variation of the cross-section area and implicitly of the target diameter of 5.5 mm along the length was considered negligible. In order to evaluate the meshes obtained by the 3D measurement, firstly, eventually occurring holes in the mesh were closed and the mesh was aligned in space with the freeware GOM Inspect [42]. Secondly, the mesh was imported to the software Rhinoceros 3D [43], where the cross-section area in a large number of sections along the length of the bar as well as various fictive diameters and radiiuses in these sections were calculated with the help of a Grasshopper script. Fig. 5 depicts the workflow applied for geometry measurements and their evaluation.

Additionally, one can also assess the closeness to the rotational symmetry of the 3D-printed bars as well as the eventual variation in smoothness (depth of crevices between layers) depending on the nozzle and build angle by comparing fictive diameters and radiiuses from the defined sections in specific directions. Fig. 6 illustrates which diameters and radiiuses were evaluated to characterize these aspects.

3.3.2. Uniaxial tensile tests

The uniaxial tensile tests were performed on a Zwick universal testing machine able to apply loads up to 200 kN. The tests were carried out in a conditioned room at 23 °C and 50% relative humidity. The specimens were clamped on each side over a length of 40 mm. Fig. 7a shows the whole test setup. For the specimens with as-printed surfaces and those with milled surface different clamping jaws were used, because of the different geometry of the specimens. The load was applied displacement-controlled with a constant displacement rate of 0.01 mm/s. This displacement rate was determined according to method A2 from EN ISO 6892-1 [40] and corresponds to a strain rate of 0.0002 s⁻¹ ± 20% for both the specimens with as-printed surfaces and those with milled surfaces. This strain rate or the corresponding displacement rate can be used for the entire tensile test until fracture according to [40]. First, three load cycles were completed up to approximately 2/3 of the expected yield strength (to a load of 6 kN for the specimens with milled surfaces and a load of 12 kN for the specimens with as-printed surfaces). Afterwards, the specimens were tested to failure.

In addition to measurements of the applied load and the traverse displacement of the machine, a touching extensometer with sharp callipers was used to measure the elongation over the predefined initial gauge length. Moreover, a digital image correlation...
A DIC system capable to measure strains in a predefined area of the specimens was used. A field of view with a height of approximately 80 mm was used for both specimen types. To allow the DIC-measurements, a speckle pattern was sputtered on the specimens (see example in Fig. 7c). The field of view was first sprayed with an acrylic matt white paint and afterwards, black ink was applied with an airbrush, procedure that allows reaching very small irregularly distributed dot sizes. Generally, a dot size of approximately five pixels should be aimed, which results for the desired field of view and a camera with a resolution of 12 MP to a dot size of approximately 0.1 mm. For capturing and evaluating the images, the VIC-3D 8 system from Correlated Solutions, Inc. was used.

The Young’s modulus was determined based on measurements from the three load cycles performed in a first step. For the failure cycle, the touching extensometer was removed during the hardening phase of the specimens to avoid its potential damage during fracture of the specimens. Therefore, strain values could be determined only up to a certain displacement based on measurements with both the touching extensometer and the DIC-system. After passing this displacement, only the measurements with the DIC-system could be used.

3.3.3. Model characteristics for finite element simulations

Based on the material properties evaluated from the uniaxial tensile tests on WAAM-bars with milled surfaces, a material model for the 3D-printed steel was derived. This material model was then applied and validated in finite element simulations of the performed tensile tests on WAAM-bars with as-printed surfaces. For the simulations, the computer-aided engineering (CAE) software Abaqus [44] was used. Only the part of the bars in which strain measurements were carried out was considered in the model (L₀ = 35 mm).

For the material, elastic and plastic properties were defined. The elastic properties include a Young’s modulus of E = 195,000 MPa, assumed according to the results of the performed uniaxial tensile tests on specimens with milled surfaces, and a Poisson’s ratio of ν = 0.30, which is the generally assumed value for structural steels.

For the plastic properties data pairs of yield stress and plastic strain as true values are necessary as input for the software. The true yield stress values σ_true can be determined with Eq. (1), where σ_eng is the engineering stress value, e_eng is the engineering strain, F is the recorded force, A₀ is the initial cross-section, L₀ is the initial gauge length and ΔL is the elongation:

\[
\sigma_{\text{true}} = \sigma_{\text{eng}} \left( 1 + e_{\text{eng}} \right) = \frac{F}{A_{0}} \left( 1 + \frac{\Delta L}{L_{0}} \right)
\]  (1)

The true plastic strain values ε_true,pl can be determined with Eq. (2) by subtracting the true elastic ε_true,el strain from the total true strain ε_true (all other used variables were already described above):

\[
\varepsilon_{\text{true,pl}} = \varepsilon_{\text{true}} - \varepsilon_{\text{true,el}} = \ln \left( 1 + e_{\text{eng}} \right) - \frac{\sigma_{\text{true}}}{E}
\]  (2)

The data pairs used as input for the simulations of the uniaxial tensile tests on the 3D-printed steel bars are provided in Table 4. These data pairs were determined to fit the average values of the true stress vs. true plastic strain curves determined for the specimens with milled surfaces as illustrated by the diagram in Fig. 8. The true stress values after passing a true plastic strain of 0.5 were determined with the fitted power-law equation \( \sigma_{\text{true}} = 864 \times \varepsilon_{\text{true}}^{0.22} \). This procedure was proposed by Hollomon [45] and is often used to extrapolate true stress values after initiation of necking (see Tu et al. [46]).
A challenge in performing FE-simulations for components with extremely irregular geometry as the bars with as-printed surface is the generation of a suitable finite element mesh. To obtain a solid that can be meshed in Abaqus, the extremely irregular triangulated mesh obtained from the performed 3D-scans was approximated with a more regular quad mesh. The derivation of the quad mesh was carried out with a Grasshopper script in the software Rhino-keros 3D [43]. The resulting quad surface was closed at the two bar ends to be watertight and was subsequently exported to Abaqus, where the solid enclosed by this surface could then be meshed. 8-node linear brick elements with reduced integration and enhanced hourglass control (C3D8R) were used for the mesh in Abaqus. The mesh size was chosen to be approximately 0.5 mm as the result of a convergence study. Fig. 9 illustrates the steps of the workflow for obtaining a solid, which can be meshed in Abaqus.

For the application of the boundary conditions and the loading, two reference points are used (see Fig. 9). The reference points are connected with rigid body constraints to the solid, one to each of the two end surfaces. For the reference point at the bottom of the specimen, all translational and rotational degrees of freedom are restrained. For the reference point at the opposite end, all rotational degrees of freedom and the two translational degrees of freedom, which are perpendicular to the axis of the column, are restrained. Furthermore, on this reference point the loading is applied displacement-controlled with 0.01 mm/s, similar to the way the displacement was applied during the testing described in Section 3.3.2.

4. Results and discussion

In the following subsections, the results from the different performed investigations are presented and correlations between the findings are emphasized where reasonable.

4.1. Geometry evaluation

The irregular surface geometry of the WAAM-bars with the as-printed finish is a significant characteristic of these novel steel components, which can have an important influence on the structural performance of such bars. The surface irregularity can be characterized by evaluating the variation of cross-section area and fictive diameters along the length of the bars. The diagrams in Fig. 10 illustrate the variation of the cross-section area along a length of L = 40 mm (the part between the welds to the cylinders) for the various investigated test series. The cross-section area corresponding to the targeted diameter of 8 mm averages 50.27 mm².

From the diagrams in Fig. 10 one can notice, that the cross-section area of the WAAM-bars varies slightly stronger for the bars printed with a build angle of 0° (TS01, TS03, TS05 and TS13)
compared to those printed with a build angle of 45° (TS07, TS09 and TS11). Furthermore, it can be observed that the bars printed with a build angle of 0° and a nozzle angle of 0° (TS01 and TS13) exhibit the strongest variation along the WAAM-bar length. These observations prove that the studied build and nozzle angles have an influence on the way the material is deposited. In the case of the bars with a touch-sensing (TS13), the position of the sensing layer can be identified by the position of the smallest cross-section area, approximately in the middle of the bars. Beside the different nozzle and build angles, the slightly adapted input parameters (see Table 2) might also have a small influence on the variation of the cross-section area along the WAAM-bar length. However, by comparing the geometry results for TS01 and TS13, which were produced with the same nozzle and build angles, but with slightly different process parameters, no significant differences can be noticed.

In addition to the variation of the cross-section area along the length of the bars presented in Fig. 10, Table 5 provides minimum, maximum and mean values along with the standard deviation for the cross-section area and a fictive diameter, for each of the test series on WAAM-bars with the as-printed surface finish. The fictive diameters are calculated as mean values of eight measured distances, at every 22.5° in every cross-section. To ensure that significant values are included, the cross-section area and the fictive diameters are evaluated every 0.1 mm along a length of 40 mm.

The values provided for the cross-section areas in Table 5 confirm the observations discussed based on the diagrams in Fig. 10. Moreover, the fictive diameter values also substantiate these observations. The WAAM-bars printed with a build angle of 0° and a nozzle angle of 0° (TS01 and TS13) show the highest values of the standard deviation both for the area and for the fictive diameters. Analysing the diameter values, one can observe that for some series the deviation from the target value is higher than for others. At the same time, for some series the mean values are lower than the target value, while for other series the opposite is the case. These deviations could be further optimised by modifying printing parameters and by better understanding the temperature development during printing. However, certain deviations will always be present and their consideration will be necessary when designing with such components in the future.

The evaluated diameters do not directly allow characterizing the printed steel-bars in terms of rotational symmetry. However, one could observe with the naked eye, that printing with nozzle angles other than 0° for a build angle of 0° results in slightly elliptical cross-sections. This observation can be evaluated by comparing the development of two specific fictive diameters perpendicular to each other, the first one in the direction of the varied nozzle angle and the second one perpendicular to it. The variation of these two diameters along the length of the bars is shown as an example for TS01b and TS05b in Fig. 11. It can be noticed that due to an inclined nozzle while printing, the cross-section of the 3D-printed bars changes from an almost circular shape to an elliptical shape. For the nozzle angle of 45°, the differences between the two diameters can reach up to around 0.7 mm. This aspect is less important for bars subjected to tensile forces, as those discussed in this paper, but might have an increased significance when compressive forces or bending play a role. Similar discrepancies for different nozzle angles could not be observed in the case of a build angle of 45°.

Furthermore, a variation in the smoothness of the as-printed WAAM-bar surfaces in the different orientations could be observed depending on the build angle and the nozzle angle. This variation was best visible in the case of the bars printed with a build angle of 45° and a nozzle angle other than 0°. The upper surface of the bars printed at a build angle of 45°, which was also the surface towards which the nozzle angle was inclined to, had a smoother surface than the lower one. Fig. 12a shows this variation for TS09b as an example. To interpret the angles of 0° and 180° the sketch in Fig. 6 should be used. The fictive radii used for the evaluation are measured from a defined centre axis and should only be considered for a qualitative assessment. The variation of smoothness on different sides of the bars can be as well noticed in the picture of TS09b shown in Fig. 12b.

A build angle other than 0° has the consequence, that the layering is not anymore perpendicular to the axis of the bars, but at an oblique angle to it. This can be observed by comparing, for example, the specimen TS09b shown in Fig. 12b and TS03b shown in Fig. 12c.

4.2. Uniaxial tensile test results

In these test series, the focus was set on evaluating the load-displacement and the stress-strain relationships as well as mechanical properties like yield strength, tensile strength or Young’s modulus for the novel WAAM-bars. A special interest was to assess whether the varied parameters (nozzle angle, build
angle and the use of touch-sensing) have an influence on these relationships and properties as well as to characterize the size of the generated variations.

Fig. 10. Variation of the cross-section area along a length of $L = 40$ mm of the 3D-printed bars with the as-printed surfaces (between the welds to the two cylinders).

Fig. 13 provides an overview of load-displacement curves obtained for both the WAAM-bars with as-printed surfaces (diagrams on the left) and those with milled surfaces (diagrams in
Table 5
Measured cross-section area and fictive diameter values for the WAAM-bars with the as-printed surfaces.

| Target value | Evaluated parameter | TS01 | TS03 | TS05 | TS07 | TS09 | TS11 | TS13 |
|--------------|---------------------|------|------|------|------|------|------|------|
| Area         | Minimum value [mm²]  | 47.02| 44.63| 49.97| 45.62| 41.25| 50.13| 42.25|
|              | Maximum value [mm²]  | 59.00| 56.12| 58.52| 52.16| 50.41| 54.92| 56.68|
|              | Mean value [mm²]     | 53.58| 51.96| 54.81| 48.74| 46.96| 52.34| 50.83|
|              | Standard deviation [mm²] | 2.37 | 1.70 | 1.54 | 1.26 | 1.48 | 1.40 | 2.47 |
| Fictive diameter | Minimum value [mm]  | 7.63 | 7.41 | 7.75 | 7.50 | 7.10 | 7.83 | 7.19 |
|              | Maximum value [mm]   | 8.87 | 8.60 | 8.79 | 8.23 | 8.13 | 8.53 | 8.04 |
|              | Mean value [mm]      | 8.25 | 8.12 | 8.35 | 7.87 | 7.72 | 8.13 | 8.04 |
|              | Standard deviation [mm] | 0.21 | 0.14 | 0.13 | 0.12 | 0.15 | 0.11 | 0.21 |

(a) as-printed surface | nozzle angle 0° | build angle 0° | no touch-sensing
(b) as-printed surface | nozzle angle 45° | build angle 0° | no touch-sensing
(c) Oblique layering in TS09b
(d) Perpendicular layering in TS03b

Fig. 11. Variation of two perpendicular fictive diameters along a length of 40 mm of the WAAM-bars with as-printed surfaces for the test specimens TS01b with a nozzle angle of 0° (a) and TS05b with a nozzle angle of 45° (b) to illustrate the different cross-section shapes depending on the nozzle angle for a build angle of 0°.

Fig. 12. Diagram illustrating the variation in smoothness on different sides of the WAAM-bar TS09b (a), image of TS09b showing this variation and the oblique angle between layering and axis of the WAAM-bar (b) and image of TS03b showing the perpendicular angle between layering and axis of the WAAM-bar observed for build angles of 0°.
the middle) as well as stress-strain curves determined for the WAAM-bars with milled surfaces (diagrams on the right). The results for the test series on specimens produced with a nozzle angle of 22.5°, which are not included in Fig. 13, are consistent with the other series. For the load-displacement relationships, curves with the traverse displacements are plotted in black for both the specimens with as-printed surfaces and those with milled surfaces. Since these curves include movements and slippages within the machine, curves with the displacements measured with the touching extensometer are added for the specimens with as-printed surfaces, while for those with milled surfaces curves with the displacements measured with the DIC system are included. It was avoided to add curves with DIC measurements for the specimens with as-printed surfaces since results could not be evaluated over the whole test length for all specimens due to early cracks in the applied paint for part of them (see Fig. 16b). It can be observed, that both the specimens with as-printed surfaces and those with milled surfaces exhibit newly textbook-like curves with a linear-elastic part, a yielding plateau, strain hardening and necking before failure. The yielding plateau is more pronounced in the case of the milled specimens, but can be as well identified for the bars with the as-printed surface.

Generally, a good consistency can be observed between the curves plotted for specimens from the same test series, both for the milled specimens and for those with as-printed surfaces, until reaching the ultimate load or stress, respectively. Some discrepancies can be noticed in terms of the displacements or strains, respectively, after passing the maximum load/stress. Reasons for these differences can be either the variation in initial cross-section area of the necking zone or material structure aspects, like for instance the existence and density of local voids. However, results from microscopic metallography analysis of WAAM-bars from the same manufacturing batches show a homogeneous material structure along the length of the WAAM-bars, including the zones between layers of point-by-point deposited material, with no clearly recognisable local voids. A representative microstructure image is shown in Fig. 14 and additional images are included in Fig. 20 of Appendix A. The microstructure images were obtained with a Leica M60 optical microscope from polished sections of longitudinally cut WAAM steel bars. More details on the microstructure analysis can be found in Michel et al. [37].

For the specimens with milled surfaces, a good agreement can be observed as well between the curves plotted for specimens from different test series. This aspect is valid qualitatively, but also quantitatively in terms of ultimate load, yield strength, Young’s modulus, etc. (see also Table 6). This observation is important for future investigations and applications since it proves that the varied nozzle angles, build angles and the use of touch-sensing do not have a significant influence on the mechanical behaviour of the WAAM-bars, other than the different surface geometry. The influence of the latter one can be assessed by comparing the load-displacement curves for the specimens with as-printed surfaces in Fig. 13. A strong difference in terms of the displacement at ultimate load and displacement at failure is shown by the specimens with touch-sensing. The significantly lower values for these displacements are related to the smaller cross-section area at the position of the touch-sensing layer and the consequent more locally concentrated plastic strains. Such large cross-section reductions should be avoided since they lead to a lower global ductility of the bars. If influences of the touch-sensing layers cannot be excluded, the design should consider the positioning of these layers in areas with reduced stress concentrations.

Table 6 provides selected test results and mechanical material properties determined as mean values from the test series on WAAM-bars with milled surfaces. Furthermore, the determined mean values and standard deviations of these parameters over all test series on milled specimens are included. These values confirm the rather small variations between the different series already observed in the diagrams from Fig. 13. The Young’s modulus values were determined as a secant modulus between 10% and 50% of the upper yield strength. Furthermore, an average between the values determined in the second and the third loading cycles was calculated. For the Young’s modulus, a value of approximately 195’000 MPa and for the yield strength a value of around 360 MPa are assumed for the point-by-point printed WAAM-bars based on these results. Both of these values could be also chosen slightly lower considering the given standard deviations. However, the performed finite element simulations showed a better overall agreement with these values.

The variation of selected test results and mechanical material properties for the specimens with as-printed surfaces is slightly larger, as shown by the values provided in Table 7. These variations are mainly influenced by the variation of the cross-section area along the length of the bars. It is expected that by further investigations on the parameters that influence the WAAM-process (e.g. layer height, idle time between printing layers, resulting temperatures, etc., see also Section 3.1), the standard deviation of the cross-section area and implicitly of other values could be further diminished.

A significant property of the point-by-point WAAM-bars, which is illustrated both by the diagrams in Fig. 13 and by the displacements at failure and the failure strains given in Table 6 and Table 7 is the ductility of elements produced in this novel manner. The reached strain values are very suitable for structural applications.

The Young’s moduli given in Table 6 and Table 7 were determined from the touching extensometer measurements, since the DIC measurements for strains in the linear-elastic part, generally, exhibited too much noise (see diagram in Fig. 15a). For evaluation of the stress-strain behaviour in the plastic part, however, the DIC measurements are in good agreement with the touching extensometer measurements (see diagrams in Fig. 15b and c) and are considered exact enough for deriving input data for finite element simulations. This agreement is valid for both the milled bars and those with as-printed surfaces as long as the paint does not exhibit significant cracks.

The pictures in Fig. 16 show one specimen with milled surface and one with as-printed surface at different stages during testing. From the two pictures illustrating the specimens before failure, it can be observed that both specimen types exhibited necking. The failure occurred for all specimens within the initial gauge length. For the bars with milled surfaces, the failure point was situated at different spots along this length. The point at which the necking and consequently the failure occur might depend in this case on very small variations of the cross-section area and the material structure. In the case of the bars with as-printed surfaces, the failure was generally situated in points with smaller cross-section areas. However, not in all cases, the failure point matched the smallest measured cross-section area, since material structure aspects and surface smoothness might also have an influence in this case. From the pictures in Fig. 16, one can also observe, that the white paint applied as a background for the speckle pattern adhered well on the milled specimens, but exhibited cracks in the case of the bars with as-printed specimens. This resulted in limited DIC measurement results for the specimens with as-printed surfaces. To improve this aspect in further experiments, potential solutions might be a different, more elastic paint, a more thorough cleaning of the surfaces or the application of a primer.

4.3. Finite element simulations

Based on the results of the tensile tests on milled WAAM-bars, data for an elastic-plastic material model was proposed in
Fig. 13. Load vs. displacement diagrams for the WAAM-bars with as-printed surfaces (left), load vs. displacement diagrams for the WAAM-bars with milled surfaces (middle) and engineering stress vs. engineering strain diagrams for the WAAM-bars with milled surfaces (right), for selected test series.
Valley between two deposited WAAM-layers

Fig. 14. Representative microstructure image for a point-by-point WAAM-bar: (a) location of the microstructure image on the WAAM-bar of series TS01 (a) before and (b) after its longitudinal cut and (c) detailed optical microscopy image of a zone between two layers of point-by-point deposited material showing a homogeneous distribution of ferrite and perlite grains.

Table 6
Test results and mechanical material properties as mean values for the different WAAM-bars with milled surfaces.

| Evaluated parameter | Unit | TS02 | TS04 | TS06 | TS08 | TS10 | TS12 | TS14 | Mean value | Standard deviation |
|---------------------|------|------|------|------|------|------|------|------|------------|-------------------|
| Measured diameter   | d₀   | [mm] | 5.68 | 5.66 | 5.73 | 5.63 | 5.66 | 5.67 | 5.61       | 5.66              |
| Max. load           | F₀   | [kN] | 12.28| 12.28| 12.78| 12.35| 12.17| 12.17| 12.21      | 12.32             |
| Corr. displacement  | uₐ   | [mm] | 9.04 | 8.88 | 10.31| 9.32 | 9.33 | 9.53 | 9.55       | 9.42              |
| Max. displacement   | uₐ   | [mm] | 13.32| 12.60| 14.47| 13.07| 13.32| 13.69| 13.69      | 13.45             |
| Upper yield strength | Rₑ   | [MPa]| 485.25| 487.90| 496.03| 496.10| 484.42| 481.93| 493.87      | 489.36            |
| Corr. strain        | εₑ   | [%]  | 18.78| 18.38| 19.84| 20.08| 19.62| 20.48| 19.76      | 19.56             |
| Failure strain      | εₑₘ  | [%]  | 32.44| 30.54| 33.67| 31.52| 32.83| 33.70| 33.58      | 32.61             |
| Young's modulus     | E    | [MPa]| 192'905| 193'364| 194'102| 196'206| 194'705| 208'115| 203'315    | 197'531           |

a The provided values for the elongation corresponding to the maximum load are the measured traverse displacements. This way, a comparison between the milled bars and those with the as-printed surface is possible.

Table 7
Test results and mechanical material properties as mean values for the different WAAM-bars with as-printed surfaces.

| Evaluated parameter | Unit | TS01 | TS03 | TS05 | TS07 | TS09 | TS11 | TS13 | Mean value | Standard deviation |
|---------------------|------|------|------|------|------|------|------|------|------------|-------------------|
| Mean area           | Aₐ   | [mm²]| 53.58| 51.96| 54.81| 48.74| 46.96| 52.34| 50.83      | 51.32             |
| Min. area           | Aₐₘ  | [mm²]| 47.85| 47.08| 51.08| 46.15| 43.15| 50.23| 43.59      | 47.02             |
| Max. load           | F₀   | [kN] | 25.43| 24.77| 26.67| 23.51| 22.07| 24.90| 23.09      | 24.35             |
| Corr. displacement  | uₐ   | [mm] | 9.04 | 8.78 | 8.42 | 9.67 | 8.42 | 9.64 | 7.06       | 8.72              |
| Max. displacement   | uₐ   | [mm] | 13.50| 12.43| 11.96| 13.45| 11.42| 14.24| 9.39       | 12.34             |
| Upper yield strength | Rₑ   | [MPa]| 349.28| 350.28| 357.64| 351.24| 346.49| 343.72| 327.14     | 346.54            |
| Young's modulus     | E    | [MPa]| 193'871| 202'841| 204'802| 210'022| 212'670| 208'139| 205'888    | 206'605           |

a The provided values for the elongation corresponding to the maximum load are the measured traverse displacements. This way, a comparison between the milled bars and those with the as-printed surface is possible.
b The upper yield strength and the Young's modulus values were determined in the case of the WAAM-bars with the as-printed surface based on the mean area of the bars. This is done only to allow a comparison to the values for the milled bars.

Fig. 15. Comparison between stress–strain curves determined based on displacements measured with the touching extensometer and such based on displacements measured by digital image correlation exemplified for (a) a milled bar under elastic load cycles, (b) a milled bar loaded to failure and (c) a bar with as-printed surface loaded to failure.
Section 3.3.3. In this subsection, the material model is validated by evaluating results of finite element simulations for WAAM-bars with as-printed surfaces. Results for the test specimens TS05b (see Fig. 17) and TS11b (see Fig. 18) are shown in this contribution since, for these specimens, measurement data until failure was available from the DIC measurements and their load–displacement curves are slightly different from each other. Additionally to load–displacement curves, approximate Mises true stress distributions at yielding, at maximum load and at failure are evaluated.

Fig. 17a and Fig. 18a show load-displacement curves from the tests (grey curves) and simulations with the scanned geometry (continuous black curves). The simulation results are in good agreement with the experimental ones, showing only small deviations. Therefore, it can be stated that the load capacity of WAAM components and occurring stresses within such elements can be well predicted if the actual geometry is known. The diagrams in Fig. 17a and Fig. 18a also include simulation results obtained with a cylindrical geometry with a diameter of 8 mm (dashed black curves), which was the initial target diameter, and with the measured mean diameter for the respective specimen (dash-dotted black curves). The simulation results show that the best overall agreement with the experimental results is achieved by using the actual geometry in the model. However, if only the behaviour until reaching the yielding strength or the ultimate strength is of interest, which is the case for most structural design cases, a model based on a fictive diameter might be sufficient.

The Mises stress distributions in Fig. 17b–d and Fig. 18b–d exhibit irregularities already before reaching the yielding stress. This is easily understandable based on the valleys on the as-printed surface, which generate stress peaks. The stress distributions plotted in Fig. 17c and Fig. 18c at ultimate load, already suggest the area in which the necking and implicitly the failure will occur for the bars with as-printed surfaces.

Fig. 19 shows how well the simulations using the derived elastic-plastic model predict the position of failure in the WAAM-bars with as-printed surfaces. These results are illustrated here for five representative specimens, but this agreement was consistent for all WAAM-bars with as-printed surfaces. Although one would have expected an effect of the layered manufacturing method on the orientation of the fracture planes, no systematic consistency was observed for this in the conducted investigations (see for example Fig. 19b and d).

The FE simulation results presented here demonstrate that the structural behaviour of WAAM components with the investigated steel can be well predicted with an elastic-plastic material model. The assumption of a homogeneous material structure, despite the novel, non-conventional production method, is sustained by the microscopic metallography results in Michel et al. [37]. Therefore,
an elastic-plastic material model should be sufficient for common structural design tasks.

5. Conclusions

The presented findings on the properties of robotically manufactured WAAM-bars made of steel provide a strong and promising basis for further development of and investigations on novel connections between custom oriented steel profiles. Other than previous studies, this contribution set the focus on different build and nozzle angles, which are necessary and of high significance for robotically realizing the above mentioned connections. The following conclusions can be drawn based on the discussed results:

- Depending on the used build and nozzle angles and the applied printing process parameters, the cross-section area varies locally from the targeted value by up to ± 18%. A reduction of these deviations could be achieved by a better understanding of the heat development during printing and consequently adapting the printing parameters.

- Different build and nozzle angles, as well as the use of touch-sensing, have only insignificant influence on the material structure as indicated by the small variation of the material properties determined for milled WAAM-bars under uniaxial tension. The results of the microscopy analysis shown in this paper and presented in more detail by Michel et al. in [37] sustain this.

- The material properties of robotically produced point-by-point WAAM-bars can be classified based on determined strength values as similar to those of the structural steel S355. The recorded strain values substantiate a ductile behaviour of the WAAM-bars under tensile loading.

- The uniaxial tests on bars with as-printed surfaces demonstrate a ductile and well-performing overall structural behaviour, yet also show that locally reduced cross-sections lead to lower reachable maximum loads as well as to smaller total displacements at failure, which subsequently translates into lower global ductility of the bars. This fact may have significant implications for design procedures to be developed for such structural elements fabricated by WAAM and applied in civil structures.
The proposed elastic-plastic material model is suitable for predicting the structural behaviour of WAAM-bars with the as-printed surface over the entire strain range, including the position at which the failure would occur. The good agreement between simulation results and experimental ones confirms this.

Future investigations on WAAM-bars need to address the optimization of the point-by-point WAAM-process, while maintaining the promising mechanical properties, and the characterization of the fracture behaviour in more detail. Considering the aimed application of point-by-point WAAM-bars for joints consisting of several such elements between structural steel profiles, the suitability of the proposed material model for predicting the structural behaviour of more complex geometries also needs to be verified in future research steps.

6. Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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CRediT authorship contribution statement

Vlad-Alexandru Silvestru: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Project administration. Inés Ariza: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Project administration, Funding acquisition. Julie Vienne: Formal analysis, Investigation. Lucas Michel: Writing - review & editing. Asel Maria Aguilar Sanchez: Investigation, Writing - review & editing. Ueli Angst: Conceptualization, Writing - review & editing, Supervision, Project administration. Romana Rust: Writing - review & editing, Supervision, Funding acquisition. Fabio Gramazio: Supervision. Matthias Kohler: Supervision. Andreas Taras: Conceptualization, Writing - review & editing, Supervision.

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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Appendix A. Microstructure images

The representative microstructure image provided in Fig. 14 for TS01 is supplemented in Fig. 20 with microstructure images for specimens from series TS05, TS07, TS11 and TS13. These additional images validate once more the assumption of a homogeneous material, which was made for the finite element simulations.
Fig. 20. Locations of microstructure images and detailed optical microscopy images for point-by-point WAAM-bars produced with different nozzle angles and build angles: (a) TS05, (b) TS07, (c) TS11 and (d) TS13.
