

Diamond-shaped lattice steel structural elements realized with Wire-Arc Additive Manufacturing: Fabrication, testing and strength calibration

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ABSTRACT

Lattice steel elements produced by Wire-Arc Additive Manufacturing (WAAM) are emerging as promising candidates for lightweight, architected structural members, yet their structural-scale behaviour remains largely unexplored. This paper investigates the structural response of WAAM-produced diamond-shaped lattice steel elements (D-Poles) under axial compression, providing the first comprehensive experimental dataset for this new class of components. D-Poles are formed by repetition of diamond-shaped units (D-Chips) along the height and around a polygonal cross-section, resulting in continuous lattice members without discrete mechanical connections. A fabrication campaign was carried out using a robotic WAAM setup with Cold Metal Transfer, producing three-, four- and six-faced D-Poles in three different heights (0.30 m, 0.60 m and 0.90 m). The specimens were characterized by industrial computed tomography to quantify porosity and thickness distribution, followed by monotonic compression tests on short and tall D-Poles. The global response is found to be governed by flexural behaviour of the D-Chips rather than by global buckling. An analytical model is adopted to interpret yielding and ultimate capacities and to develop a Eurocode-consistent calibration of characteristic and design strength values.

1. Introduction

Lattice structures represent an emerging class of architected materials that combine geometry and material design to achieve mechanical properties rarely attainable in homogeneous solids, such as high specific strength, energy absorption, and tunable stiffness [1–4].

At the micro-scale, advances in fabrication technologies have enabled the production of lightweight periodic patterns in various materials—including polymers, elastomers, and metals—broadening their applications across mechanical, aerospace, naval, and biomedical engineering [5–7]. Through the interplay between material characteristics and geometrical design, lattice structures can be tailored to deliver desired global responses. However, their intricate cellular topology, consisting of multiple struts and nodes with millimetric dimensions, poses significant manufacturing challenges for traditional forming or machining processes. Consequently, additive manufacturing (AM) has become the preferred route for their realization. Among metal AM techniques, laser-based powder bed fusion (L-PBF, or else PBF-LB) has been widely adopted to produce fine and complex lattice components

with cell sizes in the millimeter range [8–10]. At the structural scale, the concept of lattice systems is well rooted in steel construction. Vladimir Shukhov's pioneering hyperbolic steel gridshells demonstrated the mechanical efficiency of lattice geometries for towers and roofs, although their widespread adoption was constrained by the difficulty of manufacturing customized connections among straight members [11] (Fig. 1).

Although L-PBF offers excellent geometric resolution and material efficiency for complex parts, its build dimension remains limited to the size of the contained box, usually below 500 mm, which restricts its applicability to small-to-medium components rather than truly large-scale structures [12,13]. On the other hand, Directed-Energy Deposition process with arc (DED-arc), also known as Wire-Arc Additive Manufacturing (WAAM), is inherently more suitable for large-scale fabrication [14–16]. WAAM technology adopts wire-based feedstock and arc-driven material transfer which provide a practical solution for oversized, load-bearing, and industrial-scale structures, where the spatial and economic limitations of L-PBF become prohibitive. Average deposition strategies for WAAM technology report common values of

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about 2–5 kg/h, up to 10 kg/h for steel applications [17]. This is substantially higher than powder-based AM processes, commonly adopted to realize lattice metal components to the scale of few centimeters.

The increasing digitalization of the construction sector and the introduction of large-scale metal AM processes have renewed interest in efficient steel lattice structures [12,18]. Among these processes, Wire-Arc Additive Manufacturing (WAAM) shows particular promise for producing structural-scale metallic components [19,20]. The WAAM ability to deposit molten metal in successive droplets—the so-called dot-by-dot or point-by-point strategy—enables the fabrication of continuous lattice elements (see e.g. [21,22]). This approach allows for the creation of meso-scale lattice members that transfer the principles of cellular materials to structural dimensions, while ensuring material continuity at the nodes and eliminating discrete mechanical connections.

The first demonstration of a WAAM-fabricated diamond-shaped lattice column was reported in 2018 [21]. The column exhibited a non-regular diamond topology, with varying bar lengths and internal angles along its height. Subsequent studies explored the mechanical behavior of WAAM-produced single bars under tensile [23,24], bending [25], and compressive loads [22,26,27], as well as their corrosion performance [28]. WAAM can process a wide range of structural metals, including carbon and low-alloy steels (e.g., ER70S-6, S355), austenitic and duplex stainless steels (e.g., 316 L, 304 L, 2205), aluminum alloys (e.g., ER4043, ER5356), titanium alloys (notably Ti-6Al-4V), and nickel-based superalloys (e.g., Inconel 718, Hastelloy) [14,15]. This material diversity enables WAAM to address applications ranging from civil and architectural structures to aerospace and high-temperature components.

In terms of lattice topology, very few examples stand on WAAM-fabricated single unit cells. Xu et al. [29] adopted Pulse WAAM (PWAAM) to realize large-size pyramidal lattice cells, while Grossi et al. [30] studied various deposition strategies to reduce the geometrical discrepancy between the digital input and the printed specimen for WAAM-produced intersected bars forming lattice structures. These investigations established a fundamental understanding of the mechanical characteristics of WAAM dot-by-dot printed specimens, and informed the design of WAAM lattice elements. When considering diamond-shaped WAAM columns, two features are key to their behavior: (i) the material continuity at the nodes, which provides structural stiffness in the absence of horizontal rods, and (ii) the in-plane and out-of-plane deformation modes under compression, which contribute to additional bending effects depending on the element's height.

The present work aims at providing the first experimental results and interpretation of the structural behavior of WAAM-produced diamond-

shaped lattice elements under compression (Fig. 2). First, the structural analysis of these elements under compression is summarized in Section 2. Then, the fabrication procedure of a series of lattice elements at different heights and cross-sections is explained in detail in Section 3. The experimental tests in terms of geometrical characterization and mechanical characterization under compression are fully presented in Sections 4 and 5, respectively, providing also a structural design interpretation of the compression behavior of WAAM-produced diamond-shaped lattice elements. The final aim of this work is to provide the first comprehensive experimental results on this new generation of structural elements, while proposing first design solutions of practical applications in steel construction.

2. Structural design of diamond-shaped lattice elements

In general terms, WAAM-produced diamond-shaped lattice elements are characterized by a series of elementary units, also called D-Chips, along the height of the element, repeated on a number of faces corresponding to the number of sides of the cross-sectional polygon. For elements developing along a cross-sectional polygon and with a vertical development, the elements are also referred to as D-Poles.

D-Poles are generally characterized by two types of nodes: (i) the plane node, along the face of the D-Pole, and (ii) the edge node, in correspondence with the connection of two consecutive faces.

By analyzing each elementary unit composing the D-Pole, i.e. the D-Chip, the behavior under compression of D-Poles is predominantly governed by the bending moment developed on each D-Chip forming the faces of the D-Poles (Fig. 3).

D-Poles have generally two distinguished regions, i.e. the internal region (far from the boundaries) and the boundary regions, predominantly affected by the boundaries. The structural behavior of these two regions is mainly governed by bending moment for both of them, but at the internal region the main contribution is due to the in-plane bending moment (i.e. the one acting on the plane of the D-Chips), while at the boundary regions the main contribution is due to the out-of-plane bending moment (i.e. the one acting out of the plane of the D-Chips). Depending on the geometrical configurations of the D-Poles, in terms of relative slenderness, number of faces forming the D-Poles etc, the overall structural behavior is governed either by the in-plane bending moment at the internal region or by the out-of-plane bending moment at the boundary regions. The geometrical configurations investigated in this work present 3-, 4-, 6-faced short and tall D-Poles, having global slenderness sufficiently low such that the global behavior under compression is governed by plasticity and not global buckling (Fig. 4). It is clarified that the observations refer exclusively to complete unit cells. In the case of the lower D-Pole configurations, only one full cell is involved,

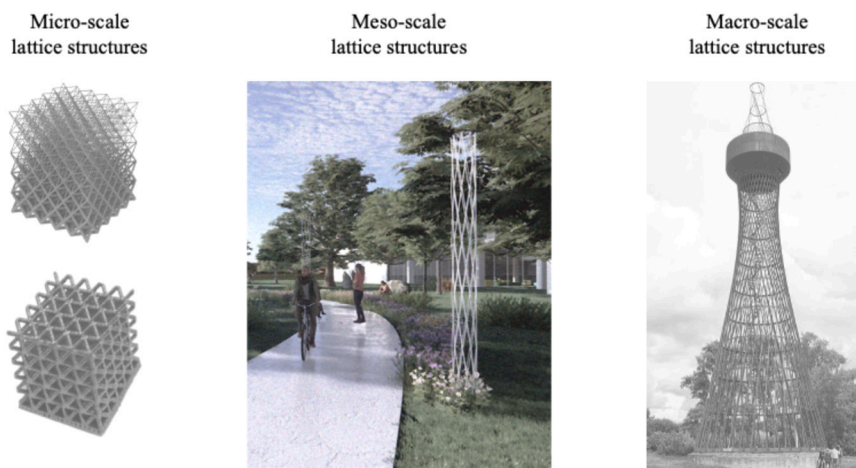


Fig. 1. From micro-scale to meso-scale to macro-scale lattice structures.

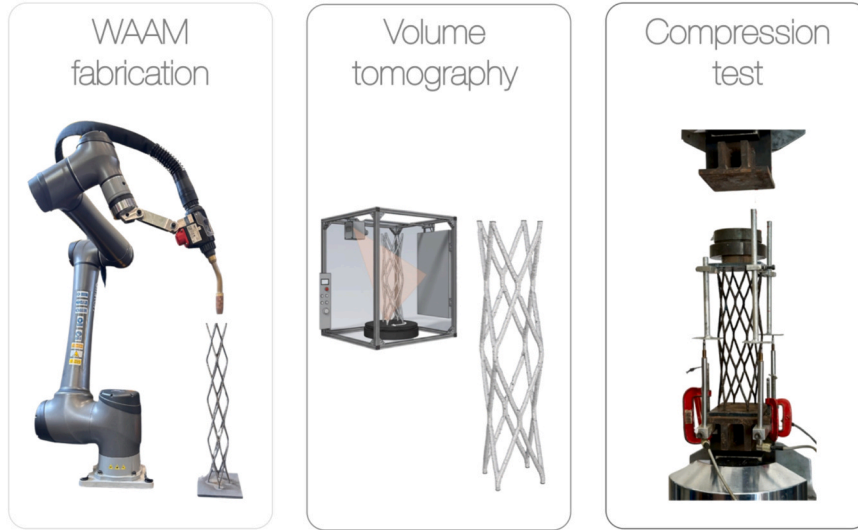


Fig. 2. Experimental steps for the comprehensive characterization of WAAM-produced lattice elements under compression.

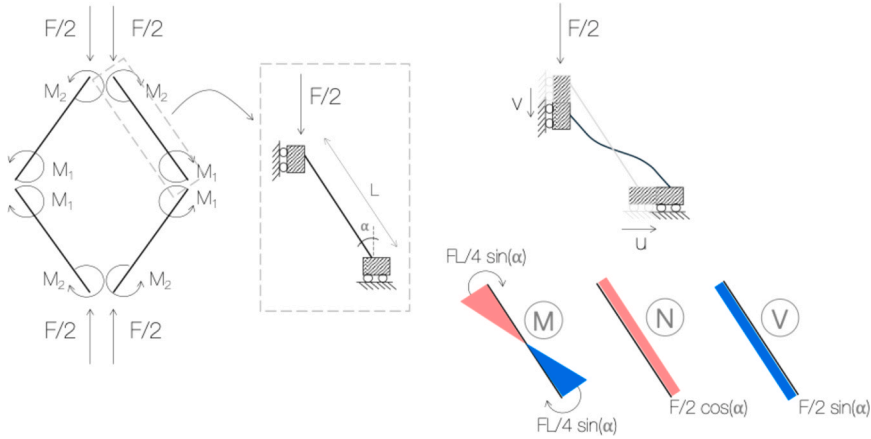


Fig. 3. Structural mechanics of the D-Chip under compression.

whereas in the lower configuration three cells are considered. In fact, the half-cells act only as load transmission paths and are not treated as unit cells in the analysis.

Considering the bending-dominated nature of the D-Poles under compression, the yielding capacity can be preliminarily calculated with the following analytical formulation:

$$F_y = \frac{2n A d f_y}{d \cos(\alpha) + 4L \sin(\alpha)} \quad (1)$$

Where: n is the number of faces of the D-Poles, A and d are the bar cross-sectional area and diameter, respectively, f_y is the yield strength, L is the bar length and α the vertical angle of the bars within the D-Chip (Fig. 3). Further information can be found in [31].

3. Fabrication of diamond-shaped lattice elements

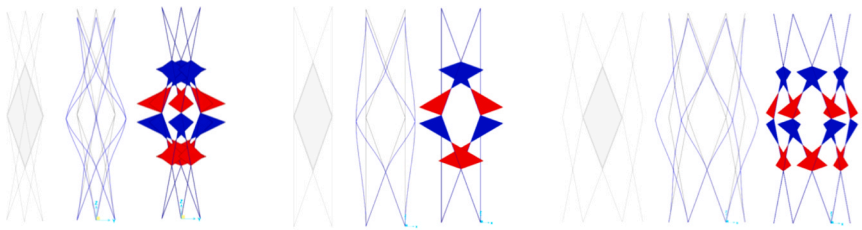
3.1. Design of D-Pole geometries

As previously mentioned, the final column configuration is obtained from a fundamental element consisting of a single bar. By intersecting with other bars, this basic element allows the development of progressively more complex geometries. The production of the columns was therefore achieved by repeating a rhomboidal base element, which

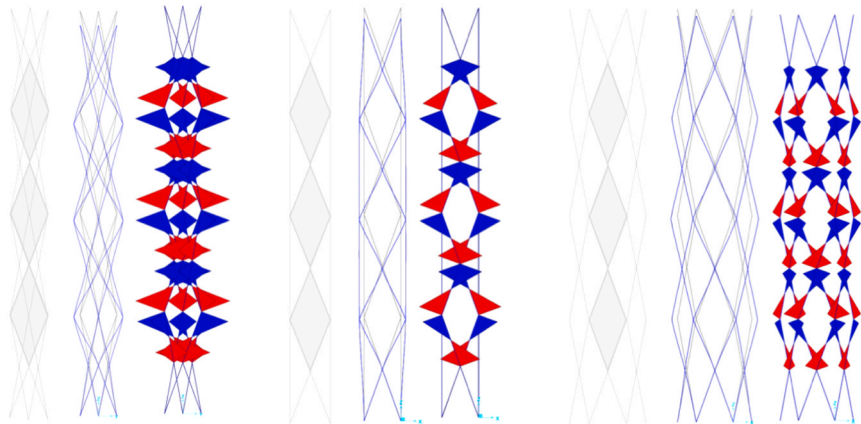
defines the fundamental unit cell of the structure (i.e. the D-Chip).

Three main base geometries were manufactured, each inscribed within the same circular diameter. The geometries differ in the number of faces forming the external configuration, by creating columns having three, four and six faces respectively (Fig. 5).

Each column typology was produced in three different sizes, varying only in height. The short columns have a nominal height of 30 cm, the tall ones of 60 cm, and the tallest ones of 90 cm. The 30-cm high columns are composed of one complete fundamental cell, connected at the top and bottom by half-cells. These half-cells were introduced to promote more effective force dissipation while concentrating the structural response within the central full cell, which represents the main focus of the structural investigation. The 60-cm high columns are composed of three complete unit cells plus two half-cells (one at the top and one at the bottom). The 90-cm high columns follow the same configuration logic but consist of five complete unit cells in addition to the two half-cells. This structural arrangement was consistently adopted for all column geometries (three-, four-, and six-faced configurations) to ensure comparability across the different typologies (Fig. 5). For the sake of the present work, only the 30-cm high and 60-cm high columns were tested under compression. For them, the specimen IDs were created according to the following pattern: "SHORT" refers to the 30-cm high columns, while "TALL" refers to the 60-cm high columns; "3f", "4f", "6f" indicate



(a)



(b)

Fig. 4. Flexural behavior of (a) short and (b) tall D-Poles under compression.

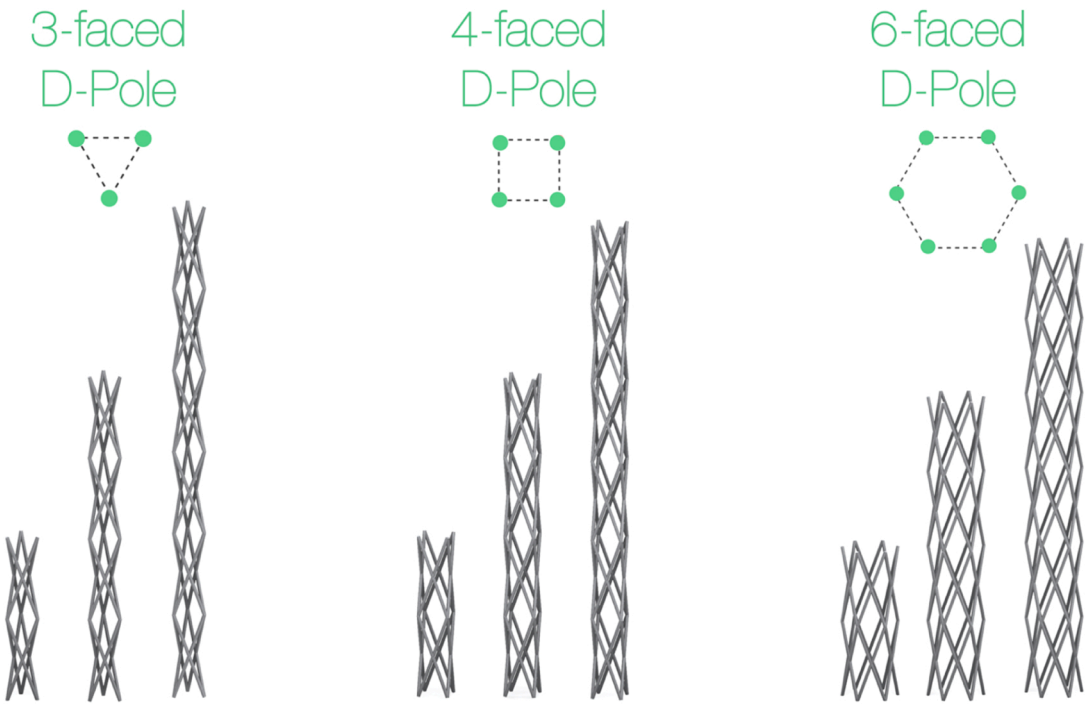


Fig. 5. Different configurations of WAAM-fabricated D-Poles under investigation.

the number of faces composing the column (i.e. 3-faced, 4-faced or 6-faced respectively); the last number indicates the repetitive specimen (having the same geometrical typology).

3.2. Materials and methods

The production of the lattice columns was carried out using a dot-by-dot deposition technique, a process that requires careful preliminary investigation of material transfer conditions to ensure stable and repeatable droplet formation. For each specimen, identical printing parameters were adopted in order to obtain three replicates for each column typology, thereby allowing the definition of a representative structural response during testing and ensuring statistical reliability of the experimental outcomes. Table 1 reports the printing process parameters adopted to manufacture all the tested specimens, while Fig. 6 presents the fabrication phases for one of the short D-Poles then tested.

All columns were manufactured using a collaborative Omron TM5 robotic arm, equipped with an NB7 operator panel and an NXP2 PLC. The system was fitted with a Fronius welding head operating in Cold Metal Transfer (CMT) mode, enabling controlled metal transfer with limited heat input. Each specimen was printed on a steel base plate measuring 120×120 mm with a thickness of 8 mm, using an ER70S-6 steel wire with a diameter of 0.8 mm. ER70S-6 was used because it offers a good balance between metallurgical quality and ease of deposition. Thanks to its relatively high manganese and silicon content, this material has strong deoxidizing properties that help reduce defects such as porosity and inclusions, especially in the open environment of an electric arc process. It also provides a stable arc, good weld pool wetting, and uniform deposition even at high travel speeds, all of which are essential for building components layer by layer in a reliable way. For these reasons, it is considered a standard and versatile choice for WAAM of low-carbon steels.

To ensure a consistent molten pool size at the moment of droplet detachment, constant average electrical parameters were imposed, namely a current of 101 A and a voltage of 14.5 V during arc ignition. These values allowed stable arc behaviour and ensured the formation of bars with an average diameter of approximately 5 mm. In order to minimize oxidation phenomena during deposition, a shielding gas mixture composed of 82% Ar and 18% CO₂ was adopted, with a controlled gas flow rate of 13 L/min to guarantee adequate protection of the molten pool.

The welding speed was set to 10 mm/s, a value selected to balance geometric accuracy and thermal input, preventing excessive heat accumulation while maintaining dimensional consistency of the deposited elements. The wire feed speed was fixed at 5 m/min, ensuring a stable material supply rate compatible with the selected current and voltage levels. A nominal layer height of 1 mm was adopted to achieve uniform vertical growth and consistent droplet stacking throughout the lattice structure.

The CMT process was configured with 40 cycles per sequence, enabling controlled short-circuit transfer. A short CMT waiting time of 0.02 s was introduced to regulate the interval between successive

droplet transfers, thereby limiting overheating and improving geometric repeatability. Additionally, a pre-gas time ranging between 0.3 and 0.4 s was applied prior to arc ignition to purge atmospheric air from the deposition zone, while a post-gas time of 0.8 s ensured continued shielding during the initial cooling phase, further reducing oxidation risk.

The measured deposition rate was approximately 42 mm³ /s. The deposition rate represents a key parameter in WAAM processes, as it directly affects productivity, heat input per unit volume, and dimensional stability of the printed geometry. In the present case, the effective deposited volume was partially influenced by unavoidable material losses due to spatter, residual accumulation, and the presence of complex geometrical intersections typical of lattice configurations. Consequently, the actual deposition efficiency must be interpreted considering these process-related losses.

In the final stage of production, a second steel plate was manually welded at the top of each column by using the same welder machine used by the Cobot. Particular attention was devoted to ensure proper alignment and planar parallelism between the two end plates in order to avoid eccentricities or geometric imperfections that could alter the stress distribution during the subsequent compression testing phase.

4. Geometrical characterization

The geometrical characterization was carried out on 9 short D-Poles, later tested under compression. In particular, the characterization consisted in a complete volume tomography analysis, from which an analysis of the porosity and thickness distribution was carried out.

4.1. Set up and methodology

Industrial computed tomography (iCT) is a key technique for inspecting components with complex geometries, such as additively manufactured parts. During a scan, multiple X-ray projections are acquired from different angles by rotating the sample. The resulting images are based on differences in X-ray attenuation between materials, which appear in the dataset as grey value variations. From these data, reconstruction algorithms generate a virtual 3D volume of the component.

This reconstructed volume is mainly used for defect analysis, allowing the identification of internal flaws, and for metrology and dimensional validation, since iCT enables full characterization of internal geometries in a non-destructive way.

In this study, micro-CT scans were performed using a North Star Imaging X5000 system (Rogers, USA), with a 240 kV microfocus X-ray source (filtered with 2 mm Cu) and a 127 μ m detector. A total of 9004 projections were acquired in helicoidal mode, achieving a voxel resolution of 70 μ m (Figure A10 in Annex A). The reconstructed volume is composed of a regular three-dimensional grid of volumetric elements called voxels (an abbreviation of "volume pixel"), each assigned a grey value proportional to the local X-ray attenuation. The voxel size, i.e., the edge length of each cubic volume element, defines the spatial resolution of the iCT dataset and is determined by the system geometry (source-to-detector and source-to-object distances), the detector pixel pitch, and the reconstruction parameters [32]. The voxel size directly governs the smallest feature that can be resolved and the achievable measurement uncertainty: smaller voxels increase spatial resolution and allow more accurate localization of surfaces and defects, but also increase scan time, data volume, and noise per unit volume, while larger voxels can introduce partial-volume effects that bias both defect sizing and dimensional measurements [33].

The reconstructed volumes were processed using NSI software and then imported into VGSTUDIO MAX (Volume Graphics). The first step of the analysis is typically surface determination (Fig. 7), which defines the material boundary with sub-voxel accuracy based on local grey value gradients. Compared to simple isovalue thresholding, the advanced

Table 1
Summary of the main printing parameters.

Wire	ER70S-6
Wire diameter	0.8 mm
Welding speed	10 mm/s
Wfs	5 m/min
Layer height	1 mm
CMT cycles	40
CMT Waiting time	0.02 s
Pre gas	0.3–0.4 s
Post gas	0.8 s
Gas flow	13 L/min
Current	101 A
Voltage	14.5 V



Fig. 6. Fabrication steps of a short 3-faced D-Pole.

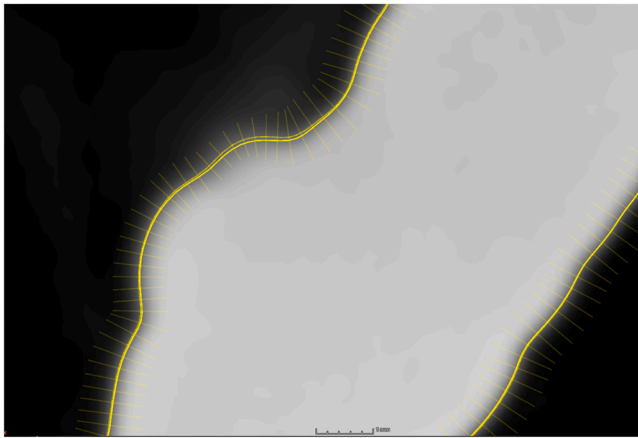


Fig. 7. Surface calculation from the 3D volume reconstruction.

method provides a more accurate reconstruction by compensating for artefacts such as beam hardening, since grey values are interpreted in relation to the surrounding voxels.

With the surface determined, it is possible to proceed with the defect analysis and the dimensional validation. The defect analysis was performed with VG Studio MAX's Easy Pore Analysis module to perform automated void quantification and manually, by a trained operator. The dimensional validation was performed using the wall thickness analysis module in VG Studio MAX, with the inscribed sphere method. The inscribed sphere method calculates local thickness via the diameter of the largest sphere that fits entirely within the structure at each surface point. This approach provides robust measurements for uniform wall features and highlights thinning due to process variation. Finally, a STL file was exported for further studies as a full 3D model reconstruction.

4.2. Results from volume tomography

Regarding the defect analysis, different porosities were identified for each component. The quantification of the amount of discontinuity for each component was calculated with the use of the VG Studio MAX Easy Pore Analysis module. Table 2 summarizes the results in terms of microporosity detection: for each specimen investigated, the module registers the number of pores identified, the percentage of volume of these pores

Table 2

Results from volume tomography in terms of porosities.

Specimen ID	Number of pores	% Volume of pores	Max pore volume [mm ³]
SHORT-3f-1	190	0.09	2.37
SHORT-3f-2	325	0.17	1.74
SHORT-3f-3	84	0.04	1.48
SHORT-4f-1	850	0.42	6.88
SHORT-4f-2	565	0.23	9.61
SHORT-4f-3	394	0.14	2.40
SHORT-6f-1	554	0.21	6.66
SHORT-6f-2	220	0.07	5.42
SHORT-6f-3	233	0.07	3.05

with respect to the overall volume of the specimen, and the maximum pore volume identified, in mm³. The results confirm a small percentage of volume porosity, well below the 0.5% range.

It should be highlighted that in some specimens (especially SHORT-3f-1 and SHORT-6f-1) the porosities are not homogeneously distributed throughout the whole volume, but instead they are localized at some intersection of the bars forming the D-Chips (Fig. 8). This aspect can be crucial to interpret the structural behavior of D-Poles under various loading conditions, and possible preliminary failure occurring at the intersection zones of the bars.

4.3. Investigation on the minimum thickness

Wall thickness analysis was performed using the sphere method, as described in Section 4.1. The obtained results are related to the wall thickness distribution within the CT volume. For each sample, a histogram of the wall thickness distribution together with an image highlighting the location of the minimum thickness are reported in Annex A. In addition, Table 3 summarizes the wall thickness distribution for each specimen in terms of mean value, minimum value, maximum value, and coefficient of variation. It should be noted that, for the investigated geometries, the wall thickness corresponds to the diameter of the bars forming the D-Poles. Overall, the measured mean bar diameter ranges between 4.60 mm and 4.88 mm, with an average value of approximately 4.68 mm, compared to the nominal value of 5 mm adopted as digital input for sample fabrication. These results indicate a relatively good agreement with the nominal geometry and a satisfactory global geometric consistency among the investigated specimens. However,

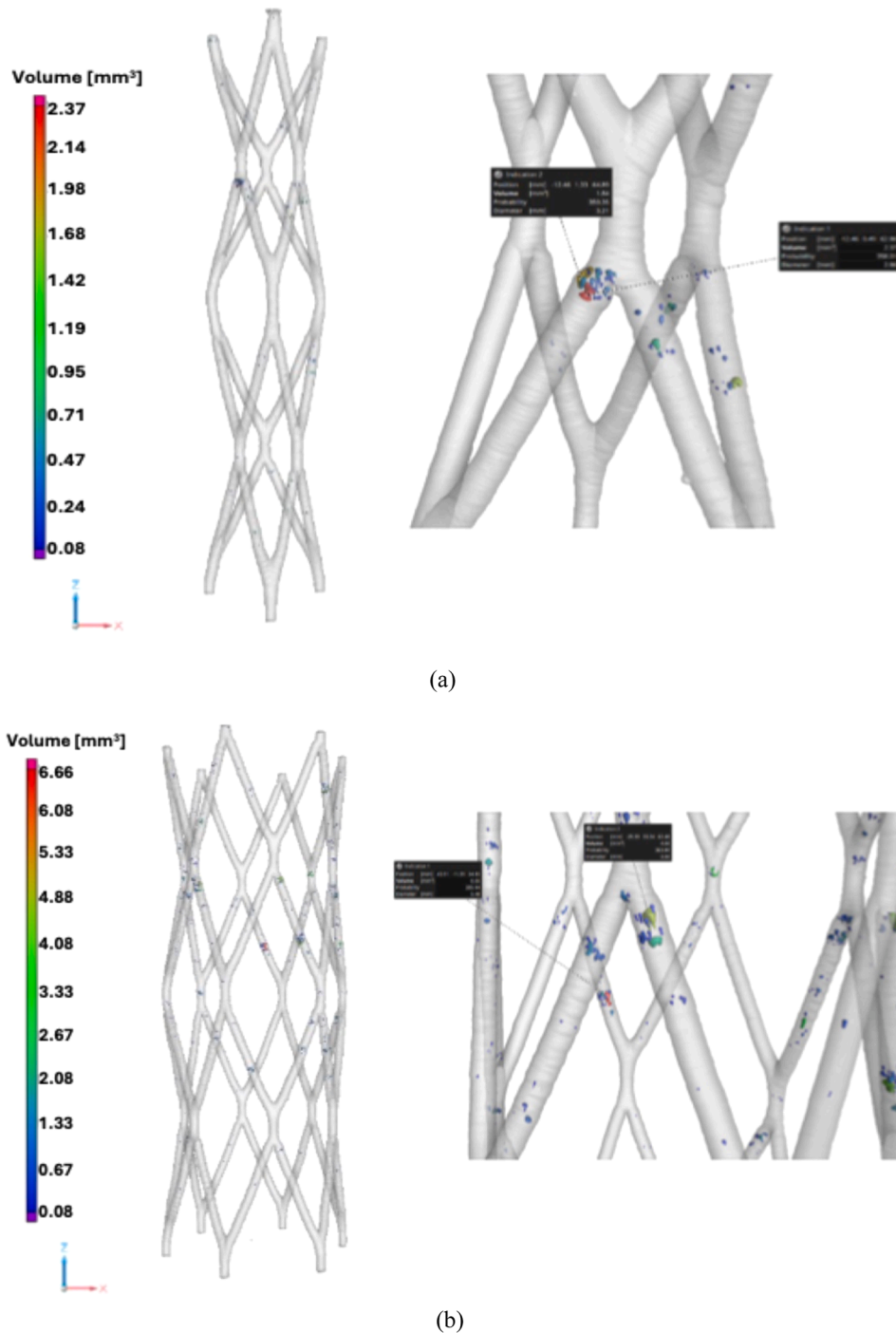


Fig. 8. Concentration of porosities for specimens (a) SHORT-3f-1 and (b) SHORT-6f-1.

localized deviations are also observed. In particular, the minimum measured thickness reaches values close to 3.00 mm in SHORT-4f-2 specimens visible in Fig. 9, while the coefficient of variation ranges between 6% and 15%, with average values around 7–10%.

The obtained thickness distributions highlight that, although the manufacturing process ensures a relatively stable global geometry, local thickness heterogeneities remain significant. Such deviations are likely associated with process-induced effects inherent to the adopted fabrication technique, including local deposition non-uniformities. From a structural standpoint, these localized reductions in thickness may contribute to stress concentration effects and influence the mechanical response of the specimens. Potential improvements in geometric

consistency could be achieved through further optimization and control of the manufacturing parameters.

5. Mechanical characterization

5.1. Set up

The mechanical behavior of D-Poles was investigated through compression tests on 15 specimens fabricated, in particular 9 short and 6 tall D-Poles.

All D-Poles were subjected to axial compression tests conducted under displacement control. The loading rate was set to 1 mm/min, and

Table 3

Wall thickness distribution.

Specimen ID	Mean thickness [mm]	Max thickness [mm]	Min thickness [mm]	COV [%]
SHORT-3f-1	4.88	5.45	3.31	7
SHORT-3f-2	4.64	5.19	3.30	15
SHORT-3f-3	4.78	5.20	3.01	6
SHORT-4f-1	4.65	5.42	3.01	10
SHORT-4f-2	4.60	5.22	3.00	11
SHORT-4f-3	4.67	5.52	3.01	11
SHORT-6f-1	4.64	5.14	3.56	6
SHORT-6f-2	4.65	5.38	3.26	6
SHORT-6f-3	4.61	5.06	3.43	6
mean	4.68	5.28	3.21	8.67
st.dev	0.09	0.15	0.20	3.06

the tests were continued until maximum vertical displacements of 10 mm and 15 mm were reached for the short and tall specimens, respectively. To ensure uniform load transfer and prevent unwanted node movements, both ends of the specimens were welded to square steel base plates. The tests were performed using a universal testing machine with a maximum capacity of 500 kN. Vertical displacements were recorded by three linear variable displacement transducers (LVDTs). In more detail, the test setup included a spherical upper loading plate, providing a self-aligning system intended to compensate for possible plate non-planarity and to ensure uniform and planar load transfer. The load was then transferred to the upper plate, welded to the D-Pole. Both upper and lower plates were welded to the D-Pole, thus being schematized as fixed boundary conditions.

A single unloading–reloading cycle was introduced after the onset of plastic deformation, at a vertical displacement of 2 mm (1.5 mm for specimen SHORT-6f-2). The purpose of this cycle was to evaluate the residual deformation accumulated during loading, identify potential progressive damage mechanisms, and assess possible stiffness degradation. The tests were not continued up to complete structural collapse.

Instead, loading was stopped once a stable plastic plateau was reached, at 10 mm vertical displacement for short D-Poles and 15 mm for tall D-Poles, respectively.

5.2. Results on the compression tests

A total of 15 specimens were tested under compression loading (Fig. 10), 9 specimens of short D-Poles grouped into 3 geometrical configurations (i.e. having 3 identical specimens for the same geometrical configuration) and 6 specimens for tall D-Poles grouped into 3 geometrical configurations (i.e. having 2 identical specimens for the same geometrical configuration).

Fig. 11 shows the graphs of the compression tests for short (Fig. 11a) and tall (Fig. 11b) specimens. The total compression load applied on the D-Poles was normalized by the number of faces of the D-Poles (F/n), while the total vertical displacement was normalized by the total height of the D-Poles (v/H). In particular, the yielding capacity is defined as the load corresponding to the first onset of permanent plastic deformation, identified as the deviation from linear elastic behaviour in the load–displacement response. The ultimate capacity is defined as the maximum load sustained by the specimen under compression loading. In terms of compression capacity, the tall D-Poles showed slightly higher values of maximum compression load with respect to the short ones. On the other hand, the latter showed higher deformation capacities, which could lead to some dissipative properties which should be further investigated and exploited for energy-absorption applications. Tables 4 and 5 collect the results in terms of yielding and maximum compression capacity and corresponding deformation for short and tall D-Poles, respectively.

Fig. 12 reports the values of yielding and ultimate compression capacity normalized by the number of faces of the D-Poles (F_y/n , F_u/n). By comparing the various cross-sectional configurations of the investigated D-Poles, a linear increase in the performances under compression can be seen by increasing the number of faces of the D-Poles, reaching +50% increase for 6-faced D-Poles over 3-faced ones. This aspect suggests that

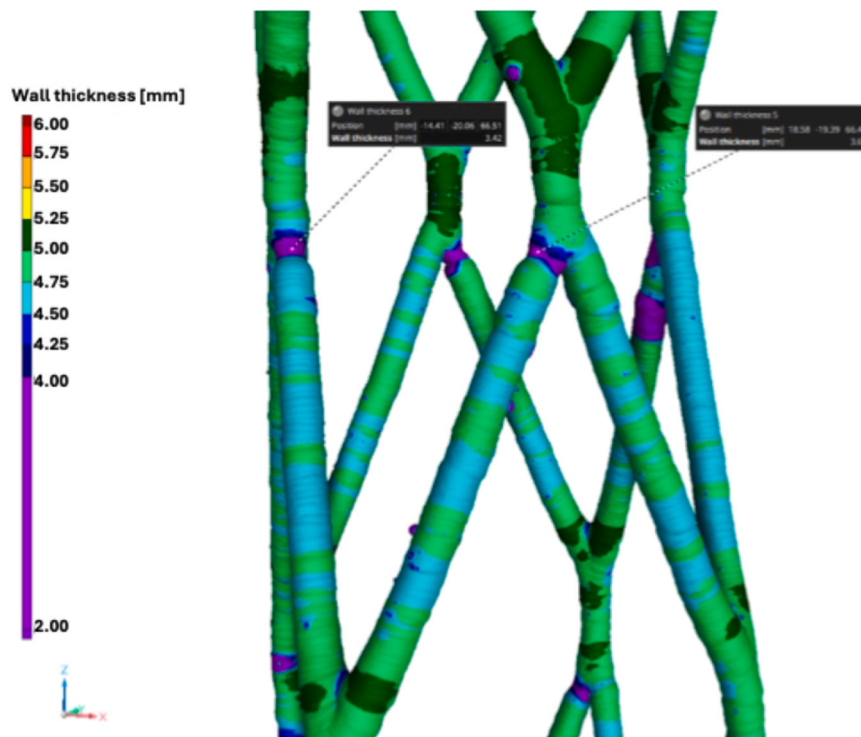


Fig. 9. Sample SHORT-4f-2, with the smallest wall thickness in the entire batch.

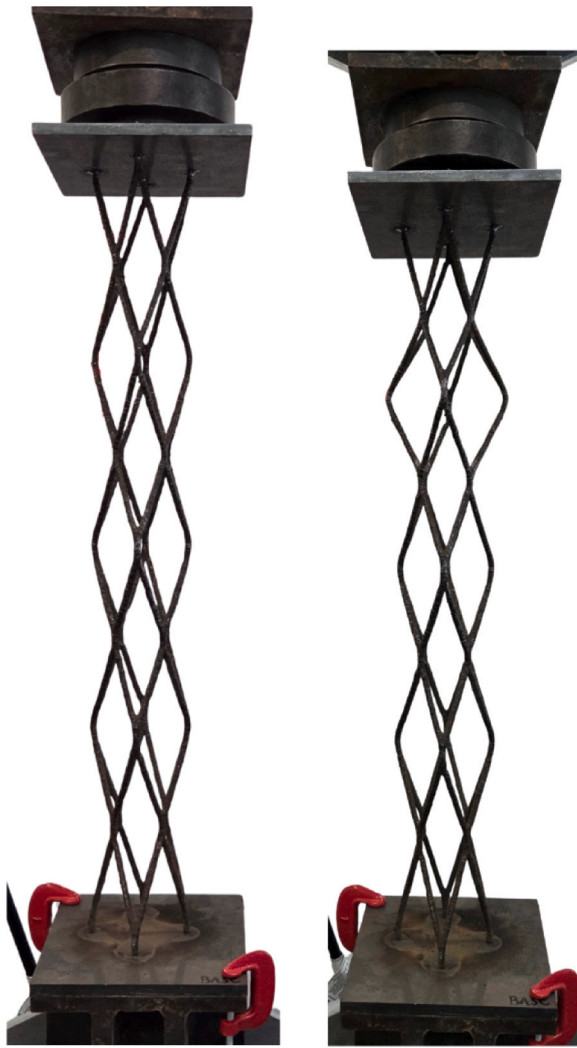


Fig. 10. Specimen TALL-4f-1 before and after compression test.

the structural behavior of D-Poles under compression is significantly affected by its geometrical configurations, which could be adequately engineered to tailor the requested structural performances. By comparing short and tall D-Poles, an increase in the performances of the latter is visible, with a 5–20% increase for both values of yielding and ultimate capacity.

The results show that both the yield and ultimate strengths increase with the number of faces for both short and tall D-Poles. From a mechanical perspective, increasing the number of faces improves the distribution of compressive stresses and reduces the tendency for local instability of individual panels. As a result, specimens with a higher number of faces can develop greater load-carrying capacity before failure. From the normalized results, specimen SHORT-4f-2 appears to have the lowest compression capacity among all tested cases. When correlated with the results from the wall thickness distribution (Section 4.3), it is also found to be the specimen with the lowest average values of wall thickness, thereby providing a possible rationale for its lower normalized response.

The differences between short and tall D-Poles can be primarily attributed to the increase in global slenderness. Due to their greater height, the tall specimens exhibit higher deformation capacities (v_y/H and v_u/H), indicating a response more strongly influenced by global instability phenomena and second-order effects. In addition, the presence of multiple cells may promote the development of localized deformations and local instability mechanisms, although these do not

appear to govern the overall response. The increased slenderness also makes the tall specimens more sensitive to initial geometric imperfections, which tend to amplify during loading and affect the structural behavior. In contrast, the short specimens exhibit a more stable and uniform response, largely governed by section resistance and less affected by instability phenomena and imperfections.

6. Considerations on the structural design of D-Poles

With the intention of providing guidelines and strength values for preliminary structural design estimation, in the present section a Eurocode-based approach for the assessment of the design values and partial safety factors of D-Poles are provided. These values are intended to be the first results of a calibration based on a limited amount of data from the first experimental tests carried out on short and tall D-Poles (as presented in Section 5.2). Therefore, these values will be expected to be updated with further experimental and numerical investigations. Nonetheless, the proposed calibration approach remains valid and within the European structural design guidelines.

Eurocode 0 (EC0) provides the basis of structural design, detailing in particular in Annex C and Annex D the details for partial factor design and reliability analysis, as well as providing guidelines for design assisted by testing. In Annex C precise reference on the calibration of partial safety factors is explained, specifying that this is possible either on the basis of calibration to a long experience of building tradition, or else on the basis of statistical evaluation of experimental data and field observations, within the framework of probabilistic reliability theory.

Probability reliability methods are based on the comparison of the failure probability p_f with its target value, or of the reliability index β with its target value β_t . It is generally required to design the structures in such a way that the determined values of the basic variables are close to the target values specified in appropriate code provision. The target reliability index β_t stated in Eurocodes derives from previous reliability studies of structural members made from different materials, therefore having a great scatter, but however consists of a reasonable average value of the reliability level to be considered. In particular, EC0 provides the recommended minimum values for the target reliability index β_t (associated with the probability of failure p_f) based on the reliability class for the structure to be designed. Typically, reliability class RC2 is considered for residential and office buildings, with an associated $\beta_t = 3.8$ for a reference period of 50 years.

In general terms, the design resistance is a function depending on the material properties (X), the geometrical properties (a) and the model uncertainties (θ). All quantities are generally considered as random variables, thus the suffix “d” refers to their design values.

$$R_d = R\{X_d, a_d, \theta_d\} \quad (2)$$

Considering the semi-probabilistic approach, the design resistance can be computed assuming a probability of failure (i.e. when exceeding the design resistance) of 0.1%:

$$p_f = P(R < R_d) = \phi(-\alpha_R \beta_t) \quad (3)$$

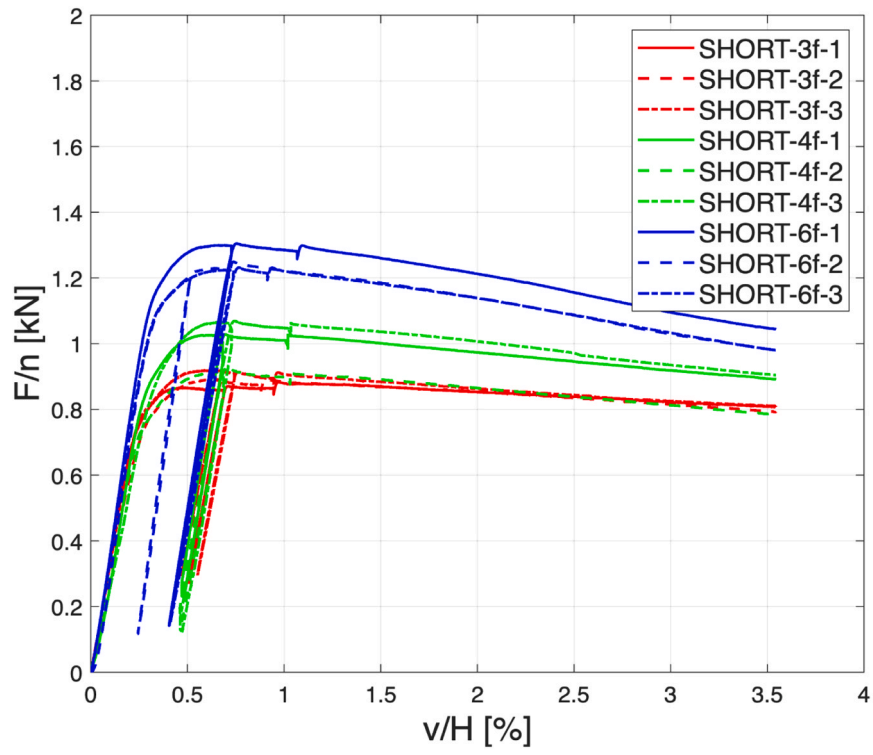
where α_R is the first order reliability method (FORM) sensitivity factor, and β_t is the target reliability index. The suggested value for the FORM sensitivity factor is $\alpha_R = 0.8$.

The design value for a variable related to the resistance as the material property X is defined as:

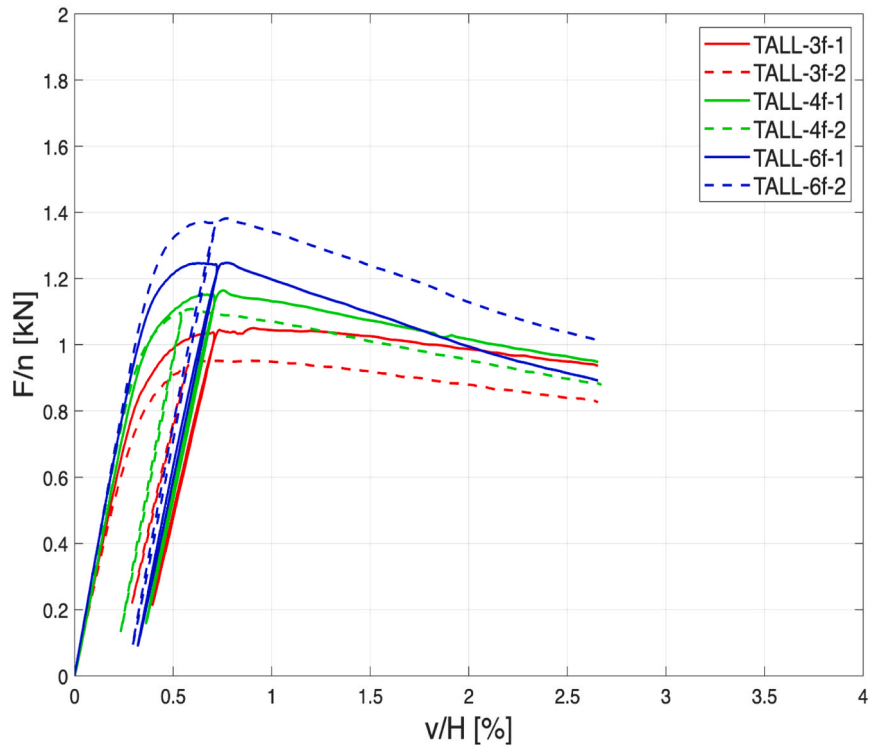
$$X_d = \frac{X_k}{\eta \cdot \gamma_m} = \frac{X_k}{\gamma_{M_0}} \quad (4)$$

Where X_k is the characteristic value, γ_m the partial safety factor related to the specific material property, and η is the model uncertainty.

The commonly used fractiles adopted in structural design are the fractiles corresponding to a probability of 5% ($p=0.05$), usually applied for the assessment of the characteristic value of material properties, and



(a)



(b)

Fig. 11. Compression results of (a) short and (b) tall D-Poles.

Table 4

Compression results of short D-Poles.

Specimen ID	F_y/n [kN]	v_y/H [%]	F_u/n [kN]	v_u/H [%]
SHORT-3f-1	0.65	0.20	0.88	0.49
SHORT-3f-2	0.71	0.24	0.89	0.64
SHORT-3f-3	0.67	0.20	0.92	0.52
mean – SHORT-3f	0.67	0.21	0.90	0.55
COV – SHORT-3f	4%	9%	2%	11%
SHORT-4f-1	0.79	0.24	1.04	0.61
SHORT-4f-2	0.63	0.21	0.93	0.70
SHORT-4f-3	0.82	0.29	1.07	0.65
mean – SHORT-4f	0.74	0.25	1.01	0.65
COV – SHORT-4f	11%	13%	6%	6%
SHORT-6f-1	1.01	0.24	1.31	0.58
SHORT-6f-2	0.97	0.21	1.26	0.64
SHORT-6f-3	0.99	0.26	1.23	0.65
mean – SHORT-6f	0.99	0.24	1.26	0.62
COV – SHORT-6f	2%	9%	2%	5%

Table 5

Compression results of tall D-Poles.

Specimen ID	F_y/n [kN]	v_y/H [%]	F_u/n [kN]	v_u/H [%]
TALL-3f-1	0.74	0.27	1.06	0.77
TALL-3f-2	0.67	0.28	0.97	0.69
mean – TALL-3f	0.71	0.27	1.07	0.73
COV – TALL-3f	5%	2%	4%	5%
TALL-4f-1	0.98	0.33	1.17	0.79
TALL-4f-2	0.87	0.28	1.12	0.78
mean – TALL-4f	0.92	0.31	1.15	0.78
COV – TALL-4f	6%	9%	2%	1%
TALL-6f-1	1.07	0.35	1.26	0.65
TALL-6f-2	1.10	0.34	1.39	0.64
mean – TALL-6f	1.08	0.34	1.32	0.65
COV – TALL-6f	1%	3%	5%	1%

the fractile corresponding to a probability of 0.1% ($p=0.001$), usually applied for the assessment of the design value of dominant variables [34].

In case of Lognormal distribution, commonly considered for random variables describing the material properties, the following expression might be used to derive the characteristic and design values of a material property with the given probability distribution:

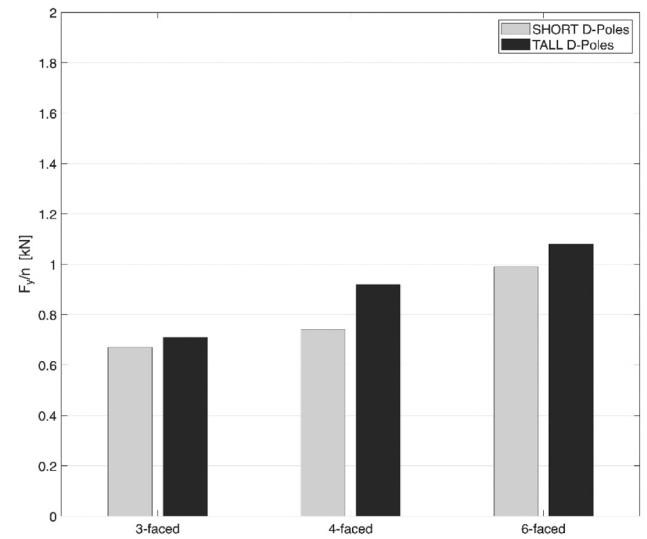
$$X_k = \mu_X \cdot \exp(u_{0.05} \cdot w_X) \quad (5)$$

$$X_d = \mu_X \cdot \exp(u_{0.001} \cdot w_X) \quad (6)$$

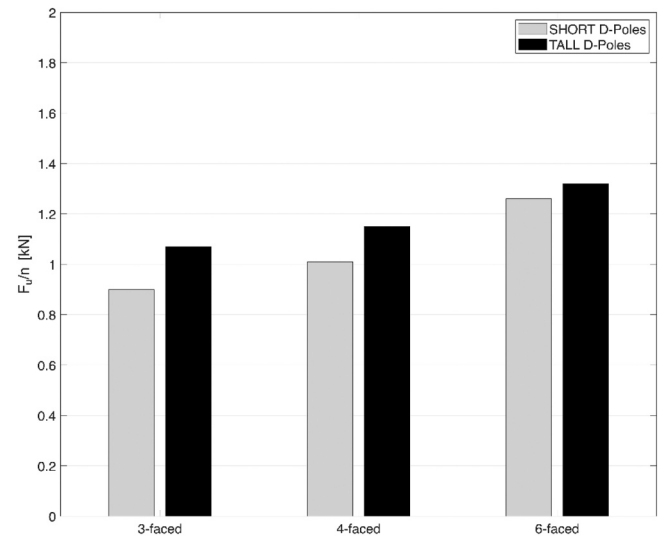
Where $u_{0.05}$ and u_p are the 5%-fractile and 0.1%-fractile of a standardized random variable with a Normal distribution, respectively.

By following the semi-probabilistic approach adopted by Eurocode 0 to estimate the design values and partial safety factors of all construction materials, the value of strength to be adopted for preliminary design purposes is obtained accounting for all the sources of uncertainties related to the nature of the construction material itself. For the case of WAAM-produced steel, previous work confirmed the need of proper re-calibration of the partial safety factors, which should consider the uncertainties related to: (i) the geometrical irregularities inherent of the fabrication process, (ii) the printing process parameters altering the final outcome in terms of both material homogeneity and strength, (iii) the material variability which can be due to possible errors during fabrication, and (iv) the discrepancy with the adopted model. The former three sources of uncertainties are commonly grouped in the material partial safety factor γ_m , while the latter is usually accounted in the model uncertainty factor η .

Based on the approach adopted in Eurocode 0, the value of the partial safety factor for the material strength can be preliminarily estimated based on the ratio between the design strength value and the characteristic one, by assuming the 0.1% and 5% fractiles (respectively)



(a)



(b)

Fig. 12. (a) yielding and (b) ultimate compression capacity of D-Poles for various geometrical configurations.

of the experimental distribution of strength values, assuming a Lognormal distribution (Fig. 13).

Following Eqs. 5 and 6 and the approach of Annex D “Design assisted by testing” from Eurocode 0, the characteristic and design values of strength are equal to 0.59 kN and 0.47 kN, respectively. These values are normalized with respect to the number of faces of the D-Poles (n).

From these, the value of the material partial safety factor γ_{M_0} is equal to 1.25. It should be noted that this value exceeds the commonly suggested value for structural steel (equal to 1.05), as it accounts for all the additional sources of uncertainties related to WAAM process (i.e. geometrical irregularities, process uncertainties, etc).

For the present study, the model uncertainty factor can be first computed as the ratio between the analytical prediction of the yielding capacity of D-Poles and its corresponding experimental value, as follows:

$$\eta = \frac{F_{y,analytical}}{F_{y,experimental}} \quad (7)$$

Fig. 14 shows the value of η for both short and tall D-Poles. The mean

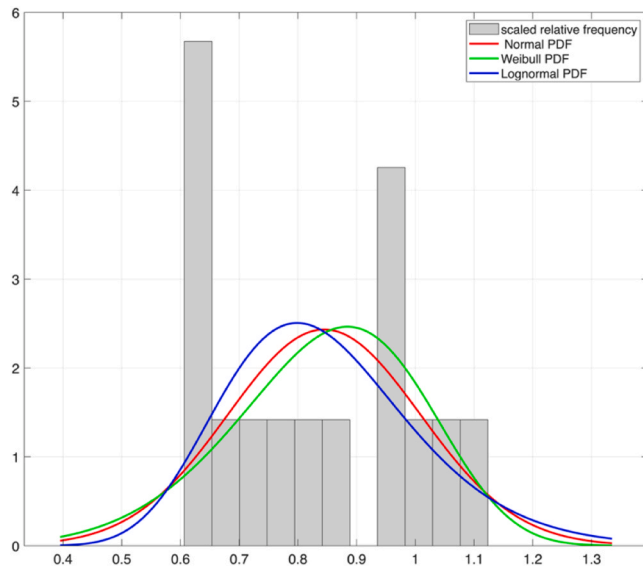


Fig. 13. statistical distribution of yielding capacity of D-Poles under compression.

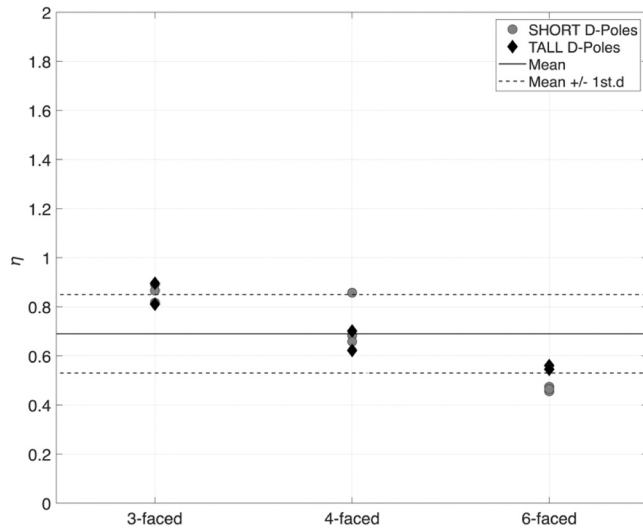


Fig. 14. Model uncertainty factor for D-Poles under compression.

value of the model uncertainty factor is equal to 0.69 with a 20% coefficient of variation, due to the high discrepancy of the η value between D-Poles having different number of faces. In particular, for lower values of n , the value of η is between 0.75 and 0.9, while for 6-faced D-Poles the value lowers to 0.5. This aspect is particularly significant for the influence of the number of faces in the overall structural behavior of D-Poles under compression loading, which should be properly investigated with further experimental and numerical analyses.

The limited number of tested specimens does not allow a statistically robust characterization of the lower tail of the strength distribution. Consequently, the fitted probability distribution and the derived characteristic and design values should be interpreted as preliminary estimates rather than definitive design parameters.

7. Conclusions

This study provides a first systematic experimental and design-oriented assessment of WAAM-fabricated diamond-shaped lattice steel elements (D-Poles) under axial compression, bridging fabrication

aspects, material and geometrical characterization, and structural performance into a unified framework suitable for structural steel design practice. D-Poles are generated by repeating a rhomboidal D-Chip around three-, four- and six-sided polygons and along the height, leading to continuous lattice members with material continuity at the nodes and no discrete mechanical connectors. A dot-by-dot WAAM process using a CMT-equipped robotic arm was employed to fabricate families of D-Poles at various heights, up to 90 cm.

The following main results can be drawn:

- Industrial computed tomography allowed full reconstruction of the printed geometries, enabling the assessment of porosity and thickness distribution and thus quantifying fabrication-induced irregularities that influence structural performance. Overall, the results suggest minimum porosity, specifically located in some samples (SHORT-3f-1 and SHORT-6f-1) at the bars intersection. Wall thickness distribution registered an average bar diameter of 4.68 mm vs the nominal value of 5 mm adopted as input for the fabrication, with a coefficient of variation of 5–10%.
- Compression tests on short and tall D-Poles provided yielding and ultimate capacities normalized with respect to the number of faces, forming the statistical basis for strength calibration. All tested configurations were designed with sufficiently low global slenderness such that the compressive response was governed by bending-dominated plastic failure rather than global buckling.
- Following Eurocode 0 Annexes C and D, a semi-probabilistic procedure was applied assuming Lognormal strength distributions and target reliability consistent with RC2 structures. The resulting characteristic and design normalized strengths led to a preliminary partial safety factor of 1.25, larger than the usual 1.05 for structural steel due to process- and geometry-related uncertainties intrinsic to the WAAM fabrication process.
- An additional model uncertainty factor was calibrated, defined as the ratio between analytical and experimental yielding capacities, reflecting the sensitivity of the analytical model to the number of faces and, in particular, its lower prediction accuracy for six-faced D-Poles.

These results should be considered strictly valid for the investigated WAAM process, material, geometries (three-, four- and six-faced D-Poles) and slenderness ranges where plastic and flexural mechanisms dominate. Future work should extend the investigation considering larger test populations, exploring alternative geometries and higher slenderness ratios, to refine the analytical model predictions. Indeed, thanks to the significant potential of WAAM technology, and by exploiting a dot-by-dot fabrication strategy, it is possible to produce lattice geometries of varying complexity. Given that WAAM is particularly well-suited for large-scale production, this geometric freedom can be effectively leveraged for applications in the construction sector, enabling the development of load-bearing structural elements or energy-dissipative components, which require application-specific investigation and tailored optimization.

In the future, the inherent versatility of WAAM could enable the parallel production of identical structural elements, thereby reducing manufacturing variability. Moreover, it may be feasible to integrate batches of lattice columns fabricated using different metallic materials, in order to support systematic comparison, characterization, and cataloguing of their respective mechanical and structural performances.

CRedit authorship contribution statement

Vittoria Laghi: Writing – original draft, Investigation, Conceptualization. **Elisabetta Savino:** Visualization, Investigation. **Fabio Esposito:** Investigation, Data curation. **Giada Gasparini:** Writing – review & editing, Supervision, Funding acquisition. **Tomaso Trombetti:** Supervision, Funding acquisition, Conceptualization.

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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Annex A

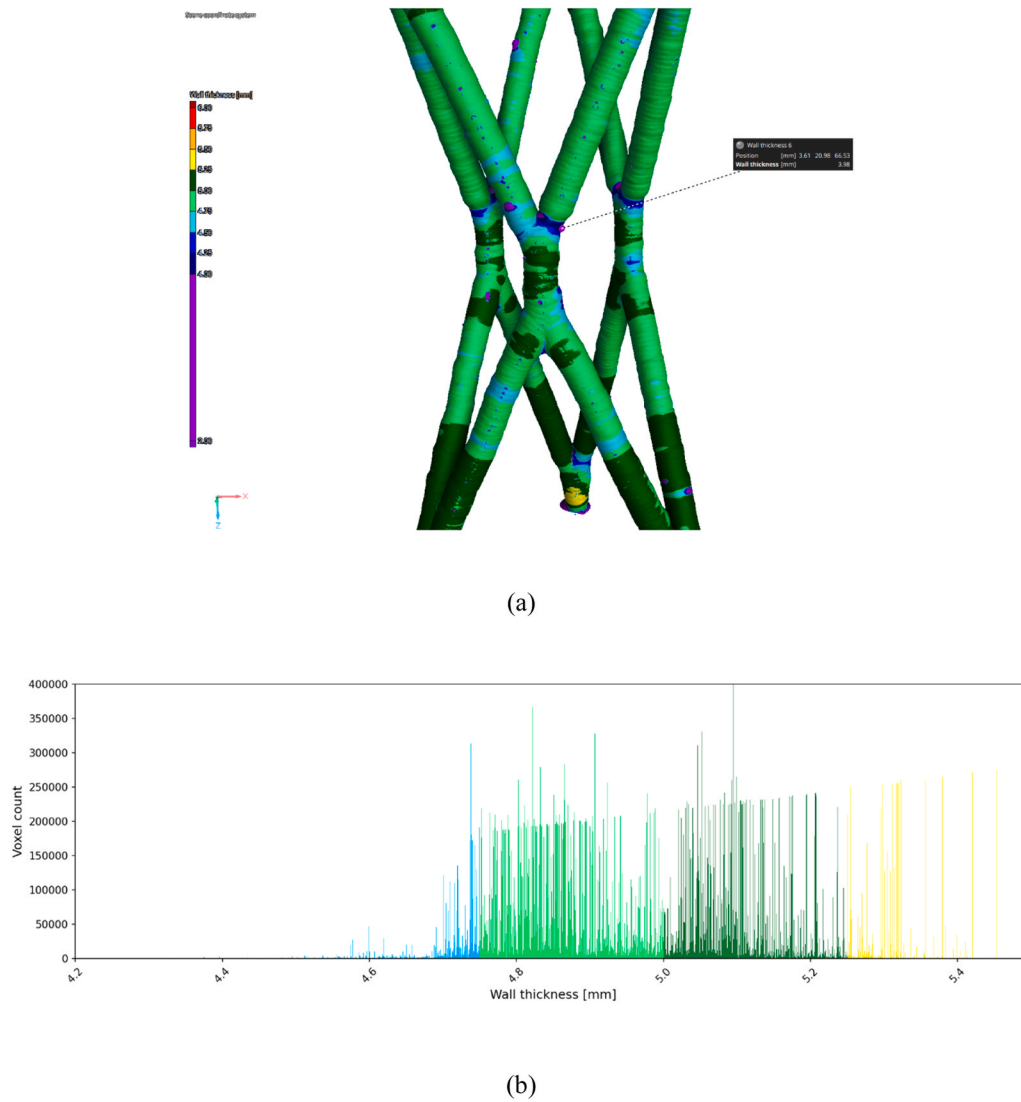


Fig. A1. Wall thickness analysis for specimen SHORT-3f-1: (a) minimum thickness location and (b) wall thickness distribution

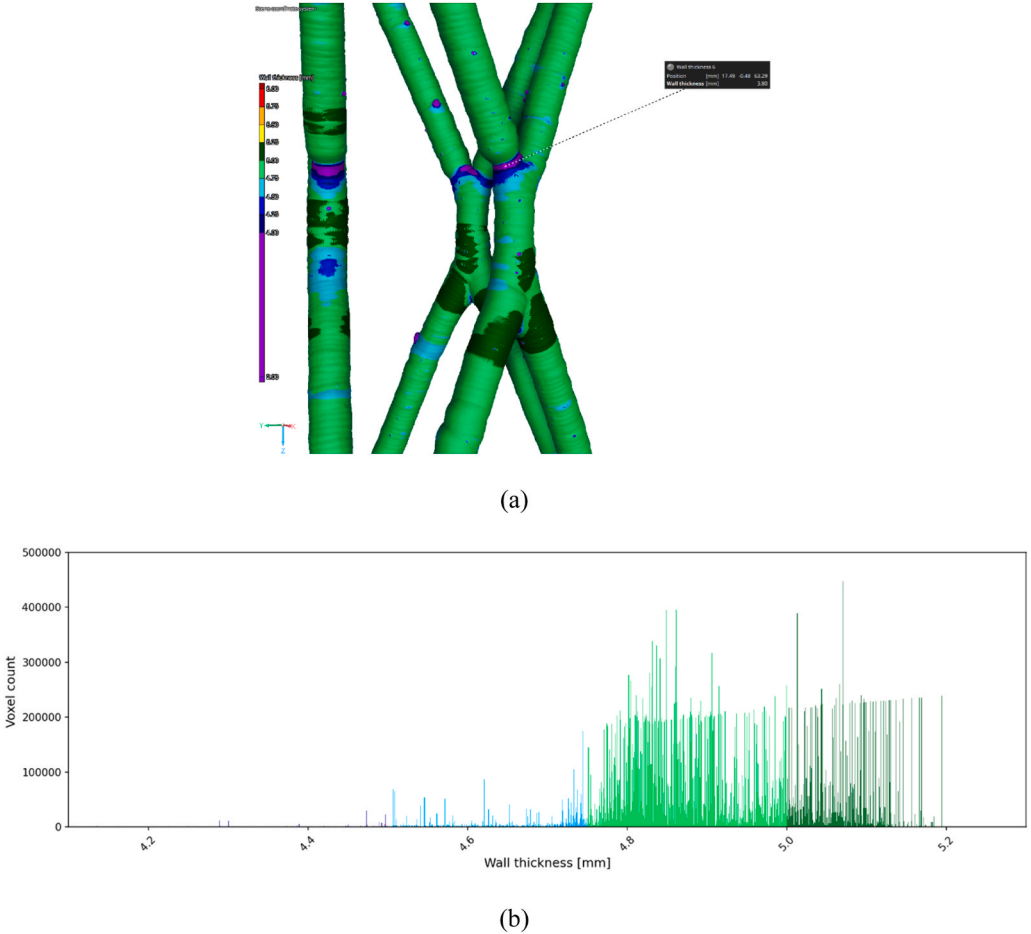


Fig. A2. Wall thickness analysis for specimen SHORT-3f-2: (a) minimum thickness location and (b) wall thickness distribution

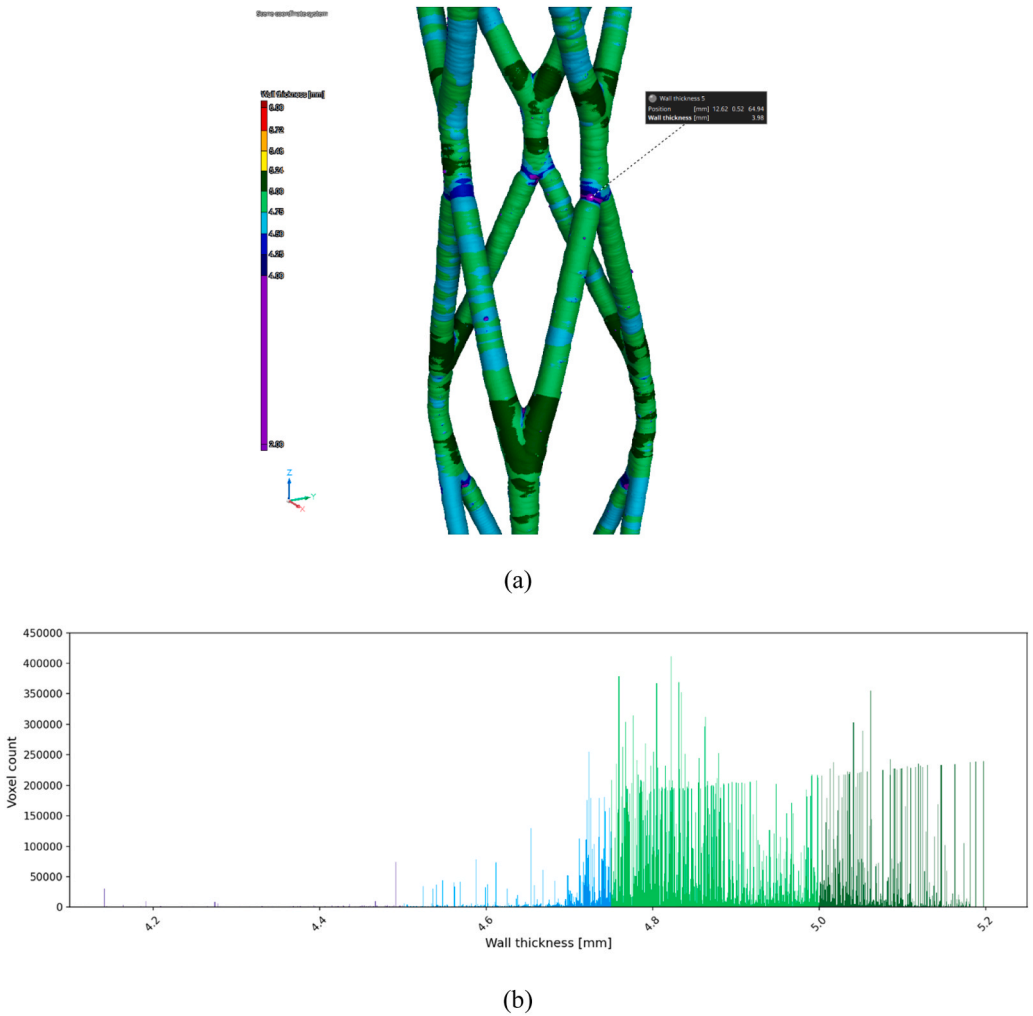


Fig. A3. Wall thickness analysis for specimen SHORT-3f-3: (a) minimum thickness location and (b) wall thickness distribution

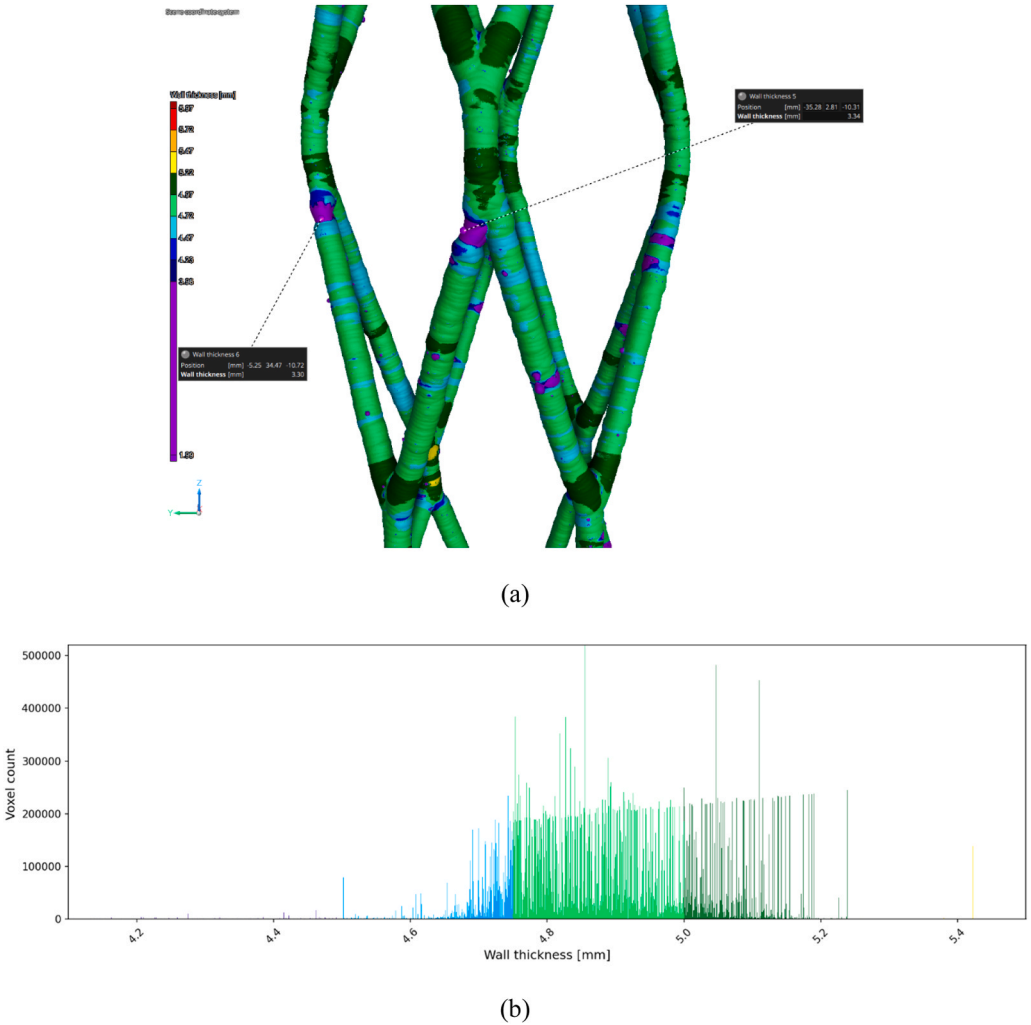


Fig. A4. Wall thickness analysis for specimen SHORT-4f-1: (a) minimum thickness location and (b) wall thickness distribution

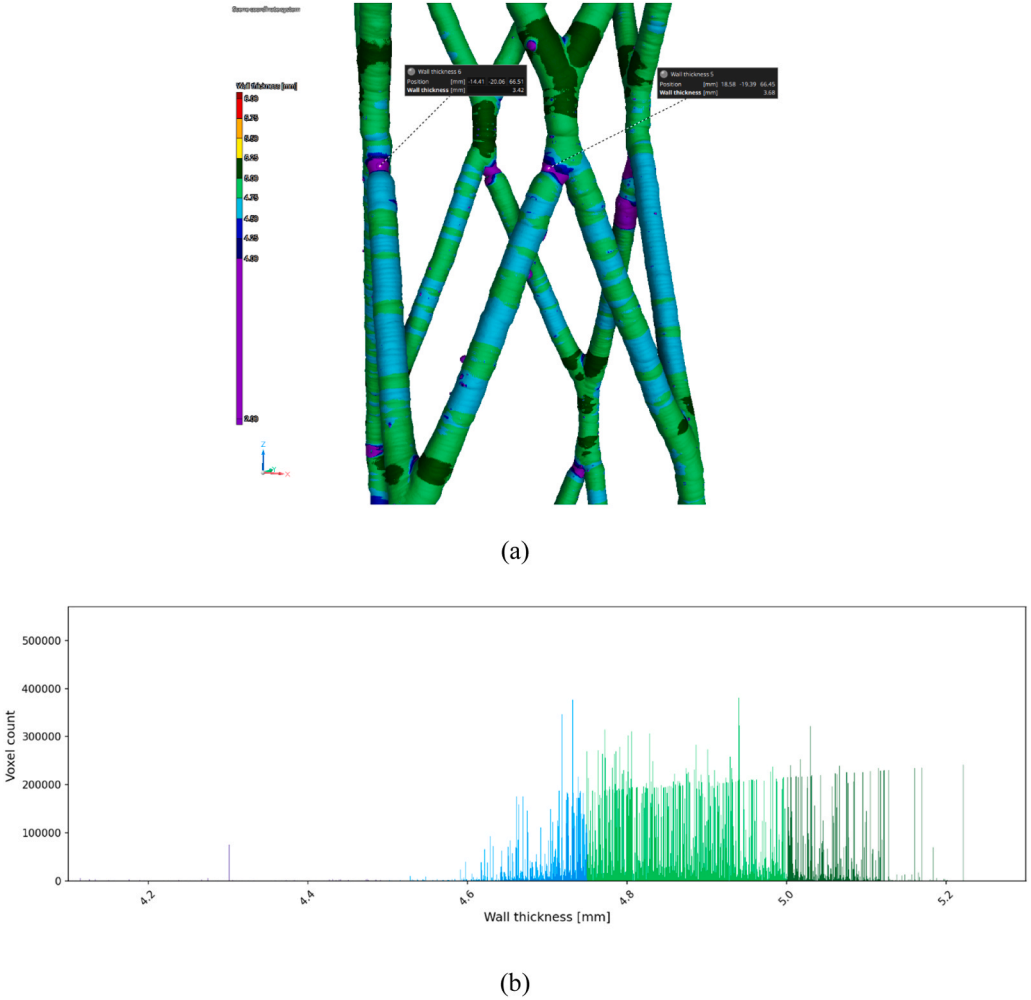


Fig. A5. Wall thickness analysis for specimen SHORT-4f-2: (a) minimum thickness location and (b) wall thickness distribution

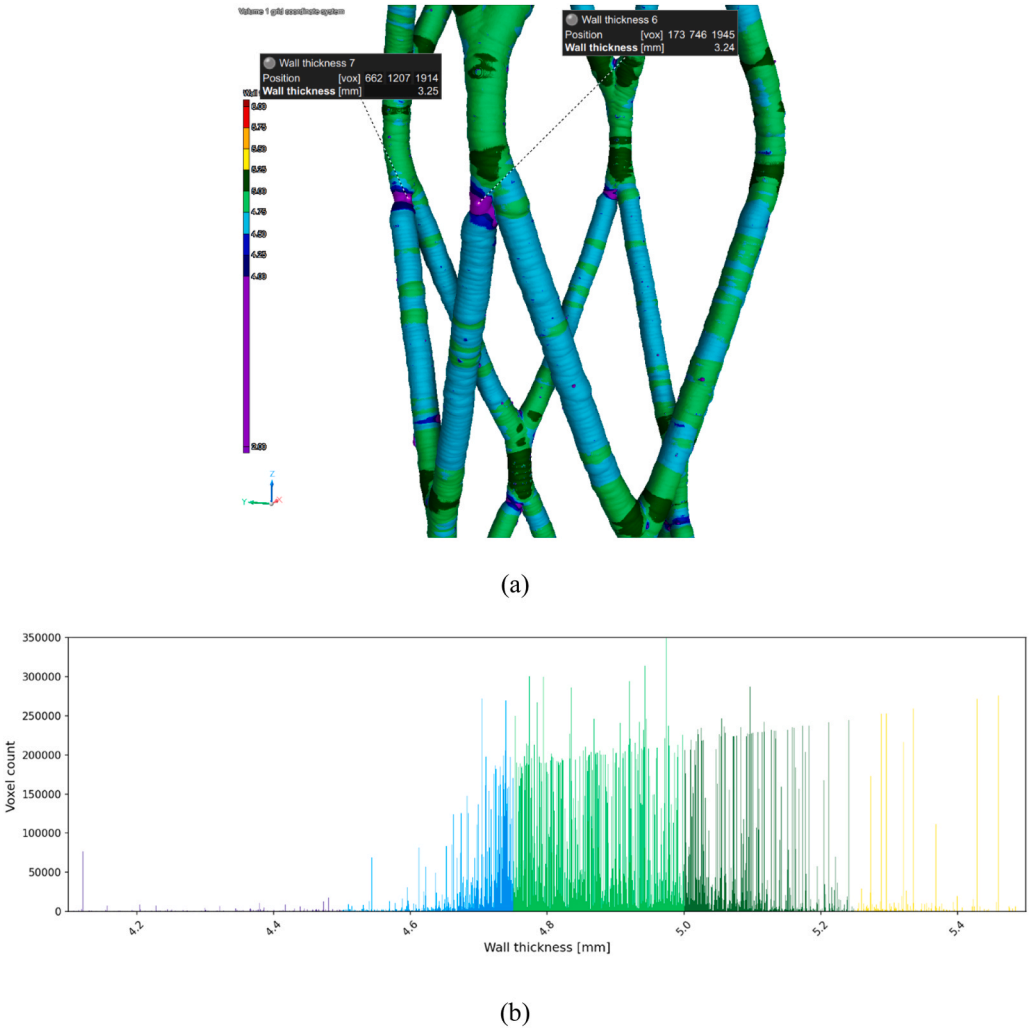


Fig. A6. Wall thickness analysis for specimen SHORT-4f-3: (a) minimum thickness location and (b) wall thickness distribution

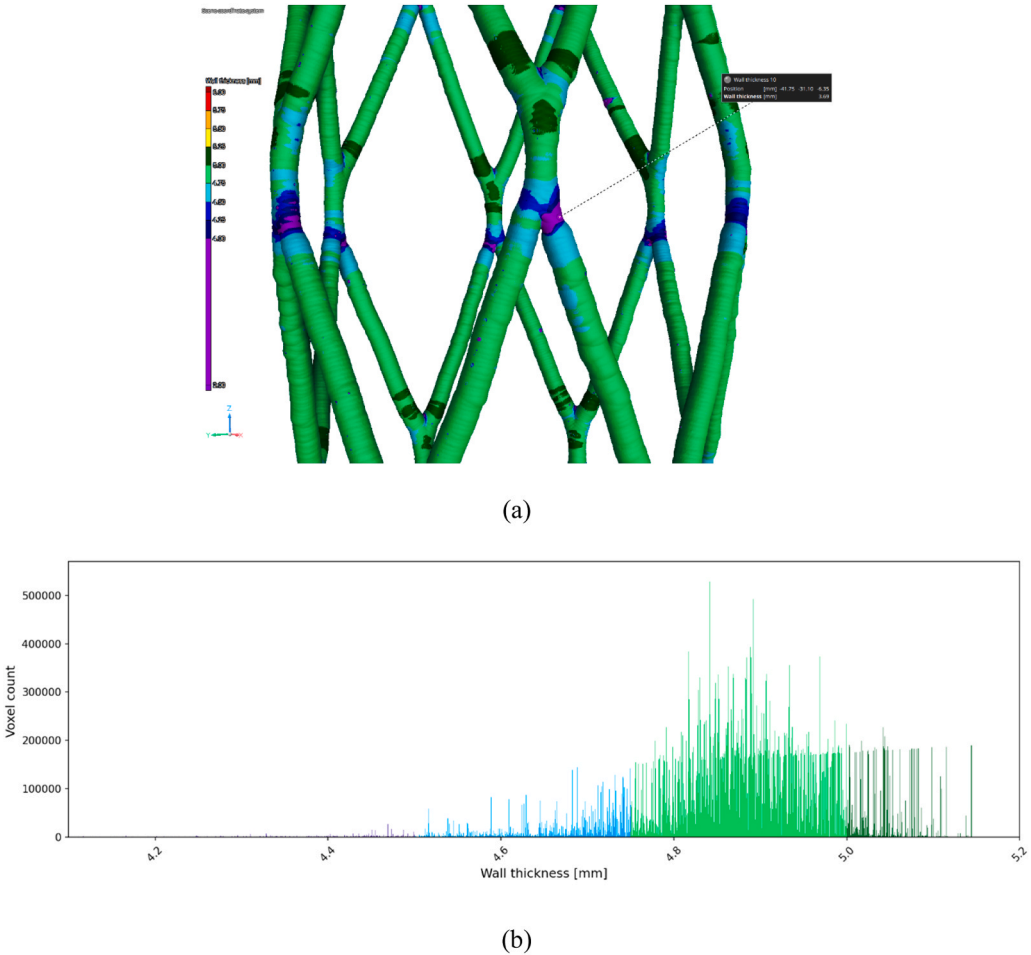


Fig. A7. Wall thickness analysis for specimen SHORT-6f-1: (a) minimum thickness location and (b) wall thickness distribution

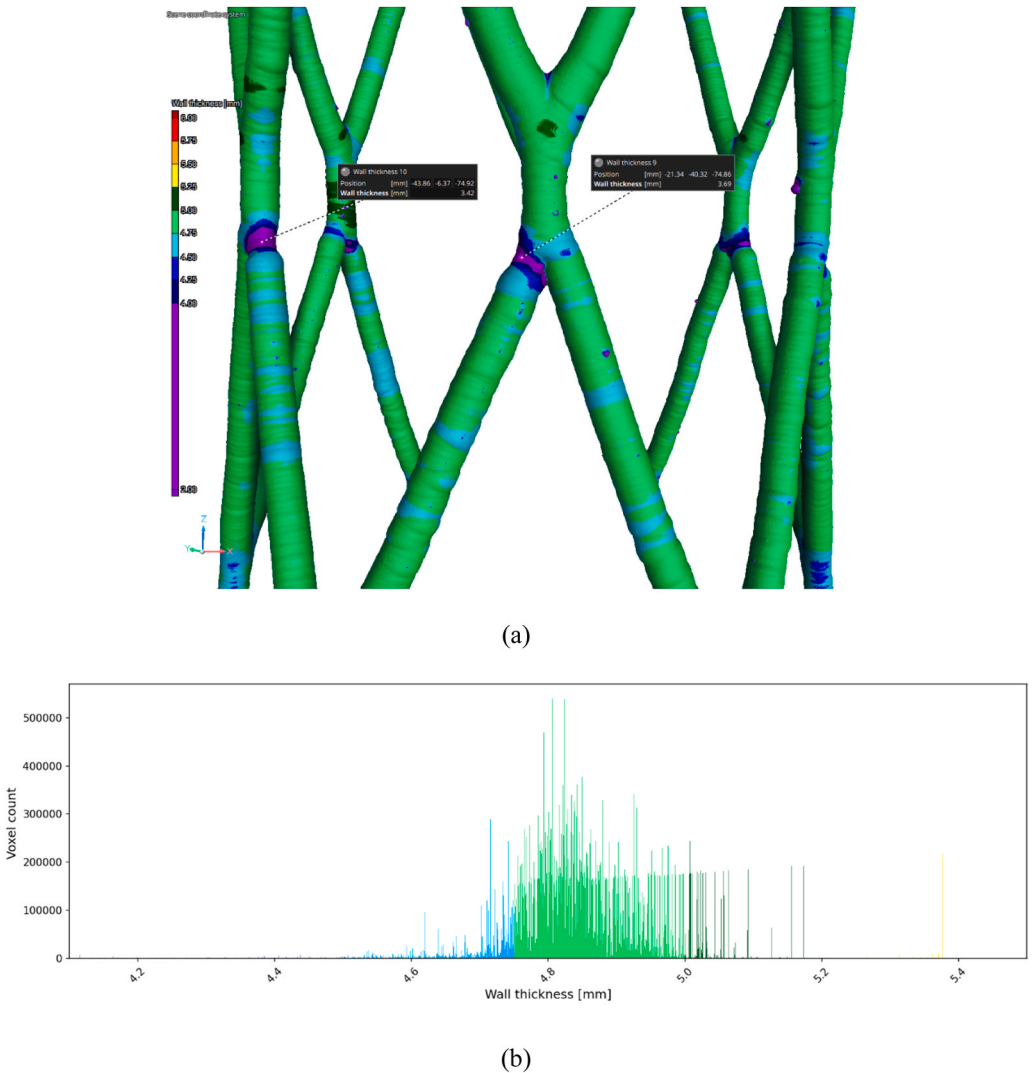


Fig. A8. Wall thickness analysis for specimen SHORT-6f-2: (a) minimum thickness location and (b) wall thickness distribution

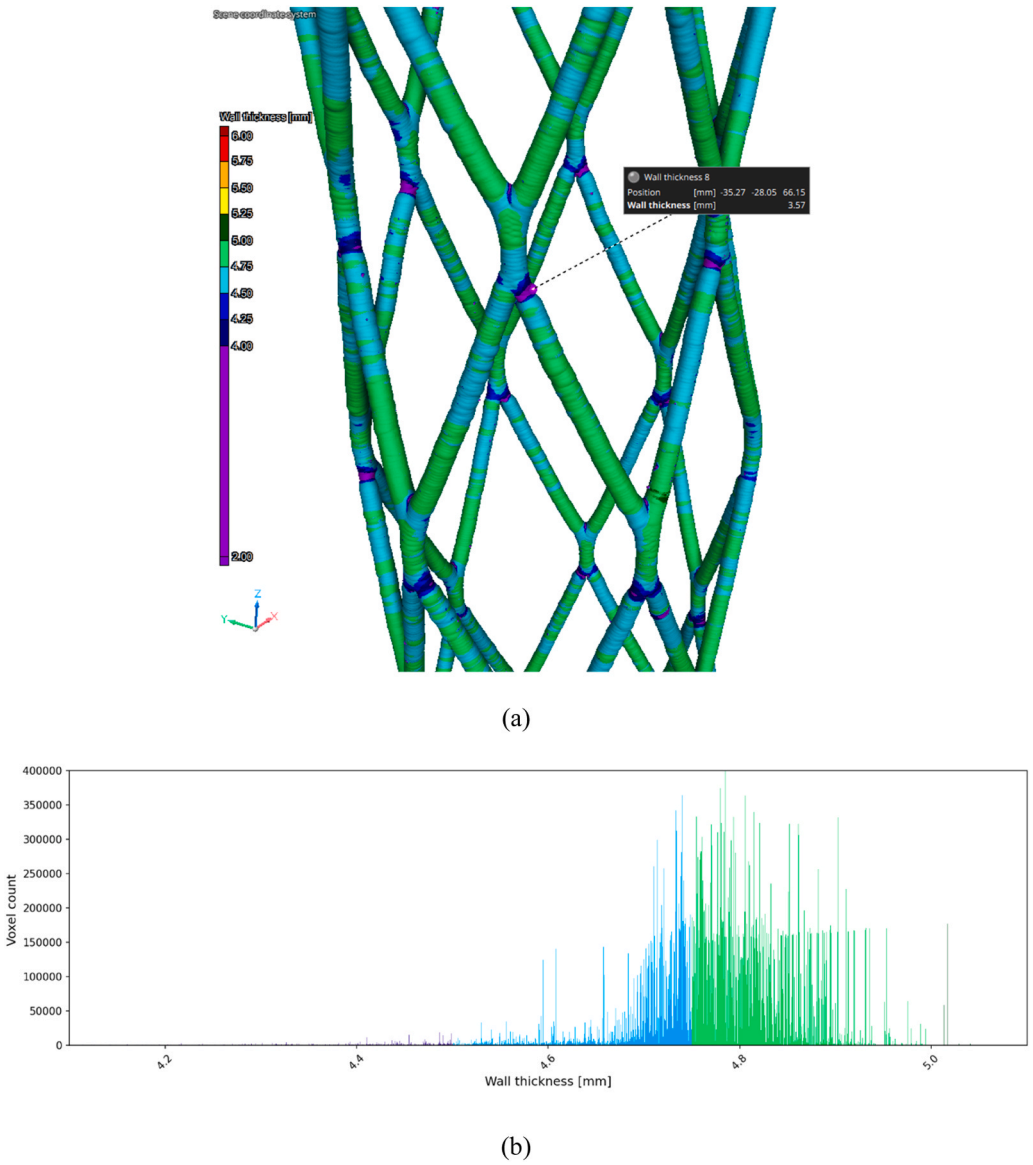


Fig. A9. Wall thickness analysis for specimen SHORT-6f-3: (a) minimum thickness location and (b) wall thickness distribution



Fig. A10. micro-ICT imaging setup

Data availability

Data will be made available on request.

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