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# Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook

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ABSTRACT

Although still in its infancy, metal additive manufacturing (AM) or 3D printing has now arrived at a scale suitable for use in construction. The new technology offers the potential for improved economy, sustainability, safety and productivity through greater automation, enhanced customisation, reduced material usage and reduced wastage. In this paper, a review of recent developments in metal AM in structural engineering is presented, including the latest research advances, current trends and applications in practice. Emphasis is placed on Directed Energy Deposition-arc (DED-arc) AM or wire arc AM (WAAM) since this is deemed to be the most promising technique for the requirements of the construction sector. A description of the observed material response of both steel and stainless steel WAAM elements, as well as the structural behaviour of cross-sections, members, connections and systems, is provided. The challenges surrounding the inherent geometric variability of as-built WAAM material, as well as the implications of possible anisotropy, are discussed.

Optimization and additive manufacturing go hand in hand, with the latter now enabling the former to be more readily realised in practice. Every kilogramme that can be saved by optimization reduces production times and makes additive manufacturing more economical, more sustainable and ultimately more viable. Recent examples of optimized, additively manufactured structural components are presented. Additive manufacturing is likely to complement, rather than replace existing construction methods – with this in mind, hybrid applications, as well as opportunities for strengthening and repair, are explored. The economics and sustainability of WAAM in construction, together with the key influencing parameters, are then discussed. Finally, with a view to the future, the opportunities, outlook and challenges for the wider use of metal additive manufacturing in structural engineering, are presented.

## 1. Introduction

Metal additive manufacturing has already made inroads into a number of engineering disciplines, including in the aerospace [1], bioengineering [2] and maritime [3] sectors, and is beginning to gain traction in structural engineering [4–7]. There are many potential uses and benefits, such as reduced material consumption, the ability to readily produce intricate, optimised structural geometries, less wastage, ease of production in remote locations, mixed materials, hybrid construction, strengthening and repair. There are of course also numerous challenges, barriers and as-yet unanswered questions surrounding, for example, fundamental mechanical properties, consistency of both short-term and long-term structural performance, geometric accuracy and variability, speed and cost of construction, quality assurance, design, certification and so on. Widespread adoption of metal additive manufacturing in structural engineering will require these issues to be addressed. While safety is the primary concern, economics and sustainability are also of crucial importance to the wider application of the technology. With an emphasis on Directed Energy Deposition-arc (DED-arc) AM or wire arc AM (WAAM), the above issues are explored in the present paper. Studies into the fundamental material properties of WAAM steel and stainless steel are reviewed in Section 2. The behaviour of structural cross-sections, members and systems is examined in Section 3. The promising area of WAAM connections is considered in Section 4, including a review of experiments on the ubiquitous lap spice and *T*-stub connection details, produced by WAAM, as well as an exploration of opportunities for more optimised connections. In fact, the subject of optimisation, which is likely to be pivotal to the viability of additive manufacturing in structural engineering, features throughout the paper, including in the context of the exploitation of material anisotropy in Section 2, the geometric optimisation of cross-sections, members and structures in Section 3, connections in Section 4 and strengthening and

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repair in Section 5. Economics and sustainability are addressed in Section 6 and an outlook for the use of metal additive manufacturing in structural engineering is presented in Section 7.

## 2. Material behaviour and influence of surface undulations

The behaviour and design of structures is dominated by the mechanical performance of the constituent material, with strength, stiffness and ductility, as well as fatigue and fracture performance, being among the key properties of interest. The stress–strain characteristics of WAAM materials are discussed in Section 2.1, fatigue and fracture are the subject of Section 2.2, while a brief discussion of other material-related topics is given in Section 2.3.

### 2.1. Stress–strain characteristics

Unlike for traditional hot-rolled and cold-formed structural material, where there are established quality assurance protocols and large bodies of experimental data, for additively manufactured material, such protocols and datasets are hitherto somewhat lacking owing to the relatively fresh introduction of the technology. There have however been a number of recent studies into the tensile mechanical properties of WAAM steels and stainless steels, suitable for construction, as summarised in Tables 1 to 3. Most of the reported coupon tests have been performed on material cut from plates produced using the continuous layer-by-layer WAAM process, though results on bars printed using the dot-by-dot (or point-by-point) WAAM method have also been carried out. For normal strength steel (see Table 1), the majority of tests have been performed on ER70S-6 (EN ISO 14341-A G 42 3M21 3Si1) material, with a nominal yield strength of 420 MPa, while for high strength steel (see Table 2), ER110S-G (EN ISO 16834-A G 69 4M21Mn3Ni1CrMo) material, with a nominal yield strength of 690 MPa, has been the most widely studied. Coupon tests on intermediate strength steel grades are currently limited. For stainless steel (see Table 3), austenitic grade 308LSi has been the most commonly tested, and there remains considerable scope to explore the stress–strain behaviour of other grades produced by WAAM [8].

**Table 1**
Summary of previous studies into mechanical properties of WAAM normal strength steel material.

| Reference | Welding wire | Printed part | No. of tests and orientation |
|---|---|---|---|
| Haden et al. (2017) [9] | ER70S-6 | WAAM plate | 8 tensile coupon tests in 2 orientations |
| Dirisu et al. (2019) [10] | ER70S-6 | WAAM plate | 6 tensile coupon tests in 2 orientations |
| Müller et al. (2019) [11] | ER70S-6 | Dot-by-dot WAAM bars | 3 tensile coupon tests |
| Aldalur et al., (2020) [12] | ER70S-6 | WAAM plate | 24 tensile coupon tests in 2 orientations |
| Kotteman (2020) [13] | ER70S-6 | WAAM plate | 60 tensile coupon tests, 2 nominal thicknesses, in 3 orientations |
| Ermakova et al. (2020) [14] | ER70S-6 | WAAM plate | 4 tensile coupon tests in 2 orientations |
| Lange et al. (2020) [15] | ER70S-6 | WAAM plate | 7 tensile coupon tests in 1 orientation |
| Silvestru et al. (2021) [16] | ER70S-6 | Dot-by-dot WAAM bars | 31 tensile coupon tests on bars built at 2 angles to the vertical |
| Al-Nabulsi et al. (2021) [17] | ER70S-6 | WAAM plate | 7 tensile coupon tests in 2 orientations |
| Xin et al. (2021) [18] | ER70S-6 | WAAM plate | 8 tensile coupon tests in 3 orientations |
| Huang et al. (2022) [19] | ER70S-6 | WAAM plate | 112 tensile coupon tests, two nominal thicknesses, in 5 orientations |
| Guo et al. (2022) [20] | ER70S-6 | WAAM plate | 29 tensile coupon tests, two nominal thicknesses, in 3 orientations |
| Feucht et al. (2022) [21] | ER70S-6 | WAAM plate | 17 tensile coupon tests in 2 orientations |

**Table 2**
Summary of previous studies into mechanical properties of WAAM high strength steel material.

| Reference | Welding wire | Printed part | No. of tests and orientation |
|---|---|---|---|
| Rodrigues et al. (2019) [22] | ER110S-G | WAAM plate | 4 tensile coupon tests in 2 orientations |
| Dirisu et al. (2019) [10] | ER90S-B3 | WAAM plate | 6 tensile coupon tests in 2 orientations; |
| Dirisu et al. (2019) [10] | ER120S-G | WAAM plate | 6 tensile coupon tests in 2 orientations |
| Ermakova et al. (2020) [14] | ER100S-1 | WAAM plate | 4 tensile coupon tests in 2 orientations |
| Sun et al. (2020) [23] | A-Fe-W-86 | WAAM plate | 6 tensile coupon tests in 2 orientations |
| Huang et al. (2022) [19] | ER110S-G | WAAM plate | 25 tensile coupon tests, two nominal thicknesses, in 5 orientations |

**Table 3**
Summary of previous studies into mechanical properties of WAAM stainless steel material.

| Reference | Welding wire | Printed part | No. of tests and orientation |
|---|---|---|---|
| Chen et al. (2017) [24] | 316L | WAAM plate | 3 tensile coupon tests in 1 orientation |
| Haden et al. (2017) [9] | 308LSi | WAAM plate | 8 tensile coupon tests in 1 orientation |
| van Bolderen (2017) [25] | 308LSi | WAAM plate | 6 tensile coupon tests in 2 orientations |
| van Bolderen (2017) [25] | 308LSi | Dot-by-dot WAAM bars | 6 tensile coupon tests |
| Gordon et al. (2018) [26] | 304L | WAAM plate | 7 tensile coupon tests in 2 orientations |
| Laghi et al. (2020) [27] | 308LSi | WAAM plate | 9 tensile coupon tests in 3 orientations |
| Laghi et al. (2020) [28] | 308LSi | WAAM plate | 10 tensile coupon tests in 2 orientations |
| Kyvelou et al. (2020) [29] | 308LSi | WAAM plate | 51 tensile coupon tests in 3 orientations |
| Pragana et al. (2021) [30] | 316L | WAAM plate | 3 tensile coupon tests in 3 orientations |
| Tonelli et al. (2021) [31] | 308LSi | WAAM plate | 26 tensile coupon tests in 3 orientations, considering active and natural cooling |
| Laghi et al. (2021) [32] | 308LSi | WAAM plate | 44 tensile coupon tests in 2 orientations |
| Laghi et al. (2022) [33] | 308LSi | Dot-by-dot WAAM bars | 29 tensile coupon tests; bars built at 3 angles to the vertical |
| Evans and Wang (2022) [34] | 316L | WAAM plate | 6 tensile coupon tests in 3 orientations |

From the studies listed in Tables 1 to 3, the following conclusions can be drawn: (1) there is a growing body of data demonstrating the sound mechanical response of WAAM material, (2) cooling rates, as influenced by heat input, build geometry, proximity to build plate and the use of active cooling [31,35,36] affect the mechanical properties and speed of production, (3) the strengths of WAAM steels are typically lower than the stated nominal values owing to the slower cooling conditions (relative to traditional welding) and the repeated thermal cycles experienced, (4) varying degrees of anisotropy can arise, depending on the material type and thermal gradients experienced during printing, and (5) surface undulations (roughness) cause a weakening effect on the mechanical properties, emphasising the importance of print quality. The data summarised in Tables 1 and 2, together with additional results, have been analysed in [37] and used to propose stress–strain models (i.e. predictive expressions to describe the form and key points of the uniaxial

engineering stress–strain curves) for WAAM steels. The importance of the WAAM welding method (Gas Metal Arc Welding – GMAW, Gas Tungsten Arc Welding – GTAW and Plasma Arc Welding), process parameters (e.g. voltage, current, type of shielding gas and flow rate), deposition strategy or path planning (e.g. parallel and oscillating) and interpass temperature has also been studied and shown to influence productivity, residual stresses, geometric accuracy, defects and mechanical properties [12,38–43]. It was shown in [37] that excessively high interpass temperatures have a clear negative effect on the material yield strength. The link between surface undulations and WAAM printing parameters was systematically studied in [44]; it was found that lower interpass temperatures and lower wire feed speeds generally resulted in improved surface quality, but at the expense of deposition rates.

Structural steel generally exhibits essentially symmetric stress–strain behaviour i.e. the tensile and compressive responses are very similar. For this reason, mechanical properties are typically determined by means of tensile coupon tests, which are more straightforward to perform than their compressive counterparts owing, particularly in the case of coupons cut from sheet material, to the challenge of preventing buckling without restraining Poisson expansion [45]. The study presented in [46] indicated a similar situation of very mild tension–compression asymmetry for WAAM low alloy steel; comparable results were also shown in [47] for nickel–chromium alloys produced by laser powder bed fusion.

In the comprehensive study presented in [19], steel tensile coupons of two nominal thicknesses ($t_{nom}$ = 3 mm and 8 mm) were tested in five directions relative to the print layer orientation, in both the as-built (i.e. with no surface machining after printing) and machined (i.e. where the surface undulations were removed after printing by machining) conditions, as shown in Fig. 1. The coupon testing direction can be seen in Fig. 1 from the surface undulations and was defined though the angle θ relative to the print layer orientation, with θ = 0° corresponding to coupons where the print layers were parallel to the testing direction and θ = 90° corresponding to coupons where the print layers were perpendicular to the testing direction. There are strong practical and economical incentives to use WAAM parts in their as-built condition (i.e. avoiding machining operations), particularly at the scale of elements required for structural engineering, but the consequences of the lower geometric accuracy and the likely poorer mechanical and fatigue performance need to be understood and suitably accounted for. In some instances, subsequent machining will be necessary to ensure that the geometric tolerances or performance requirements of the printed parts are met [48,49].

Typical stress–strain (σ-ε) curves obtained from tensile tests on 3 mm thick as-built steel coupons [19] are presented in Figs. 2 and 3. Note that the stress was calculated based on the average cross-sectional area along the parallel length of the coupons. The initial stages of the stress–strain responses are shown in Fig. 2, where a relatively small change in Young's modulus and yield strength, of up to about 10 %, with loading direction can be seen; as expected, reducing effective properties with increasing angle θ are observed, with θ = 90°, where loading is across the print layers, exhibiting the weakest response. Note that the yield response is slightly rounded, as opposed to the sharply defined yield point typically associated with hot-rolled steel; this is caused by the geometric surface undulations resulting in some cross-sections of the coupons yielding slightly before others. The underlying material stress–strain response, as determined from tensile tests on machined coupons, exhibited the anticipated sharply defined yield response [19].

The full range stress–strain curves are shown in Fig. 3, revealing the more pronounced influence of loading direction on ductility. This is to be expected, since, upon the onset of plasticity, more concentrated regions of deformation arise in the localised troughs of the as-built geometry, particularly in the θ = 90° coupons, as can be clearly seen in the longitudinal strain fields obtained by means of digital image correlation (DIC) shown in Fig. 4 [19], and reduce the observed ductility when

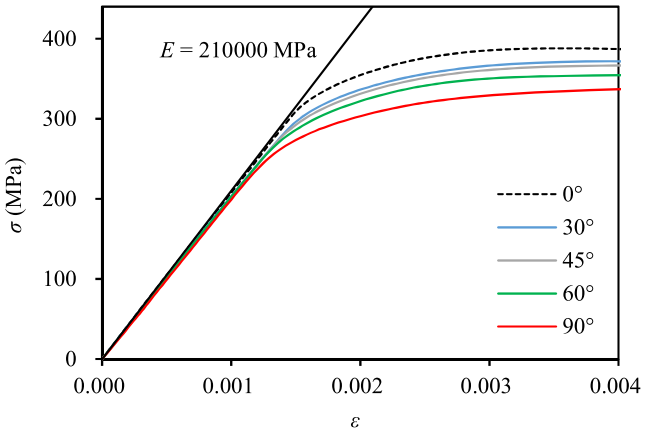



**Fig. 2.** Initial stage of stress–strain curves obtained from tensile coupons on as-built WAAM steel material tested in [19].

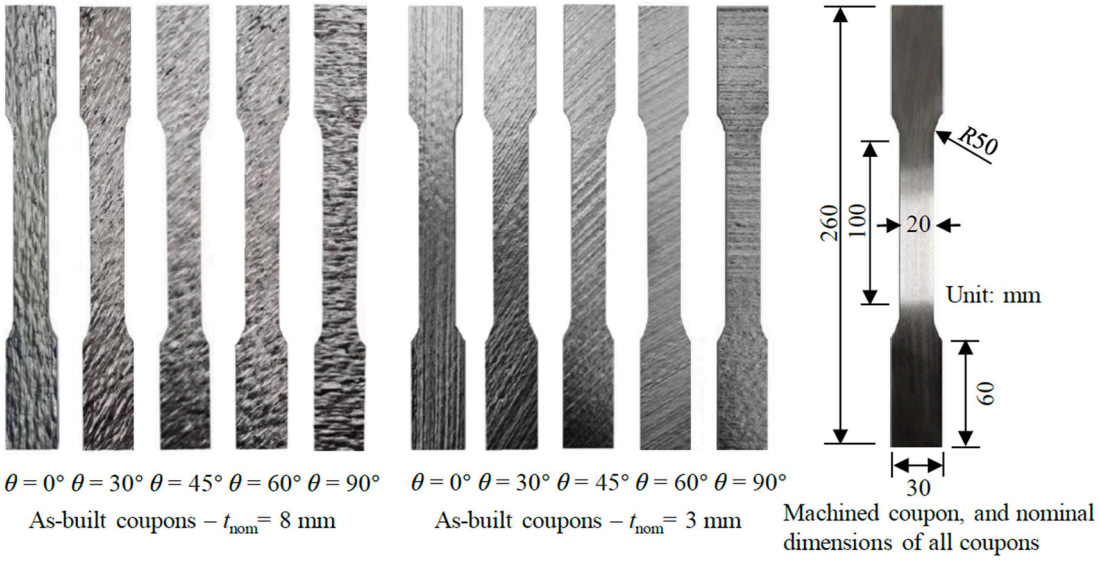



**Fig. 1.** WAAM tensile coupons, extracted at different angles $\theta$ relative to the print layer orientation [19].

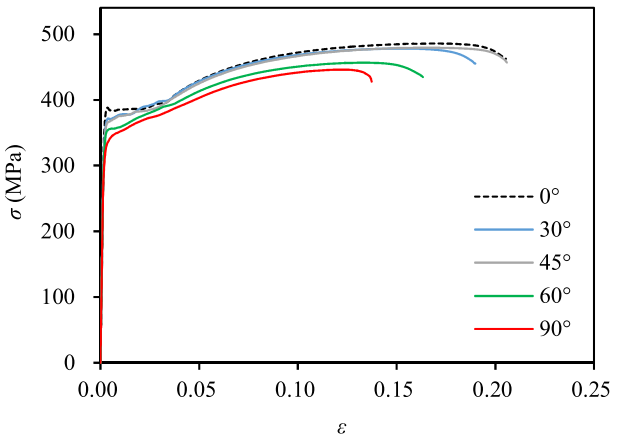



**Fig. 3.** Full range stress–strain curves obtained from tensile coupons on as-built WAAM steel material tested in [19].

measured over the full parallel length. Less variation in properties was observed for the machined coupons, for which the response was shown to be almost isotropic.

Corresponding stress–strain curves from typical tensile tests on machined and as-built stainless steel coupons [29] are shown in Figs. 5 and 6, respectively. Far greater variation in properties between loading directions can be observed. This time, the variation was caused by a combination of anisotropy in the underlying material properties, as determined from the tensile tests on the machined coupons (see Fig. 5), together with the influence of the as-built geometry (see Fig. 6). The weakening effect of the as-built geometry (i.e. the greatest reduction in mechanical properties from the machined to the as-built coupons) can again be seen to be most severe when loading is in the $\theta = 90°$ direction.

The primary source of the underlying anisotropy was identified by means of electron backscatter diffraction (EBSD) analysis, which revealed that the tested material had a strong crystallographic texture, induced by the thermal gradients that arose during the printing process. Typical pole figures, revealing the predominance of $\langle 1\,1\,0 \rangle$ and $\langle 1\,1\,1 \rangle$ type crystal orientations in the 45° direction, hence explaining the stiffer response in this direction, are shown in Fig. 7, with the axes LD, TD and ND being parallel (i.e. $\theta = 0°$), transverse (i.e. $\theta = 90°$) and normal to the print layer orientation. Similar findings were reported in [50] for thick-walled WAAM stainless steel plates, which experience more complex multi-directional thermal gradients. Constitutive models to describe the observed anisotropic response of WAAM stainless steel in both the elastic [51,52] and plastic [52] ranges have been established, while optimisation studies seeking to exploit the anisotropy in additively manufactured structures have also been performed [53,54].

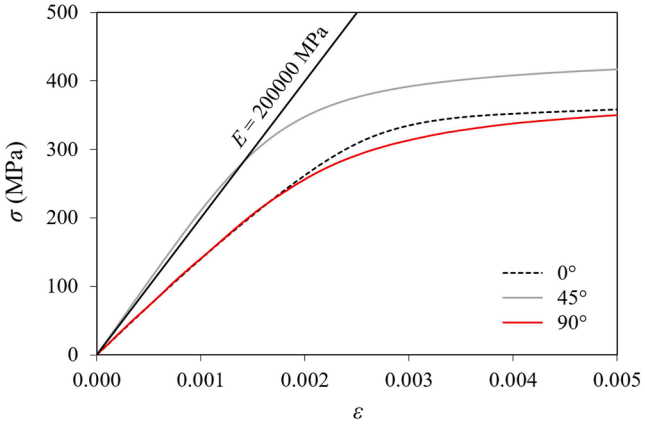



**Fig. 5.** Initial stage of stress–strain curves obtained from tensile coupons on machined WAAM stainless steel material tested in [29].

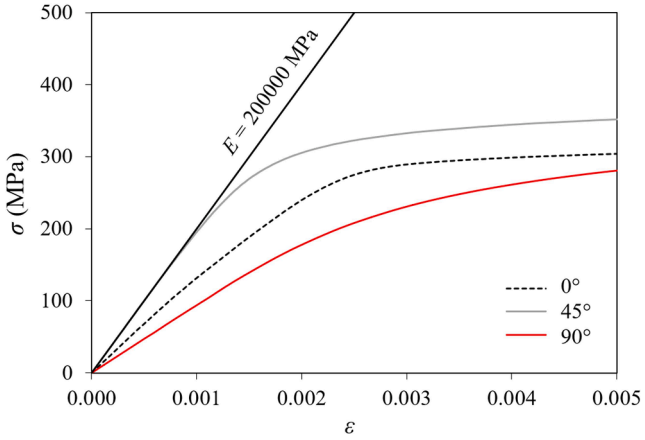



**Fig. 6.** Initial stage of stress–strain curves obtained from tensile coupons on as-built WAAM stainless steel material tested in [29].

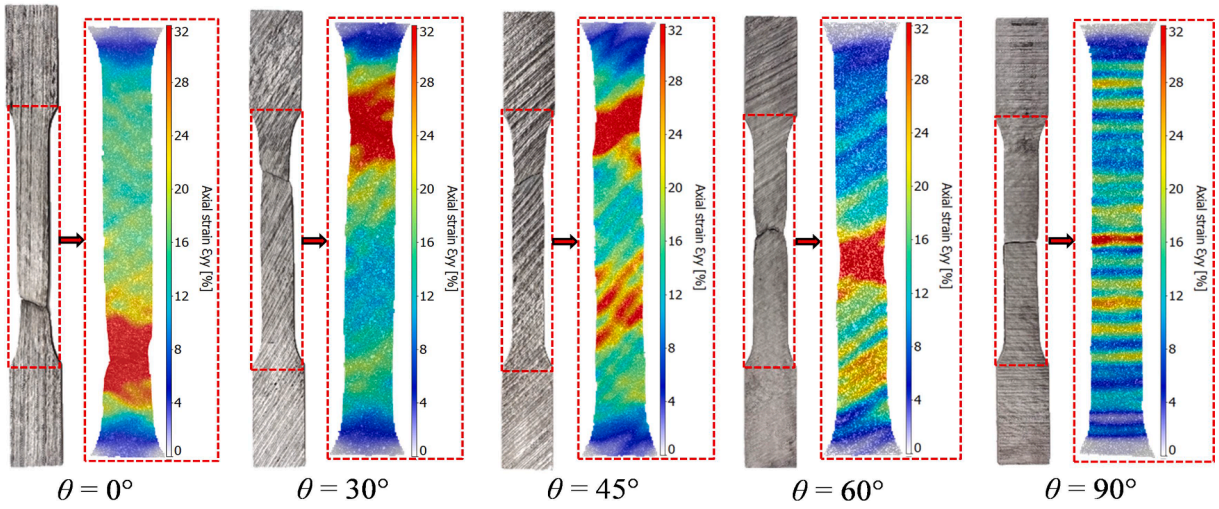



**Fig. 4.** Fractured tensile coupons and longitudinal strain fields at fracture obtained from DIC for as-built WAAM steel material tested in [19]. Strains become more concentrated, resulting in reduced ductility, as measured over the full parallel length, with increasing angle $\theta$.

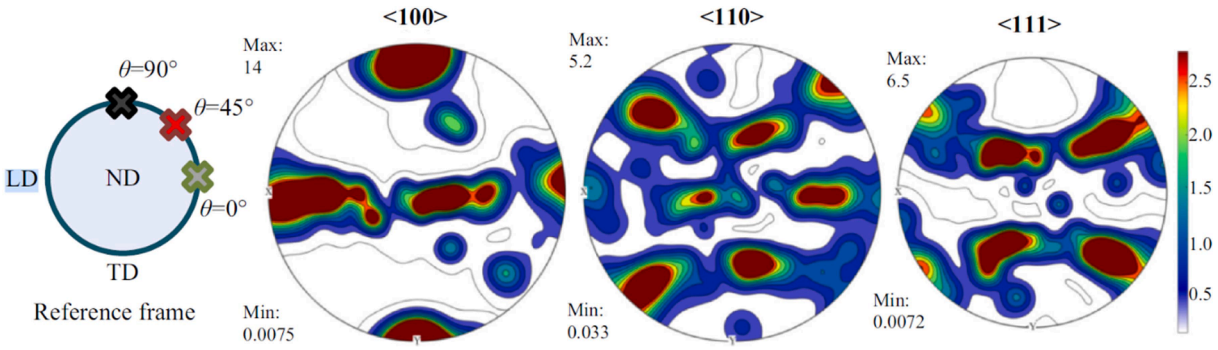



**Fig. 7.** Pole figures of WAAM stainless steel presented in [29].

The formability of WAAM sheets and cylinders has been examined in recent studies. Specifically, the feasibility of using WAAM stainless steel in sheet metal forming operations, which involve large plastic deformations, was investigated in [30]; it was found that the additively manufactured sheets could met the required deformation demands. In [55], the feasibility of flow-forming WAAM steel and stainless steel cylinders into tubular profiles was investigated; again, positive results were achieved. Both studies [30,55], together with the hybrid hot-rolled and WAAM process route presented in [42], show the potential for using WAAM in combination with other forming processes.

### 2.2. Fatigue and fracture

Studies into the fatigue and fracture properties of WAAM material, particularly structural steels, are relatively limited in number to date, although valuable insights can be gained from previous analyses of conventional welds [26]. Dedicated investigations are nonetheless required to assess the influence of build geometry, thermal history, direction of loading relative to the weld layer orientation and residual stresses on the fatigue and fracture performance. Consideration should also be given to the surface finish i.e. whether the surface has been machined to a smooth finish or left in its undulating as-built condition, which is likely to have a strong influence on the fatigue performance, even more so than under static loading.

Fatigue refers to the initiation and propagation of cracks under variable stress conditions, and is particularly important in structures or parts of structures where cyclic loading is prevalent, such as in road and rail bridges. Fatigue performance is hindered by the presence of defects, such as pores and surface undulations (that are characteristic of WAAM parts in the as-built condition), which create local stress concentrations and act as fatigue crack initiation sites. Microstructure and residual stresses also play an important role. Some small pores (generally resulting from gas being trapped in the weld pool during solidification) and a moderate degree of surface roughness is inevitable in AM parts, while larger defects tend to be associated with sub-optimal process parameters [56] or welding conditions. Gordon et al. [26] reported that the resistance to fatigue crack growth of WAAM stainless steel in the machined condition compared favourably to that of conventionally formed material. Bartsch et al. [57] studied the fatigue behaviour of WAAM G3Si1 structural steel, produced using both single-wire and multiple-wire printing, in the as-built condition, and proposed preliminary design recommendations. It was noted that avoiding machining (and hence maintaining the as-built surface condition) was not only desirable from a cost point of view but may also be necessary for accessibility reasons. Based on experimental results and numerical results with simulated surface roughness, preliminary S—N (stress range versus number of cycles to failure) curves were explored for WAAM structural steel in the as-built condition. A nominal stress-based fatigue class (FAT) of 125 MPa (i.e. a reference fatigue stress of 125 MPa at $2 \times 10^6$ cycles) with an inverse slope of $m = 5$ was found to be reasonable for the tested WAAM structural steel produced using single-wire printing. The general applicability of the effective notch stress concept (ENSC) [58] to WAAM material was also demonstrated, and an ENSC FAT class of 755 MPa with $m = 5$ was put forward for the same material based on a maximum observed notch factor $k_n$ of 5.9, though it was noted that further experimental verification of these of initial proposals is required.

Fracture toughness refers to the ability of a cracked material to resist brittle fracture and is essential for structural integrity [59]. The fracture toughness of ER70S-6 WAAM material has been studied in [10,14,60], while higher grades were also tested in [10,14,61]. The WAAM material was found to have lower fracture toughness than that typically observed, and both anisotropy and specimen location dependency were seen in the measured properties, with the latter relating to the different thermal histories to which the material was subjected. Notched bar impact tests on ER70S-6 WAAM material were reported by Feucht et al. [21] and shown to satisfy the EN 10025–2 [62] impact energy requirements.

### 2.3. Further investigations into performance of WAAM material

The corrosion performance of WAAM ER70S-6 steel has been studied in [63] by means of immersion testing, salt spray testing and electrochemical analysis. Stress corrosion behaviour was also assessed. It was concluded that there was no deterioration in corrosion performance relative to equivalent conventionally produced material. The wear resistance of WAAM mild steel and stainless steel has been studied in [9], while insight into the elevated temperature performance of WAAM steel has been obtained in [64]. Further research is needed on these topics.

## 3. Cross-section, member and system behaviour

The behaviour and design of metal additively manufactured cross-sections, members and systems have been examined experimentally in a number of recent studies. These studies can be divided into two broad categories: (1) those featuring tests on standard geometries (such as tubular members with square and circular cross-sections) designed to enable the influence of the manufacturing method (e.g. WAAM) to be isolated and to allow comparisons to be made against the structural performance of equivalent conventionally produced sections as well as that predicted by current design provisions, as described in Section 3.1 and (2) those involving tests on more intricate and optimised geometries that can provide insight into the material savings and performance enhancements that can be achieved through additive manufacturing, as described in Section 3.2.

### 3.1. Structural elements with standard geometries

At the cross-section level, stub column tests on square and circular hollow sections (SHS and CHS respectively), produced by laser powder bed fusion (PBF), have been reported in [65–67]. For specimens

produced by WAAM, tests on SHS stub columns have been reported in [68], while tests on CHS stub columns have been reported in [25,28]. Tests on angle section stub columns have been presented in [34]. The experiments performed on the SHS enable the local buckling behaviour of WAAM plates with simply-supported boundary conditions on both longitudinal edges, termed internal elements [69,70], to be studied, while the experiments carried out on the angle sections allow the local buckling behaviour of WAAM plates with one longitudinal edge simply-supported and the other free, termed outstand elements [70,71], to be studied. Bending tests on WAAM CHS and SHS have been presented in [25] and [72], respectively. The latter study included SHS specimens with a range of cross-section dimensions and local slenderness values (covering all four cross-section classes with $c/t\varepsilon$ ranging from 17.1 to 51.5, where $c$ is the flat plate width of the SHS, $t$ is the plate thickness and$\varepsilon = \sqrt{(235/f_y)/(E/210000)}$, in which $f_y$ and $E$ are the 0.2 % proof (yield) strength and Young's modulus of the as-built material respectively), as well as irregular tubular cross-sections, as part of the verification of the MX3D bridge – the tested specimens are shown in Fig. 8.

The results revealed that additively manufactured structural elements generally follow the anticipated behavioural trends of conventionally produced sections and exhibit good ductility and familiar failure modes, though geometric imperfections (e.g. out of flatness) and variability of geometry (e.g. wall thickness) and load-carrying capacity tend to be higher than for conventionally produced sections. Typical failure modes for the tested WAAM tubular stub columns and beams [72] are shown in Fig. 9.

Full section tension tests on WAAM steel CHS were reported in [73]; the experimental resistances were found to be consistent with those of conventional rolled elements. Tests on WAAM bearing stiffeners were also reported in [73,74] and shown to provide comparable resistances to conventional, manually welded stiffeners.

The behaviour and load-bearing capacity of structural elements, particularly those where stability effects are dominant, are well known to be influenced by the presence of geometric imperfections and residual stresses [75], both of which are strongly related to the method of manufacture. Geometric imperfections are typically considered at two levels – (1) cross-sectional (or local) geometric imperfections that have half-wavelengths that are broadly similar to the cross-section dimensions and are important for triggering local buckling [76], and (2) member (or global) imperfections in the form of an out-of-straightness (or bow) along the member length [75], which are important for triggering member buckling. Note that the described local geometric imperfections are distinct from the surface undulations mentioned above – the difference between the two is shown in Fig. 10 [68]. Local and global geometric imperfection amplitude measurements in WAAM stainless steel profiles have been reported in [68,72] and [77,78] respectively, based on the analysis of laser scan data. More data and deeper analysis will be needed to determine statistical information on geometric imperfection amplitudes in WAAM structural elements, and the concept of quality classes, as used in shell structures [79], could be introduced based on tolerable imperfection levels.

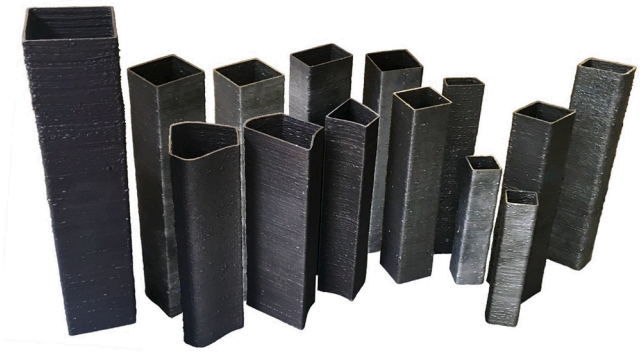


**Fig. 8.** WAAM steel tubular specimens tested in bending in [72].

Residual stresses in additively manufactured structural elements will generally be higher than those in conventional structural elements owing the high thermal gradients that exist during production. Early measurements of residual stresses in WAAM stainless steel plates and tubes have been presented in [80], revealing compressive residual stresses in the print layer direction (i.e. the circumferential direction in tubes built vertically) near to the base plate and tensile residual stresses away from the base plate. Residual stresses measurements on additively manufactured high strength steel hollow sections, produced by selective laser melting, have been reported in Yan et al. [81]. It should of course be borne in mind that the distribution of residual stresses is also related to the printing strategy; strategies can be sought in which the residual stresses are minimised or even 'tuned' to have a positive influence on structural performance. Further experimental and numerical studies are needed on this topic.

With the structural design of cross-sections in mind, initial comparisons [68,72] have shown that provided the weakening effect of the geometric undulations inherent to as-built WAAM profiles are considered through the use of mechanical properties derived from coupon tests on as-built, rather than machined, material, reasonably accurate capacity predictions are obtained using established design methods, such as those set out in EN 1993-1-1 [82] and AISC 360 [83]. The weakening effect of the as-built geometry on the effective mechanical properties typically amounts to a reduction in capacity, relative to a conventionally formed section, of around 10 %, though this depends on the quality of the printing.

At the member level, buckling tests on WAAM stainless steel SHS and CHS columns have been presented in [25,73,77], while buckling tests on WAAM steel CHS columns have been reported in Kraus et al. [78]. Compression tests on stainless steel bars, produced using the dot-by-dot printing method, have been described in Laghi et al. [84]. A typical buckled WAAM stainless steel SHS column, with DIC results, is shown in Fig. 11 [77].

Despite generally having slightly larger initial imperfections, the structural performance of the WAAM columns tested in [77,78] was comparable with that of conventionally produced members and, as in the case of cross-section level design, it was shown that, provided the effective mechanical properties associated with the as-built material are used, reasonably accurate predictions of the load-carrying capacity of WAAM structural members are achieved using existing design formulae. This can be seen in the results presented in Fig. 12 for the stability design of WAAM stainless steel members [77], where the ultimate loads achieved in a series of column buckling tests $N_u$, normalised by the corresponding yield loads $N_y = Af_y$, where $A$ is the cross-sectional area of the column and $f_y$ is the yield (0.2 % proof) strength based on coupon tests conducted on as-built material, have been plotted against the relative slenderness$\bar{\lambda}$, defined as:

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} \tag{1}$$

where $N_{cr}$ is the elastic buckling load of the column. The trend of the WAAM stainless steel column test data follows closely the buckling curve specified in prEN 1993-1-4 [85,86] for the design of hot-finished SHS/CHS and cold-formed CHS columns. While further analysis is required to determine suitable safety factors for the structural stability design of WAAM members, the comparisons shown in Fig. 12 demonstrate that the general behaviour of WAAM tubular columns is similar to that of their conventionally formed counterparts, providing a firm basis for further developments, including the production and assessment of more optimised WAAM profiles.

### 3.2. Structural elements and systems with optimised geometries

Additive manufacturing lends itself, to a far greater extent than

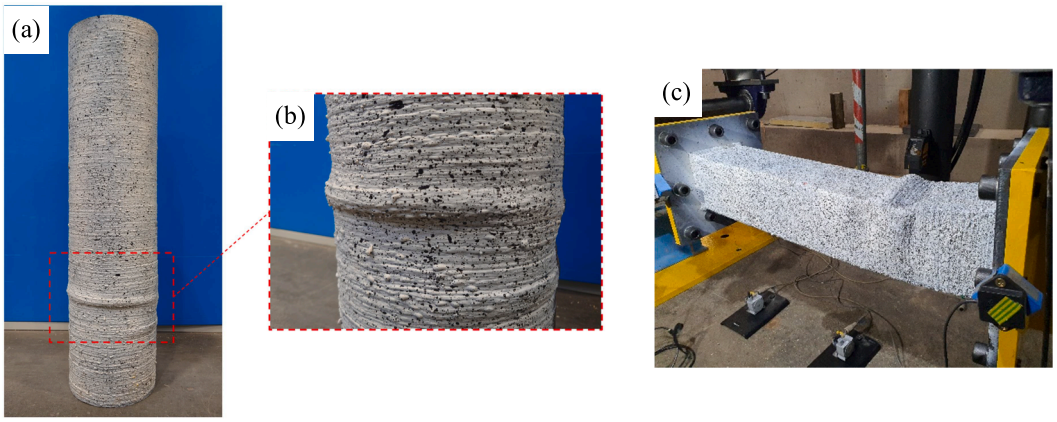



**Fig. 9.** Typical failure modes from tests on WAAM tubular cross-sections showing (a) an overall and (b) a close up of local buckling of a CHS stub column and (c) local buckling of the compression flange of an SHS beam [72].

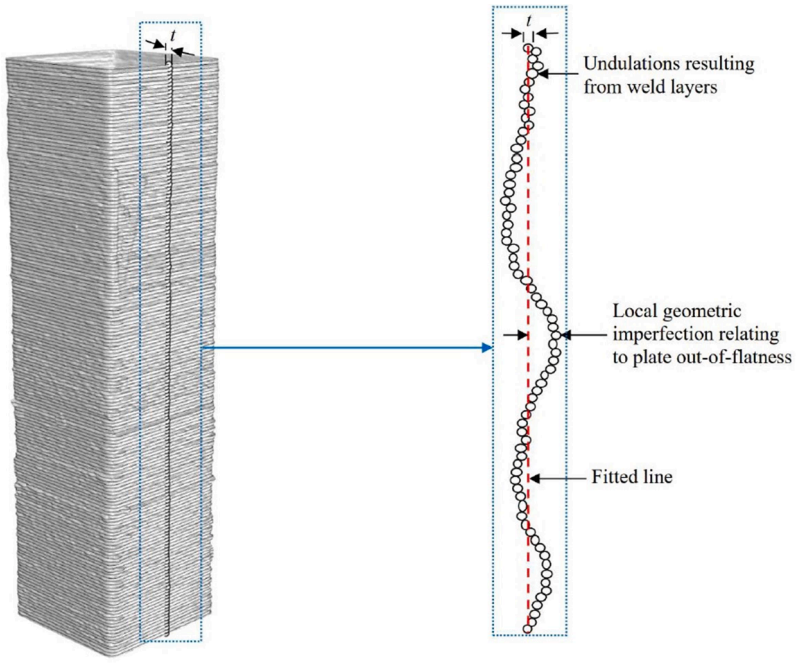



**Fig. 10.** Distinction between surface undulations (roughness) and local geometric imperfections in WAAM tubular sections [68].

conventional manufacturing processes, to the production of optimised geometries. Early studies into the simulation and testing of structural elements optimised for additive manufacturing have been performed over the past few years. Wang et al. [87] explored numerically the potential benefits that could be gained by printing plates with deliberate geometric imperfections that delay local buckling and hence enhance load-carrying capacities. An analogous study [88,89] on corrugated shells – see Fig. 13, featured geometric optimisation [89], additive manufacturing by powder bed fusion and structural simulations and testing [88]. The corrugated shells were shown to offer considerably enhanced load-carrying capacities and reduced sensitivity to imperfections relative to reference circular shells. Additively manufactured steel beams with corrugated webs have been explored in Abureden et al. [90]. The capacity for energy absorption of additively manufactured circular tubes with varying wall thicknesses under lateral loading was investigated in Baroutaji et al. [91]; compared to circular tubes of uniform thickness, the additively manufactured tubes were found to absorb about 80 % more energy per unit mass.

The optimisation and manufacture of a 2 m stainless steel diagrid column, produced using the dot-by-dot WAAM method, were described in Laghi et al. [92]. The optimisation featured mechanical data obtained from prior tests on individual bars loaded in tension and compression. The study highlighted the importance of taking due account of the particular imperfections associated with the adopted WAAM method and provides insight into the design process and outcomes for optimised WAAM structures. An end-to-end framework for the design, optimisation and manufacturing of WAAM trusses was presented in Ye et al. [93], in which 2 m span trusses with different boundary conditions were produced. The trusses, an example of which is shown in Fig. 14, featured members of varying cross-sectional dimensions (diameter and thickness) to match the demands imposed by the applied loading, but also considering manufacturing constraints. The trusses were shown to provide structural solutions that utilised approximately half the amount of material in comparison to benchmark steel I-section beams. A blended structural optimisation approach featuring topology optimisation, basic principles, manufacturing constraints and numerical simulations, was put forward in Laghi et al. [94], and similar material savings to those achieved by Ye et al. [93] were quoted. The optimisation study of [94]

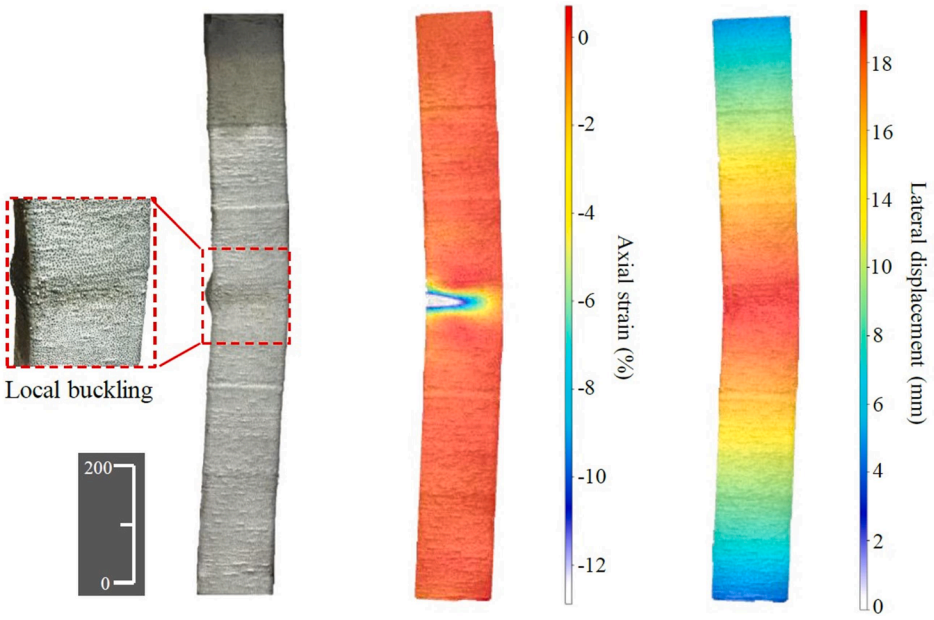



**Fig. 11.** Typical buckled WAAM SHS column, with axial strain and lateral displacement fields at ultimate load from DIC [77].

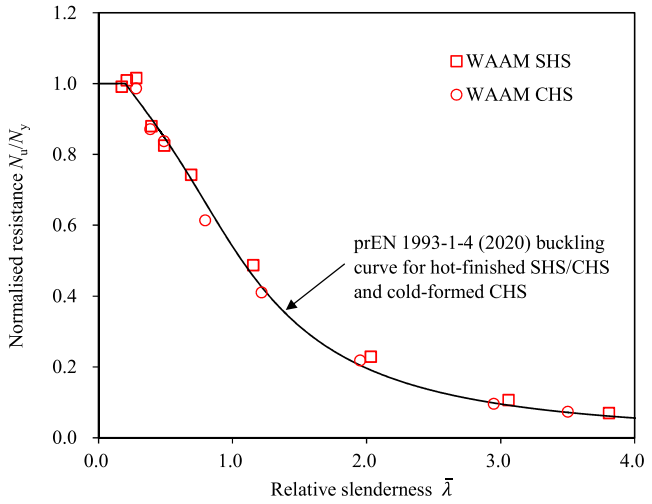



**Fig. 12.** Comparison between experimental results on WAAM stainless steel SHS and CHS columns and the existing Eurocode 3 buckling curve for equivalent conventionally formed compression members [77]. Note that the test data have been plotted on the basis of the measured as-built mechanical properties.

focussed on stainless steel trusses, and also considered material anisotropy [52,53,95]. WAAM columns for architectural applications were designed and manufactured in Waldschmitt et al. [96].

Manufacturing constraints generally inhibit the internal stiffening of steel tubular profiles, but this limitation does not exist with WAAM. The optimisation and testing of WAAM SHS profiles with internal stiffeners are being investigated as part of ongoing research in this area at Imperial College London – see Fig. 15. The 3D printing of optimised bearing stiffeners in I-sections has been successfully implemented in [15,74]; this is considered to be a first step in using WAAM towards the more automated fabrication of structural steelwork, in place of the traditional manual welding of plates. The improved production logistics and reduced need for handling, transporting and storing materials (e.g. a range of different plate thickness) offered by WAAM were also highlighted [15].

Although not specifically optimised, the landmark MX3D bridge offers insight into the potential of WAAM to produce intricate, streamlined geometries at the scale required by the construction industry, while the potential for on-site manufacture was demonstrated by the WAAM steel bridge in Darmstadt [15,21,97] – see Fig. 16. A comprehensive program of physical testing [98] and numerical modelling [99] was used for the safety verification of the MX3D bridge, shown in Fig. 17 after the completion of the final load testing (in Fig. 17(a)) and after being fully opened to the public (in Fig. 17(b)), while the long-term performance

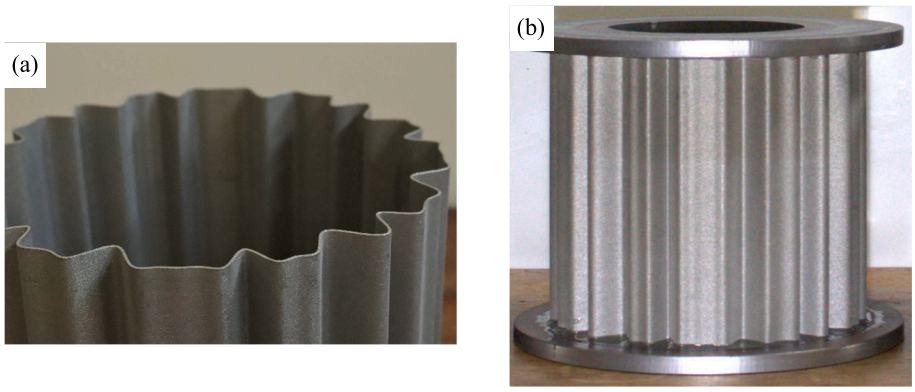



**Fig. 13.** Optimised corrugated shells (a) close-up view after printing and (b) prepared for compressive testing [88].

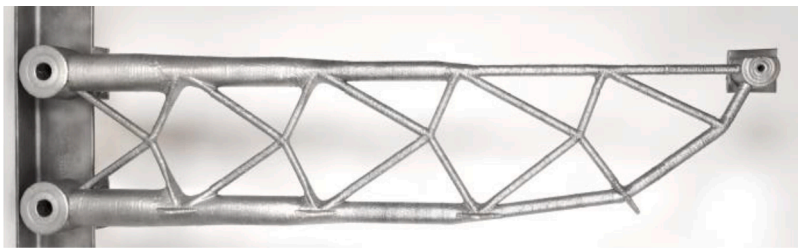


**Fig. 14.** Optimised WAAM steel cantilever truss [93].

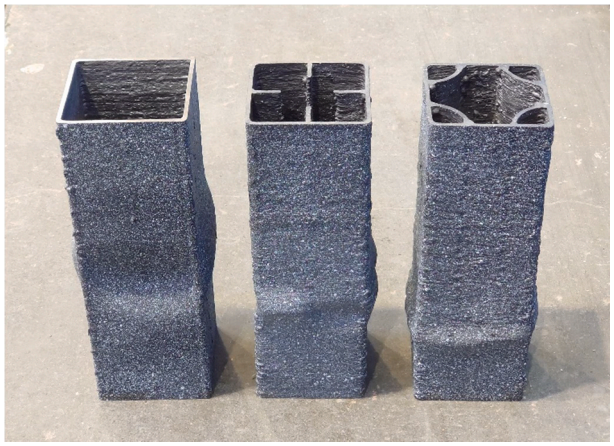


**Fig. 15.** Unstiffened and stiffened WAAM steel SHS after compression testing.



**Fig. 16.** Footbridge manufactured on-site across a stream at TU Darmstadt [21].

continues to be monitored.

## 4. Connections

Connections are regarded as an aspect of steel construction that could benefit almost immediately from the opportunities offered by additive manufacturing – the connections themselves represent a relatively small portion of the total weight of the structure, so the challenges associated with the relatively slow rate at which material can be deposited is minimised, while the technology and scope for automation can be brought to bear on what is traditionally a rather manual and labour-intensive operation – the fabrication of steel connections. At the same time, there is significant potential for enhancing the performance of connections through innovation and optimisation, with additive manufacturing enabling geometries to be printed that have thus far, not been possible.

A number of studies have been performed to date to assess the performance of WAAM connections. These studies can be broadly grouped into two categories: (i) those that focus on simple geometric arrangements (e.g. the ubiquitous lap shear and *T*-stub connection arrangements), seeking to the examine the fundamental behaviour of WAAM connections and allow comparisons to be made against equivalent conventionally-produced steel connections, as well as existing codified provisions, and (ii) those that seek to exploit the geometric freedom, flexibility and potential for optimisation offered by additive manufacturing for enhanced performance, efficiency, economics or aesthetics.

### 4.1. Fundamental behaviour of WAAM connections

Studies into the fundamental behaviour of WAAM connections are important to allow the performance to be benchmarked against conventional steel connections and existing design rules, as well as to consider how WAAM structural elements can be connected to other conventional structural elements in hybrid construction. A program of experiments on WAAM steel single-lap and double-lap shear bolted connections has been carried out in [20,101]. Different specimen thicknesses, loading directions (relative to the print layer orientation) and geometries were considered, enabling a range of failure modes to be explored. The specimens consistently exhibited good ductility and their resistances were generally well predicted using existing design provisions; there were some exceptions to this, but these were more reflective of known shortcomings in the code provisions than unexpected structural performance in the tests. Examples of the tested single-lap shear bolted connections, displaying a transition in failure mode from shear-out to localised tearing (moving from left to right) as the geometry of the test specimens is varied, are presented in Fig. 18(a), while strain fields at different levels of loading for a WAAM specimen failing in net section tension is shown in Fig. 18(b). Further tests on double-lap shear bolted connections in WAAM steel plates, focussing on the shear-out failure, have been reported in Kotteman [13].

The testing of *T*-stubs, featuring different deposition strategies and different transitions between the flange and stem plates has also recently been carried out at Imperial College London. An example of a WAAM steel *T*-stub specimen during testing is shown in Fig. 19.

### 4.2. Novel and optimised WAAM connections

Novel and optimised metal AM connections have featured in several recent studies. A prominent early example is the optimised and additively manufactured Arup connection node described in Galjaard et al. [102], where weight savings of up to 75 % over traditionally fabricated nodes were reported. A further example is the so-called Takenaka node [100]. Topology optimised nodes, suitable for additive manufacture and use in a range of structural applications, including hybrid construction, have been described in [103–106], while a series of innovative additively manufactured steel connection designs, including a beam hook (see Fig. 20(a)), a brace clamping element, a node for connecting four members and a beam-to-beam connection system, have been described by Lange et al. [15]. Optimised joints between tubular members, which are widely used in structural engineering applications, were simulated,

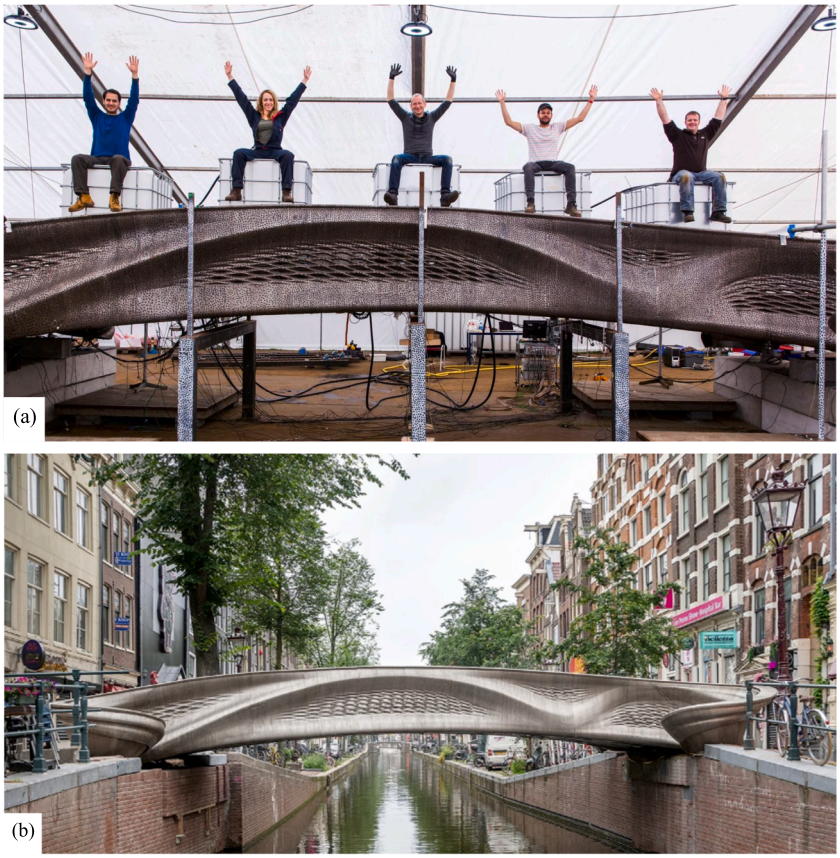



**Fig. 17.** MX3D bridge: (a) upon successful completion of final load testing, (b) in-situ and fully open to the public [100].

manufactured and tested in [107] – see Fig. 20(b). The use of 3D printing to create connections in modular buildings has been explored in Dissanayake et al. [108], while an investigation into WAAM sleeve connectors for tubular members – see Fig. 20(c) – is currently underway.

Joints for treelike column structures were studied in Wang et al. [109], where a generative design approach was used to create joint geometries that achieved more uniform stress distributions than alternative designs. Reduced-scale models of the joints were then manufactured by 3D printing. Inspired by bamboo, steel tubular joints, optimised in terms of resistance and stress-reduction (with a view to fatigue performance), as well as stiffness, were investigated in Kanyilmaz and Berto [110]. WAAM 'mortise-and tenon' joints were put forward in Silva et al. [111] and demonstrated to have substantial potential to create joints between similar and dissimilar materials. Ongoing work at Imperial College London seeks to establish optimised connections, such as those illustrated in Fig. 21, between hot-rolled structural steel members that can be printed either in the fabrication shop or onsite.

## 5. Strengthening and repair

Strengthening and repairing of structures is typically more economical and more sustainable than the alternative of demolition and reconstruction [112]. There are many scenarios in which strengthening and repair may be needed, including following damage from impact, corrosion or fatigue or to meet an increased demand in loading e.g. due to larger volumes of traffic in bridges or the construction of an additional storey on a building. The strengthening and repair of steel structures typically involves the bolting or welding of plates or the use of fibre-reinforced polymers (FRPs) [113]; the use of shape memory alloys has also been investigated [114]. WAAM represents a new alternative, and is considered to offer significant potential in the coming years. WAAM is more flexible than the existing strengthening methods, offering more potential for bespoke solutions and could be more accommodating of uneven surfaces, to which the attachment of steel or FRP plates can be challenging. WAAM also offers the potential, through thermal input, to add pre-camber (or counter long-term deflections) of beams.

Strengthening could relate to existing structures, but could also be part of the fabrication process for new structural elements. The overall premise is that considerable capacity gains can be achieved through the addition of relatively little WAAM material to existing steel elements but positioned in the optimum location to resist the applied loads. The following potential strengthening and repair features are envisaged:

(1) local increase in thickness in damaged or corroded regions,

(2) increase in geometrical properties in critical regions (e.g. second moment of area of beams or columns at midspan),

(3) addition of stiffeners to inhibit buckling modes (e.g. stiffeners along flange tips to restrict local buckling of outstand elements),

(4) induction of residual stress distributions that delay rather than promote the onset of yield,

(5) induction of residual stresses that can be used to prestress and precamber beams against the applied loading and.

(6) provision of stiffening elements at member ends to enhance warping restraint and hence resistance to lateral torsional buckling in beams.

Tests on strengthened I-sections columns featuring the addition of WAAM material of varying profiles along the flange tips have recently been conducted – see Fig. 22, benefitting from the items described under points (2), (3) and (4) above. Substantial enhancements in load-carrying capacity were obtained through the addition of very little material relative to that used in the original column.

## 6. Economics and sustainability

There is no single straightforward answer to the question of whether

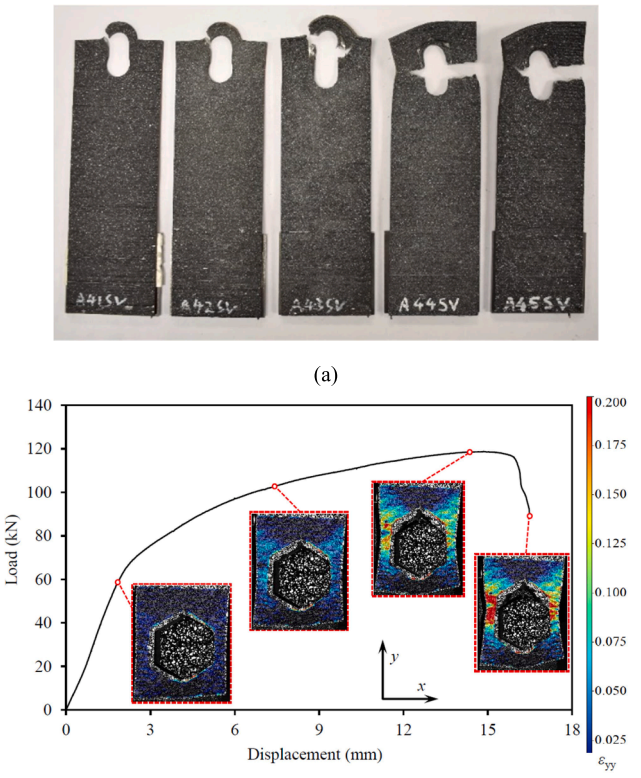



**Fig. 18.** (a) Failure mode transition from shear-out to localised tearing and (b) Load-deformation response and DIC strain fields for a specimen failing in net section tension in WAAM steel single-lap shear connections [20].

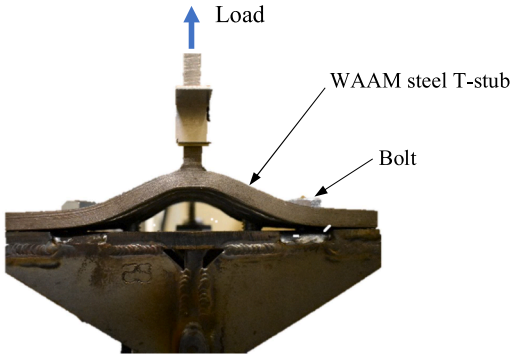



**Fig. 19.** Testing of WAAM steel *T*-stub connection.

additive manufacturing is more economical or sustainable than conventional steel fabrication. The economical and environmental advantage (or disadvantage) will vary from case to case. What is clear though, is that additive manufacturing offers the potential for reduced material use, reduced wastage, greater automation and improved health and safety relative to conventional methods, and that further exploration is warranted. Consideration needs to be given to the particular application, material and performance requirements of the additively manufactured part, against the evolving backdrop and, to some extent geographical dependency, of labour costs, rate of technological development (e.g. increasing deposition rates for WAAM) and energy generation mix (in particular renewable versus non-renewable). The key points surrounding the economics and sustainability of using WAAM in construction are discussed and assessed in the following two sub-sections.

### 6.1. *Economics of WAAM in construction*

Following equivalent assessments across other industries e.g. [115], early research into the economics of WAAM versus conventional structural steel fabrication has been conducted [116]. WAAM benefits from the fact that the means of material deposition (i.e. welding) is already very familiar to the steel fabrication sector, the feedstock material (i.e. welding wire) is standardised and widely available and the robotic hardware and control systems are not expensive. The study indicated that the cost of an established WAAM fabrication setup would be comparable to that of the current conventional labour-intensive fabrication process, and that the use of WAAM becomes increasingly favourable as deposition rates increase, parts become more optimised and human supervision is spread across a higher number of robots. In particular, it is clear that maximising WAAM deposition rates and minimising material usage (i.e. the degree of optimisation of parts and reduction of wastage) are crucial to the economic viability of this new method of manufacture. Cost models for the WAAM process have been proposed in [49,117]. Although considering a different industrial context, material usage was shown in Dias et al. [49] to be key to the financial competitiveness of WAAM relative to conventional manufacturing methods, with WAAM comparing favourably provided sufficient material savings could be made. In the case study parts considered in Dias et al. [49], material savings came through substantial reductions in wastage relative to that created by machining, rather than geometric optimisation i.e. the final manufactured part was geometrically the same. It was also noted that the energy consumption associated with machining was greater than that associated with deposition through WAAM. In the structural engineering context, the dominant source of material savings is likely to be through geometric optimisation, stiffening, exploitation of hybridisation etc, rather than reduction in wastage from machining, since subtractive manufacturing methods play a relatively minor role in steel construction.




**Fig. 20.** Examples of innovative connection elements: (a) beam hook [15], (b) planar joint for tubular members [107], (c) sleeved connector for tubular profiles.

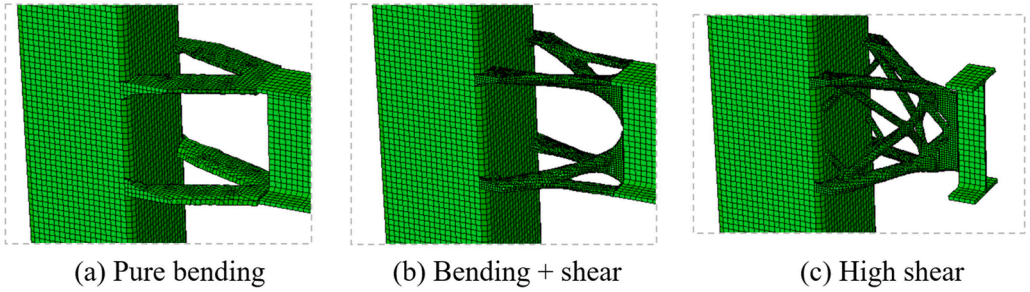



**Fig. 21.** Examples of optimised beam-to-column connections under different loading conditions.



**Fig. 22.** Testing of WAAM strengthened I-section columns.

### 6.2. Sustainability of WAAM in construction

There have been a number of general studies into the sustainability of AM e.g. [118,119], as well as a number of more industry specific studies [120–122]. The potential for reduced material use, less wastage and lower environmental impact have been consistently highlighted.

Standardised products, such as rolled I-sections and tubular sections, are extensively used in the steel construction sector. WAAM has an additional production step in comparison to these conventionally manufactured elements, which is the final deposition through welding. This increases the environmental impact to produce a given weight of material. However, ease of manufacture typically dictates that rolled products are uniform along their length, which can severely impair their structural efficiency, since large sections of material (e.g. near the supports of simple beams) are often far from fully utilised. In fact, the average utilisation of steel in structures was found in [123] to be less than 50 %. Additive manufacturing brings the potential for more bespoke solutions, where material can be placed in the most optimal locations to resist the applied load. There is also potential to strengthen and repair existing structures, thereby extending their lives, and to facilitate and promote far greater re-use of steel by, for example, making small additions through AM that could substantially expand the range of applications of an existing element. Therefore, considered holistically, and with strategic and optimised usage, despite the additional welding step, WAAM could play an important role in reducing the environmental impact of the constructional industry.

In a recent study focussed on structural engineering applications [124], it was concluded that, based on current technology and energy mixes, although WAAM is more impactful per kg than conventional steel manufacturing, with weight savings of at least 50 %, which are readily achievable through optimisation, WAAM becomes a more environmentally friendly method of manufacture. Furthermore, as the technology advances, in particular, as the rate at which material can be deposited increases (bringing savings in shielding gas usage), the argument becomes even more compelling.

## 7. Outlook and challenges

Much of the research and discussion presented above is forward looking and aiming to set the foundations for the wider adoption of metal 3D printing in structural engineering. Although good progress has already been made and initial signs of the potential for metal AM in construction are encouraging, it is still relatively early days. In this section, an outlook and the key perceived challenges and opportunities for metal AM in structural engineering are set out.

Further advances in the manufacturing process are expected in the coming years and are inextricably linked to the design of AM structures, with improved deposition speed and consistency, greater inline thermal and positional monitoring, enhanced quality control and greater use of machine learning and other techniques to detect defects all anticipated [12,125–127]. The link between all process inputs (including printing method, printing parameters and deposition strategy) and the resulting characteristics and performance of the printed output parts is extremely important and has been the subject of much recent research [128,129]; this research effort is expected to intensify further in the future. Developments in process modelling [130] are expected to bring new insights into printing strategies that can provide improved control of thermal distortions, residual stresses and ultimately mechanical performance. Greater automation in construction is also deemed to be inevitable, and necessary to remain financially competitive in the future, particularly as labour costs increase.

The evolving trends in construction, the different demands imposed on the supply chain by AM and the new technological possibilities are likely the influence the manner and location in which construction is carried out. Recent years have witnessed rapid growth in the implementation of factory-based off-site construction, such as modular buildings [131]. Numerous opportunities exist for the integration of AM into this form of construction [132], aimed at enhancing quality, productivity and safety. There is clear potential, for example, for greater automation, the manufacture of bespoke, optimised connections between modules, as well as the AM of fabricated features, such as stiffeners that are traditionally attached manually. AM could also facilitate on-site robotic repairing of structures, together with more construction and easier maintenance in remote environments, even in space [133].

New innovative structural materials, forms and products, enabled by the freedom and flexibility of AM [134], are anticipated in the future. Far greater use of optimisation tools, together with a rapidly growing

awareness of the need for design for additive manufacturing (DfAM) are expected, with prominent examples appearing in other industries e.g. [135], that may be readily translated into construction. Already, innovative connections [15,110,111] are emerging, functionally graded materials fabricated by double-wire manufacturing [136] and composite polymer-metal materials [137] have been produced, in-processing strengthening has been achieved [138] and a large body of research into the production, performance and applications of 3D printed auxetic materials [139] and honeycomb and lattice structures has been assembled e.g. [125,140,141]. The upcoming advances and innovations are expected in short order in this rapidly developing field.

Structural safety, reliability and confidence in soundness are prerequisites for any form or means of construction. Demonstrating these attributes for additively manufactured structures is essential for their more widespread use. There is currently no overarching framework for the design and manufacture of metal 3D printed structures, but there are increasing precedents from other engineering sectors, a growing body of underpinning test data, an increasing number of structural applications appearing in practice and a clear desire from structural engineers to explore the potential of this new construction method. The future design framework for additively manufactured structures will likely require the greater use of destructive and non-destructive physical testing, more advanced numerical modelling to handle and exploit the new-found geometric freedom and further data on the variability of printed geometries and material properties [142], as well as their link to the production processes, parameters and quality, to underpin the establishment of safety factors.

## 8. Conclusions

Additive manufacturing or 3D printing is a disruptive technology that is emerging as a viable method of construction. In this paper, a review of research and practical advances in metal additive manufacturing in the structural engineering domain has been presented. Directed Energy Deposition-arc (DED-arc) AM or wire arc AM (WAAM) is regarded as the technique that is best matched to the needs (appropriate speed, scale and dimensional accuracy) of construction, and there is a growing body of experimental data confirming its suitability for load-bearing applications. Material testing has generally revealed sound mechanical properties, though the influence of printing parameters and facilities, the variability in response and the occurrence of defects, among other uncertainties, all require further research. Physical tests on structural cross-sections, members, connections and indeed full systems have shown that, provided account of the influence of the as-built geometry is taken through the use of material properties determined from unmilled coupon tests, existing design approaches provide reasonable predictions of the observed structural response. Further research and data are needed to develop a design framework and safety factors for metal AM structures.

The most promising early potential applications in practice are considered to be connections, strengthening and repair and landmark structures, all with the possibility to use optimisation to exploit the available geometric freedom offered by AM. Optimisation is considered to be key to the viability, economy and sustainability of this new technology. More innovation and imagination are also needed to fully exploit the likely benefits.

Overall, although there are clear challenges ahead for the wider application of metal additive manufacturing in construction, initial signs are positive and there are clear potential benefits. Structural optimisation, reduced material usage and wastage, increased automation, more strengthening and repair of structures and the greater reuse of construction materials and products are all foreseen to be important components of a future, more sustainable construction sector, to which additive manufacturing will no doubt contribute.

## 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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