Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges

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Abstract

3D printing, more formally known as additive manufacturing (AM), has the potential to revolutionise the construction industry, with foreseeable benefits including greater structural efficiency, reduction in material consumption and wastage, streamlining and expedition of the design-build process, enhanced customisation, greater architectural freedom and improved accuracy and safety on-site. Unlike traditional manufacturing methods for construction products, metal 3D printing offers ready opportunities to create non-prismatic sections, internal stiffening, openings, functionally graded elements, variable microstructures and mechanical properties through controlled heating and cooling and thermally-induced prestressing. Additive manufacturing offers many opportunities for the construction sector, but there will also be fresh challenges and demands, such as the need for more digitally savvy engineers, greater use of advanced computational analysis and a new way of thinking for the design and verification of structures, with greater emphasis on inspection and load testing. It is envisaged that AM will complement, rather than replace, conventional production processes, with clear potential for hybrid solutions and structural strengthening and repairs. These opportunities and challenges are explored in this paper as part of a wider review of different methods of metal 3D printing, research and early applications of additive manufacturing in the construction industry. Lessons learnt for metal 3D printing in construction from additive manufacturing using other materials and in other industries are also presented.

Keywords

3D printing; additive manufacturing; applications; concrete; metal; polymers; research; review; stainless steel; structural engineering

1 Introduction

3D printing, or additive manufacturing (AM), has already gained traction in the aerospace and biomedical industries and is now being explored as a viable manufacturing method in the construction sector. Metallic structural sections and connection nodes have already been built, and a pedestrian bridge is currently being constructed. AM offers numerous benefits over conventional manufacturing methods, such as greater structural efficiency, geometric freedom, customisation and reduced material usage, along with the potential for functionally graded materials and prestressing, as well as repair and strengthening opportunities. The industry mindset will need to embrace the digital revolution and adapt from design for production to design for function, with consequential requirements for highly computer literate engineers, advanced analysis and new thinking in the verification of structures and the assurance of safety.

Construction is generally acknowledged to lag behind the aerospace and automotive industries in terms of uptake of technology, innovation and productivity levels [1]. Many construction projects still use predominantly traditional methods and working practices, such as two-dimensional drawings, controlling the placement of concrete by hand, the use of formwork and temporary structures, the manual positioning of reinforcement and levelling, and a transient

workforce, leading to a loss of knowledge upon project completion and a greater risk of accidents [2]. A major advancement in construction has been the move towards 3D CAD and building information modelling (BIM), as well as offsite manufacture, although this essentially moves the traditional techniques away from the building site. Clearly there is scope to further embrace innovation in construction and there are opportunities to be explored for the adoption of 3D printing techniques.

Conventional manufacturing techniques are either subtractive, where the amount of material within an object is reduced, such as machining a metallic block, or are formative, where the amount of material used is conserved, such as shaping (e.g. hot-rolling or cold-forming) or casting using a mould [3]. Additive manufacturing increases the component mass during the manufacturing process, typically building an object layer-by-layer from 3D model data through an automated process. The concept of additive manufacturing can be traced back to photo sculpture in the 1860s, where three-dimensional sculptures were produced from a series of two-dimensional photos [4]. Significant research effort in the 1960s and 1970s led to the development of photopolymerisation for polymers, powder bed fusion for ceramics, metals and polymers, and sheet lamination for ceramics, metals, paper, polymers and wood. Stereolithography, a type of photopolymerisation, where an ultraviolet sensitive liquid polymer is cured using a laser, was the first additive manufacturing technique commercialised in the late 1980s [3].

The rapid development of additive manufacturing (AM) has led to many different names for the field, including 3D printing (3DP), additive fabrication (AF), additive layered manufacturing (ALM), rapid casting, rapid manufacturing (RM), rapid prototyping (RP), rapid tooling and solid free form fabrication (SFF) [3,5]. An attempt to standardise the terminology has been made in ISO/ASTM 52900 [6] where the general term additive manufacturing has been adopted for all processes of making parts from 3D models and materials, and seven key groups of technologies have been identified: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerisation, covering ceramics, composites, metallic materials and polymers. These methods all broadly follow the same workflow process: firstly, a 3D CAD model is created; this is then sliced into a series of building layers; this information is then sent to the processing machine, defining the location of the building head; and finally, the part is built up layer-by-layer. Today a wide range of materials can be used in additive manufacturing processes including ceramics, chemicals, composites, concrete, foodstuffs, metallic materials (including aluminium, cobalt-chrome, copper, gold, iron alloys (including stainless steels), magnesium, nickel based alloys, titanium and tungsten), paper, plastics, sandstone, silicones, wax and wood [4,7–16].

Metal additive manufacturing is currently used in the biomedical and aerospace industries to produce high value end use parts, which are highly customised or produced in small quantities [3,17]. The total AM market was estimated to be worth over $4 billion in 2014, with the market for end use parts being $1.7 billion, and is anticipated to grow to more than $21 billion by 2020 [3]. Beyond the traditional high value sectors, additive manufacturing is starting to be explored in the construction sector to build concrete bridges, houses and offices [18,19], plastic houses [20] and metal connection nodes and bridges [21,22]. The construction sector is coming under increasing pressure from rapid urbanisation, climate change and resource scarcity leading to a desire for more efficient construction techniques. A 1% reduction in construction costs has been estimated to save $100 billion per year globally [23]. The UK Government has set the target of achieving a 33% reduction in the initial and whole life cost of construction, a halving in the time from inception to completion of construction projects and a halving in the

greenhouse gas emissions from the built environment by 2025 [24]. Architects are simultaneously pushing the boundaries in terms of shape and form [25]. AM in construction is still in the experimental phase [26], but these new forming methods offer tremendous potential to build structural components, or even entire structures, with geometric freedom, engineered material properties, reduced material usage, lessened construction waste, shortened build times and reduced transportation costs.

A review of existing additive manufacturing projects in construction is presented in Section 2, covering concrete, polymer and metal AM projects. In Section 3 of this paper, the various techniques of metal additive manufacturing are described, and their suitability for use in construction is discussed. A review of previous metal additive manufacturing research is set out in Section 4. Lessons learnt from the use of metal AM in other disciplines are set out in Section 5, and finally, with a view to the future, the opportunities and challenges ahead for metal additive manufacturing in the construction sector are discussed in Section 6.

2 Additive manufacturing in construction

2.1 Introduction

A review of early concrete, polymer and metal additive manufacturing applications in the construction sector is presented in this section. Lessons learnt and opportunities for metallic 3D construction in the future are highlighted. It should be noted that full details of these projects are often not shared for commercial reasons, such as which components have been additively manufactured and the material composition [27].

Masonry construction has been described as a primitive form of additive manufacturing with structures being built up layer-by-layer [28]. The 'modern AM' techniques have been used since the early 2000s by architectural firms for model making, resulting in significant time and cost savings, with reports of the model making process being shortened from months to hours and costs reducing fiftyfold [17,29]. Additive manufacturing is, however, still less common further down the design and build process, although it is now the subject of a wide variety of research studies and 'halo construction projects'. There has been a sharp increase in the number of publicised AM construction projects since 2012 [27].

2.2 Concrete printing

Concrete is the most widely used material in construction, with the raw materials being low cost and locally available worldwide. Traditional concrete techniques favour simple, repeatable formwork to reduce costs [25]. Scaffolding and moulds can account for half of concrete construction costs; consequently concrete additive manufacturing techniques are highly developed due to the many opportunities that these new techniques offer for significant cost savings [27]. Concrete AM is more developed and more widely utilised in construction than either metal or polymer printing. To date, residential and office buildings and multiple pedestrian bridges have been built using concrete AM; these projects are introduced herein and lessons learnt for metal 3D printing are outlined.

2.2.1 Winsun houses and offices

In 2005, a Chinese advanced materials supplier turned architectural firm, Winsun, first started exploring additive manufacturing, and by 2013 had built the first additively manufactured residential house. This was followed in 2016 by the first additively manufactured office (shown in Figure 1), which was built in China and then shipped to Dubai and is estimated to have had 80% reduced construction costs, 60% lower labour costs and produced 60% less waste than a comparable conventional office building [18]. Winsun builds the walls in a factory, using a

cement, sand, reinforcing glass fibre and a proprietary additive mix with a 150×10×6.6 m machine [1] and then assembles the components onsite on traditional foundations with additional steel or cement structural reinforcing. Printed elements are also combined with conventional beams and columns. The company has built a two storey, 1100 m^2 house that took one day to build in its factory and two days to assemble onsite by three workers, with the internal structures placed in advance. Advantages of their approach include the ability to source up to half of the raw materials from construction waste, easier incorporation of insulation, piping and wiring and a dust-free onsite construction process.

It has been necessary to build prototype structures to prove the feasibility of this new manufacturing technique due to a lack of knowledge amongst architects, designers and developers regarding the benefits of additive manufacturing. The company are also exploring printed formwork and manufacturing a high rise building (>100 m) using a mobile printer. By 2016 Winsun had sold over 100 houses, with a standard house costing approximately $30000 [18].



Figure 1 Winsun Dubai office building [30]

2.2.2 Castilla-La Mancha 3D bridge

The Castilla-La Mancha 3D bridge is described as the first 3D printed bridge; it is a 12 m span, 1.75 m wide, pedestrian bridge in the Castilla-La Mancha urban park near Madrid in Spain. The bridge, shown in Figure 2 and completed in 2016, is made up of eight parts, each with maximum horizontal dimensions of 2×2 m [31]. The bridge was built using fused concrete powder and polypropylene reinforcement [19] by the Institute of Advanced Architecture of Catalonia, a Barcelona-based research and education centre, and took two months to complete. Raw materials not used during the building process were recycled and the design process used generative algorithms to optimise the material distribution [32], which is a key benefit associated with additive manufacturing.



Figure 2 Castilla-La Mancha 3D bridge, Madrid [32]

2.2.3 Gemert bicycle bridge

BAM Infrastructure and TU Eindhoven collaborated on an 8 m long, 3.5 m wide concrete bicycle bridge in Gemert, Netherlands which is described as the first 3D printed prestressed concrete bridge. In the concrete printing process, 1 cm layers of concrete were laid down through an additively manufactured nozzle, with the concrete able to maintain its form after deposition without additional formwork [33]. The bridge was built in parts and then joined together onsite. Scale models of the structure were built and tested [34] and the finished bridge, shown in Figure 3, was opened in late 2017 [35].



Figure 3 Gemert bicycle bridge

2.2.4 FreeFAB

Laing O'Rourke have developed an alternative concrete additive manufacturing process, called FreeFAB, in which the moulds are printed and then concrete is applied using conventional techniques. The moulds are built from wax which can be removed after the concrete has hardened and the wax recycled, as shown in Figure 4. The build volume is 30×3.5×1.5 m allowing for large moulds, with complex geometry, that take three hours to produce, rather than eight days when using wood or polystyrene. This technique has been used for show homes and offices in Dubai and China and is currently being used for doubly curved wall panels on the Crossrail project in London, UK [36].



Figure 4 The FreeFAB process [37]

2.2.5 Discussion

The described concrete printing projects highlight several important factors for metal additive manufacturing in construction. Offsite manufacture was used in all of these projects, and for the Winsun Dubai office, took place in a different country with significant transportation distances involved. This allows the manufacturing equipment to be used in a more controlled environment and reduces the time and labour requirements onsite. The use of waste material and the recycling of unused material is another key theme highlighted by these existing projects. This is also applicable to metallic construction, particularly due to the high residual scrap value and economic incentive for recycling, especially for high value metallic materials such as stainless steel, which can be completely and indefinitely recycled [38]. Additive manufacturing has been used for its ability to produce new geometric forms, such as the Winsun Dubai office and the Castilla-La Mancha 3D bridge, though it has also been used for more conventional structures due to its cost advantages over traditional techniques, with the Winsun residential houses, and process advantages, such as not requiring formwork, with the Gemert bicycle bridge. The use of hybrid structures that combine printed and conventional elements has been explored, and the use of prototype structures and models to prove the structural reliability of new techniques and to gain stakeholder approval has been a feature of a number of projects; such an approach will also be essential for metal AM construction projects, where testing and inspection protocols will be needed.

2.3 Polymer printing

Polymer additive manufacturing techniques are the most commonplace additive manufacturing methods used, due to their low cost and widespread equipment availability. Polymer AM in construction is typically limited to mechanical and electrical systems and facades, hence the use of polymer AM is limited to one major project. The 3D Print Canal House in Amsterdam, Netherlands is an additively manufactured structure resembling a traditional Dutch gabled canal house [39,40]. DUS Architects developed their own 6 m tall printer capable of building the 2.2×2.2×3.5 m polypropylene blocks, that each weigh 180 kg [1,40]. Construction started in 2014 and once completed, the building will become a design museum. The project is described as ‘zero waste’ as the printed blocks can be fully recycled [1]. A photograph of a development model and an exploded isometric view of the final design is provided in Figure 5. The individual parts are being built onsite, reducing transportation costs [41]. This project again highlights the importance of reducing waste and that structures using additive manufacturing do not necessarily need to take advantage of the geometric freedom available.

The house is designed to be disassembled, transported and reassembled at another location [41].

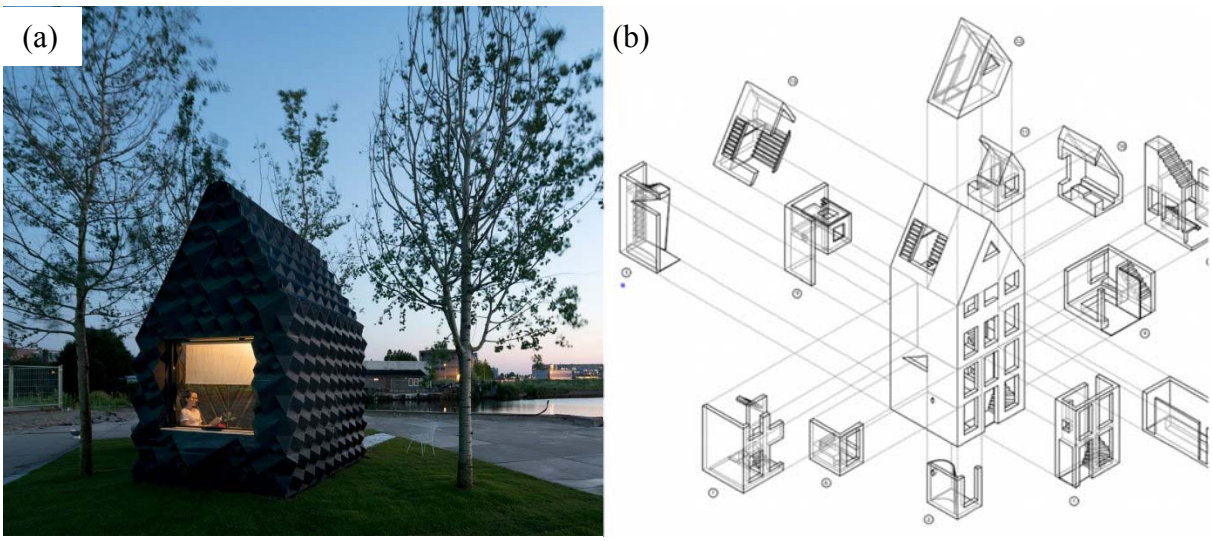


Figure 5 (a) A 3D Print Canal House development model [42] and (b) an exploded isometric view of the final house [20]

2.4 Metal additive manufacturing in construction

Early uses of metal additive manufacturing in construction have primarily featured modest-scale components such as façade nodes and connections, though a full size pedestrian bridge is also currently being developed. These pioneering projects are discussed further in this section.

2.4.1 Nematox façade node

Façade nodes often feature complex and intricate geometries to meet a series of performance demands. The Nematox façade node was developed to show how additive manufacturing processes could be used to allow more optimised façade geometries (shown in the rendering in Figure 6a), with scope for greater innovation and geometric freedom [43]. The developed solution moves the structural connections outside the node, reducing the likelihood of defects affecting the environmental sealing. A full-size prototype (shown in Figure 6b) was built using powder bed fusion (PBF), this process is described in Section 3.1, and aluminium powder, which required 120 hours of CAD design, including ten hours to convert the model into an appropriate AM file format and a further two hours to place the node within the AM equipment software. Four hours of additional finishing work was required at the end of 76.5 hours of build time. This additive manufactured node is seen as an example of how a high technology component can be used within existing verified and tested façade systems [44].

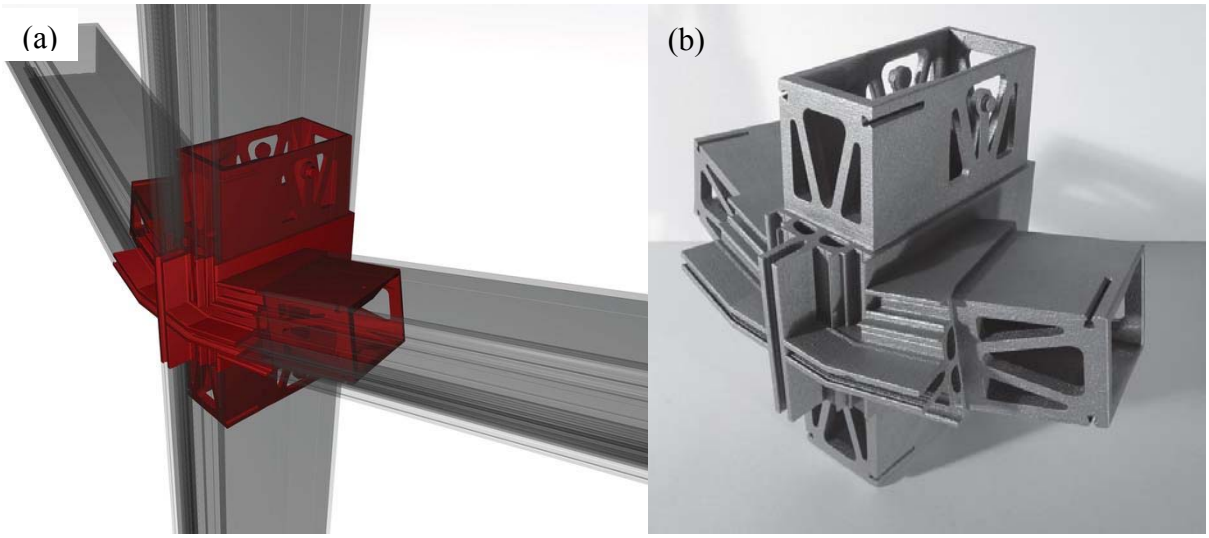


Figure 6 (a) A rendering of a Nematox façade node and (b) a full size aluminium prototype node [43]

2.4.2 Arup lighting node

A tensegrity structure lighting node was redesigned by Arup [45] to take advantage of the opportunities presented by additive manufacturing. The conventionally fabricated design comprised up to seven unique machined plates welded to a central tube. Topology optimisation was applied to this previous design, with the starting point and boundary conditions prescribed and then was software used to develop a geometrically optimised node. The design was then rationalised for manufacture – reducing the amount of material used, to minimise cost and speed up manufacture, and moving elements to act as support structures, to prevent the need for support structure removal. The final design is an organic structure which aligns with the internal forces. 40% scale models of the original and optimised nodes were produced (as shown in Figure 7), the latter using powder bed fusion with ultra-high strength steel powder. It was noted, in 2014, that the new additively manufactured node cost roughly three times that of a conventionally produced node, but that it is expected to become cheaper through manufacturing developments within five years. Developments such as more powerful powder bed fusion equipment and a further optimised node design, considering the higher strength of additively manufactured metallic materials and undertaking manufacturing optimisation in parallel with topology optimisation, will lead to reduced build times and lower costs [45].

A second optimised node was developed to take advantage of the lessons learnt from the first node. The design objective was to minimise the total weight, with material removed where it was subjected to lower stresses. The node was again built using powder bed fusion, although with Grade 316L stainless steel powder. This second iteration was 75% lighter than the conventionally fabricated node, half the height and with its integrated connections allowed the entire tensegrity lighting structure to be 40% lighter. It was highlighted that there were high level demands on computational skills and that the post-optimisation steps were time consuming [22].

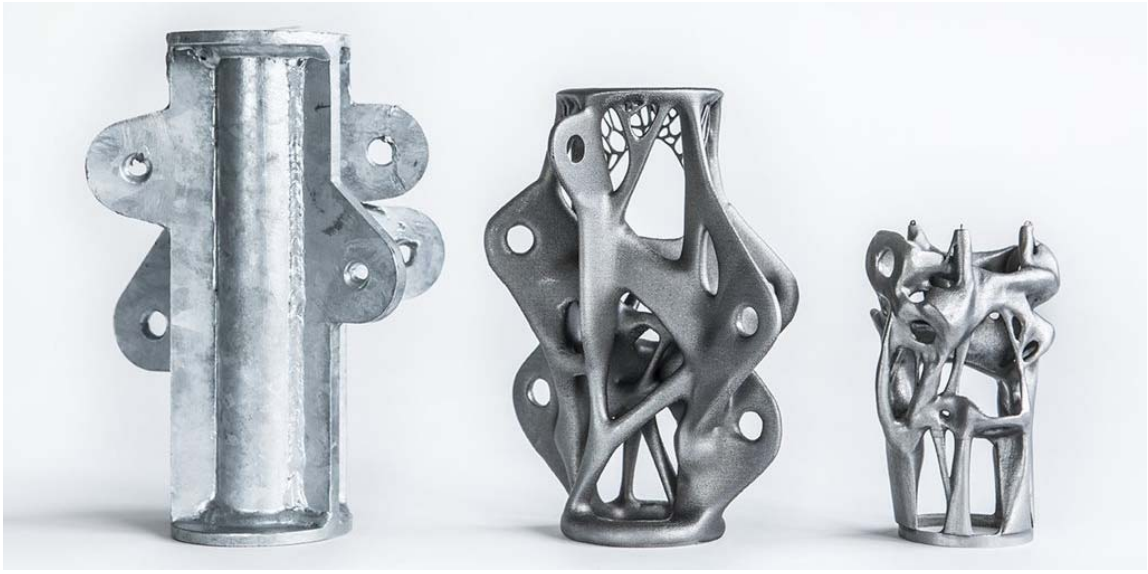


Figure 7 Progression from a conventional lighting node to two AM optimised lighting nodes [46]

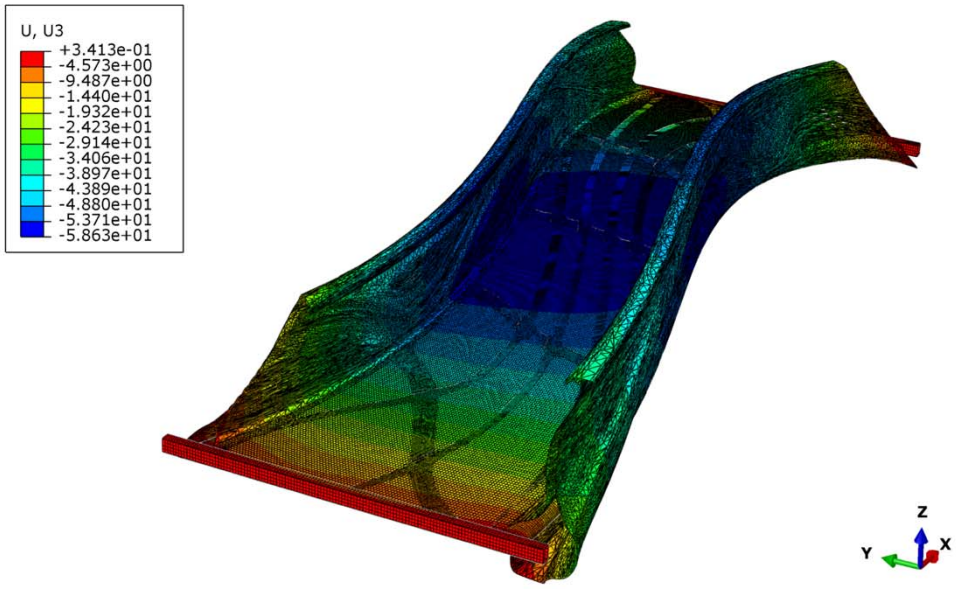


Figure 8 Finite element simulation of the MX3D bridge

2.4.3 The MX3D bridge

MX3D, in partnership with engineers from Arup and researchers from Imperial College London, through The Alan Turing Institute-Lloyd's Register Foundation programme in data-centric engineering, are designing, modelling, building and testing the first additively manufactured metal bridge. The bridge has a width of 2.5 m and a span of 10 m and is being built using Wire and Arc AM (WAAM) directed energy deposition (DED), this process is described in Section 3.2, with a 6 axis robotic welding arm [47]. The numerical simulation of the bridge, load-testing and the full bridge on display at Dutch Design Week 2018 are shown in Figures Figure **8** to Figure **10** respectively. The bridge will shortly undergo final load-testing and is anticipated to be completed by 2019 and be located in the centre of Amsterdam, the Netherlands.

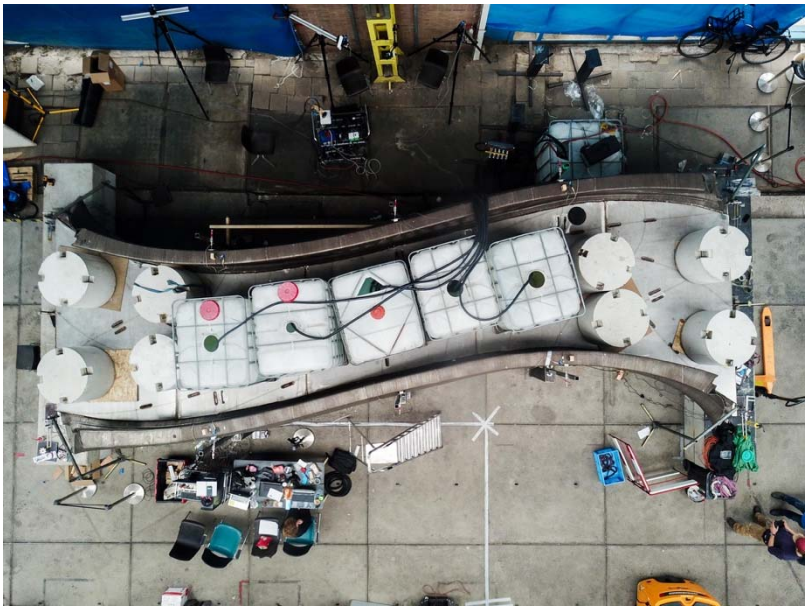


Figure 9 Load-testing of the MX3D bridge



Figure 10 The MX3D bridge at Dutch Design Week 2018

2.4.4 Discussion

These metal additive manufacturing projects highlight several important considerations for the wider adoption of 3D printing in construction. The CAD process and post-processing after manufacture can be particularly time consuming, as seen with the Nematox façade node. There is also a need to consider the limitations of the manufacturing technique while undertaking any optimisation processes, to avoid unbuildable or sub-optimal forms that require additional human intervention. Structural engineers will need to become more computationally literate and will require, or at least need access to, high level computational skills to incorporate additive manufacturing within existing structural design workflows. The optimised Arup lighting node has shown that metal additive manufacturing can enable highly optimised, lightweight, efficient structural forms that would be excessively time consuming and costly to manufacture with traditional forming techniques. The MX3D bridge shows that metal 3D printing is possible at a scale suitable for construction applications.

3 Metal additive manufacturing techniques

Metallic materials, such as carbon steel, stainless steel and aluminium, are widely used in the construction industry, but the products are typically manufactured using traditional techniques such as hot-rolling, cold-forming and extrusion. This naturally leads to structural elements that are prismatic (i.e. with uniform cross-section along their length), owing to their ease of manufacturing using these methods. In this section, an overview of the various metal additive manufacturing methods, which can be adopted within the construction sector and allow greater flexibility in the geometry of structural elements, are outlined. Powder bed fusion (PBF), directed energy deposition (DED) and sheet lamination are the forms of metal additive manufacturing included in ISO/ASTM 52900 [6]; electrochemical additive manufacturing is in the very early stages of development and is not yet commercially viable. The different processes each have their own specific limitations and characteristics, such as the maximum built part size and the building speed [48], making them suitable for different applications. The practicality and scalability of these methods for use in construction are discussed.

3.1 Powder bed fusion (PBF)

Powder bed fusion (PBF) is a method of additive manufacturing in which material within a powder bed is selectively fused together using thermal energy, from either a laser or electron beam. This method is suitable for small parts with complicated geometries [48]. The build time can currently be lengthy, taking tens of hours and melting roughly 50 g/hour, as objects are built up with individual layers, tens of microns thick. The surface roughness is typically less than 20 μm [49]. An inert atmosphere, or vacuum, is required to prevent metallic powders from oxidising [4]. This requirement has implications on the building space size and therefore the maximum dimensions of a single part, which is typically a 250 mm cube. Powder bed fusion can be used with polymers, combinations of metals, combinations of metals and polymers and ceramics. Any unused powder can also be recycled and reused [11]. Figure 11 shows stainless steel square hollow sections (SHS) being formed using laser based PBF.

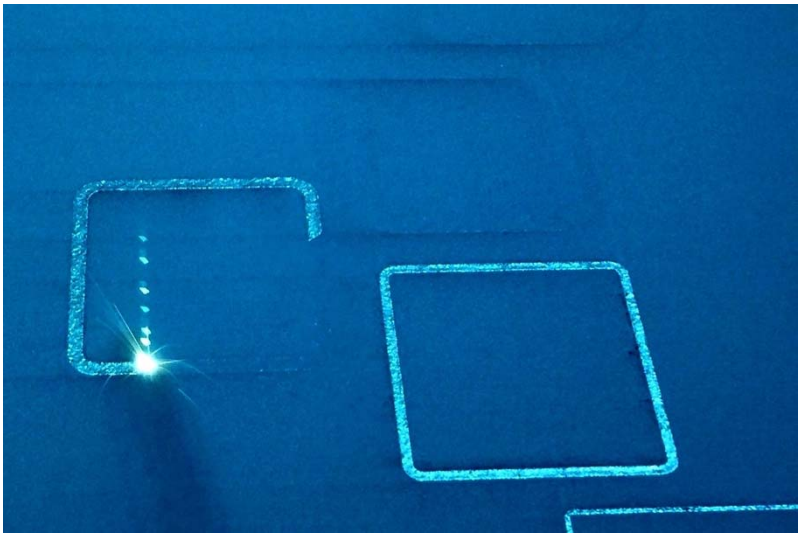


Figure 11 Stainless steel square hollow section (SHS) members being built using powder bed fusion [45]

3.2 Directed energy deposition (DED)

Directed energy deposition (DED) features metallic powder or wire being fed directly into the focal point of a laser or electron beam or plasma arc, resulting in a molten pool that can be

selectively deposited [4]. These two adapted welding techniques, using powder or wire, are described in the following two paragraphs.

Powder based DED is suitable for high complexity parts and can be used to repair damaged components [4,48]. Similar to powder bed fusion, powder based DED also requires an inert environment to prevent oxidation [11] and has maximum part size limitations, together with long build times (currently depositing roughly 1 kg/hour). The surface roughness is typically 20-100 μm [49].

Wire and arc additive manufacturing (WAAM) is a DED technique that uses arc welding tools and wire to build up a component, with the final object formed entirely from the deposited weld material. WAAM can utilise gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and plasma arc welding (PAW), among other welding processes [50]. The first patent for this form of AM was filed in 1926 [51], although it has only been investigated as a viable manufacturing technique since the 1990s. WAAM is suitable for medium to large scale parts, that would typically otherwise be forged or machined, with low to medium geometric complexity. It allows for high deposition rates (currently around 4-9 kg/hour) and can be used to produce virtually unlimited part sizes, with a 0.5 mm surface roughness [48,52]. WAAM is generally considered to be a near net shape process, which means, depending on the design requirements, the built parts may entail some additional machining to achieve the desired final shape and surface finish. Compared with other metal additive manufacturing processes, WAAM is much cheaper due to the use of standard off-the-shelf equipment, mature technology and low material costs, with the wire feedstock being an order of magnitude cheaper than metallic powder [3], making WAAM more suited to the cost-sensitive construction industry. The placement of the wire is controlled by a robotic arm (shown in Figure 12) or computer controlled gantry. The surface tension of the molten metal can be used to produce horizontal features without supporting structures, which are typically necessary with other metal AM techniques.



Figure 12 Structural sections being built with wire and arc additive manufacturing (WAAM) using a robotic arm

A major challenge with WAAM relates to the high residual stresses and distortion that can result from the high heat input. The residual stresses arise from shrinkage during cooling and are largest along the deposition direction. Symmetrical building (moving outwards from a line of symmetry), back-to-back building (two identical components built symmetrically back-to-

back at the same time) and heat treatment can be used to reduce the residual stresses [48]. The temperature must also be carefully controlled to ensure consistent deposition conditions, which can lead to the equipment sitting idle to allow cooling during building [3]. Non-destructive testing (NDT) and online monitoring (OLM) can be used to check the building process by measuring the voltage, current, porosity level, grain size and shape during deposition [48].

3.3 Sheet lamination

In the sheet lamination method, individual cross-section layers are cut out and then laminated together using diffusion binding, low melting point alloys, adhesive polymers or ultrasound [4,53]. This method is compatible with ceramics, cork, foam, metals, paper, polymers, rubber and wood [3], and multiple materials can be used in one build depending on the lamination method used. Advantages of sheet lamination include the low material and equipment costs, as well as the high strength and good quality surface finish [4,53]. Sheet lamination can also be used to embed sensors and electronics within objects. The geometry of the final part is only limited by the layer thickness and machining capabilities of the cutting device [54].

3.4 Electrochemical additive manufacturing (ECAM)

Electrochemical additive manufacturing (ECAM), not covered by ISO/ASTM 52900 [6], is a new alternative metal additive manufacturing process which is being developed and is similar to electroplating, where the part is built up at the atomic level. This process is in the early stages of development, with the maximum dimension of parts currently around 600 μm. A major advantage of ECAM is that since it is a non-thermal process, parts can be built with lower internal residual stresses [55].

3.5 Discussion

The two metal additive manufacturing techniques that are most suitable for the construction sector are powder bed fusion (PBF) and directed energy deposition (DED). Sheet lamination is unlikely to allow the geometric forms that will attract architects, structural engineers and clients to use these new forming techniques, or be viable for producing parts at a construction scale. Electrochemical additive manufacturing (ECAM) is still in the very early stages of development, and again is not anticipated to be viable at a suitable scale for construction applications anytime soon.

PBF and powder based DED methods allow for very accurate parts to be built, although with current technology the maximum dimensions are small, relative to typical structural elements, and the build times are lengthy. These techniques can still be used within construction, as shown previously in Section 2.4 with prototype façade and connection nodes already having been produced; nevertheless, currently they do not scale to full-sized structural members. Future advancements in manufacturing equipment will allow larger parts to be built and in shorter build times, although for the foreseeable future these techniques will most likely still be limited to specialised, small components where the material or geometric benefits outweigh the economic cost and long build times.

Wire and arc additive manufacturing (WAAM) DED significantly expands the maximum part size that can be built and has sufficient building speed that typical structural elements, and even entire structures, can be built, such as the MX3D bridge shown in Section 2.4.3. However, the dimensional accuracy and surface finish may require additional post-processing for many construction applications. Process advances are deemed unlikely to be able to significantly improve the dimensional accuracy and surface finish; the manufacturing technique inherently produces a rough surface and has a minimum thickness of 2-3 mm, which is slightly larger than

that of conventionally produced structural components. This method does have the potential to allow new geometric forms that can be produced relatively cheaply and quickly, provided the dimensional and surface variability is acceptable.

4 Research on additively manufactured metallic material and components

There has been significant research effort devoted to the advancement of metal AM processes and products over the past twenty years. An overview of the research into the properties of additively manufactured metallic material and components, with an emphasis on iron alloys, is presented in this section. Iron alloy based metallic materials are commonplace in construction due to their combination of strength, stiffness and relatively low cost. It is apparent that, to date, there has been limited research focussed on applying metal additive manufacturing techniques to the construction sector, despite, as later outlined in Section 6, the potential opportunities.

4.1 Powder bed fusion (PBF) manufactured material and components

Tensile coupon tests investigating the stress-strain properties of powder bed fusion manufactured Grade 316L stainless steel material in different building orientations have been undertaken in a number of previous studies [56–61]. Compressive coupon tests have also been carried out [61]. Typical measured tensile and compressive stress-strain curves from Buchanan et al. [61] are shown as Figures Figure **13** and Figure **14**, respectively. The anisotropic behaviour, arising from the novel manufacturing method, is immediately apparent from these two figures.

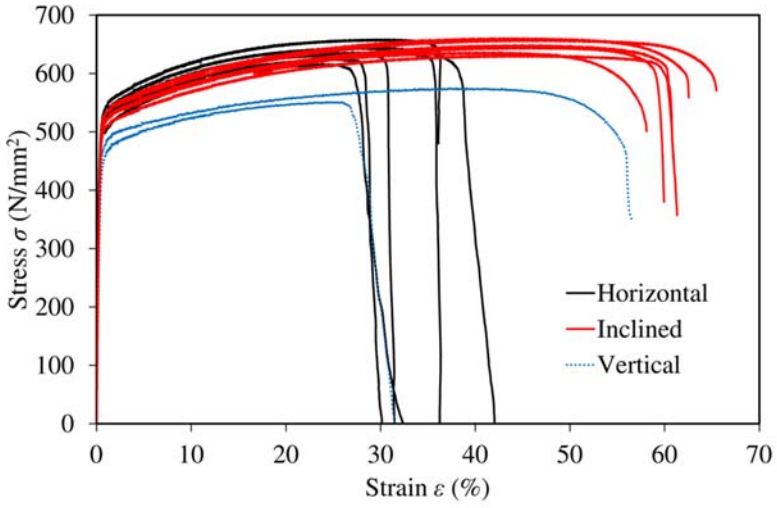


Figure 13 Measured stress-strain curves from tensile coupon tests on Grade 316L stainless steel reported by Buchanan et al. [61]

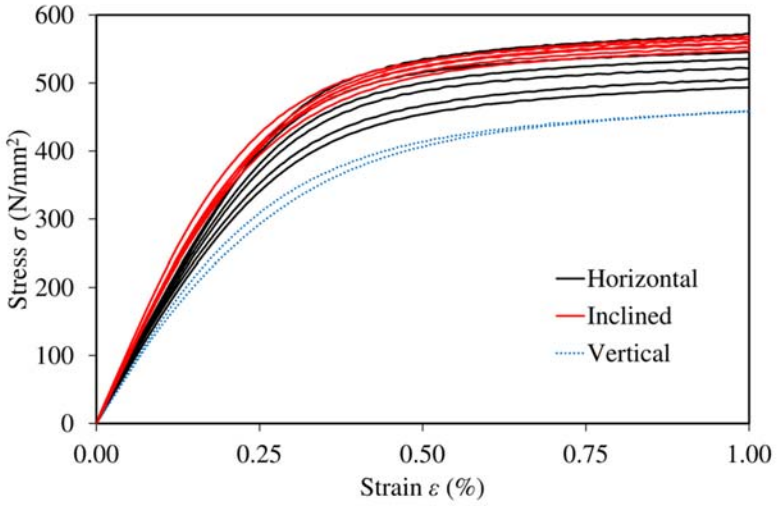


Figure 14 Measured stress-strain curves from compressive coupon tests on Grade 316L stainless steel reported by Buchanan et al. [61]

The Young's modulus E was seen to have minimal variation with building orientation, whereas the 0.2% proof stress $\sigma_{0.2}$ and ultimate stress σ_u were observed to decrease with an increase in building orientation. This is attributed to the elongated grains in the vertical direction, resulting in lower strength when loaded in this direction. The building orientation is defined as the angle measured from the horizontal building plane to the longitudinal axis of the coupon. The variation of the fracture strain ε_f with building orientation was observed to be highly scattered. Heat treatment may reduce the degree of anisotropy, although further investigation is required.

In terms of the absolute values for the key material properties of PBF manufactured Grade 316L stainless steel [56–62] relative to equivalent conventionally produced material [63,64], PBF manufactured material has a slightly lower average Young's modulus (E≈180,000 N/mm^2), a significantly higher yield stress and a more variable fracture strain. The lower Young's modulus is associated with a higher degree of porosity than conventional stainless steel. The higher strength is attributed to the rapid cooling and solidification from the manufacturing process, which leads to a fine crystalline structure [56,59,60].

The effect of laser power [9], powder particle size [58] and building layer thickness [58,60] on the mechanical properties of PBF manufactured Grade 316L stainless steel has been explored, while the level of residual stresses in PBF manufactured material was measured in [65,66] and found to be significant. The corrosion resistance of powder bed fusion manufactured 316L stainless steel has also been investigated and, provided full relative density is attained, the resistance is similar to conventionally formed material [67]. The tensile properties of PBF manufactured Grade 304 stainless steel with varying layer thickness, laser overlap, laser scanning angle and building direction have also been studied in Guan et al. [68]. Research into the weldability of PBF stainless steel was presented by Matilainen et al. [69] and it was concluded that AM parts could be welded and that the weld quality was good.

The tensile and fatigue behaviour of heat-treated powder bed fusion manufactured PH1/15-5PH martensitic stainless steel has been studied by Khalid Rafi et al. [70]. The variation in the tensile stress-strain response with building orientation for PH1/15-5PH material was investigated by Buchanan et al. [61]. Anisotropic behaviour was again observed, as shown in Figure 15, although in contrast to the 316L tests, the ultimate stress and fracture strain reduced with increasing build orientation, varying by up to 5% and reducing by up to two thirds

respectively, while the Young's modulus and 0.2% proof stress showed minimal variation with build angle.

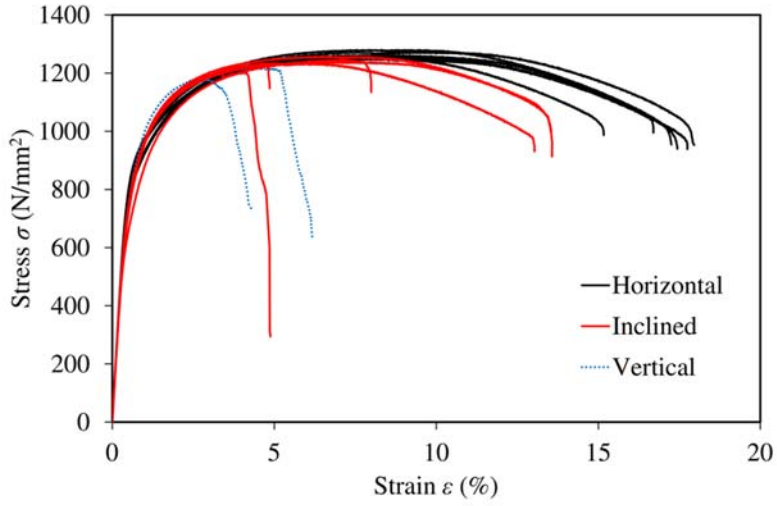


Figure 15 Measured stress-strain curves from tensile coupon tests on PH1 stainless steel reported by Buchanan et al. [61]

The fatigue performance of powder bed fusion manufactured Grade 316L and PH1/15-5PH stainless steel has been explored by Spierings et al. [71], while that of aluminium alloy AlSi10Mg, titanium alloy AlSi10Mg and Grade 316L and 17-4PH stainless steel has been examined by Mower and Long [59]. For stainless steel, fatigue behaviour similar to that of conventionally produced material was observed if the principal stresses aligned with the build planes, otherwise premature fatigue failed occurred due to separation between the layers.

Studies into the structural application of powder bed fusion metallic materials have included examining Grade 316L stainless steel open cellular lattice structures [72–74], negative Poisson's ratio structures [75] and square hollow section (SHS) compression elements [61]. A photograph of the specimen building process of the SHS, is shown in Figure 11, while their deformed shapes, following failure under concentric compression loading, are shown in Figure 16. The normalised ultimate axial cross-sectional resistance $N_u/A\sigma_{0.2}$ (where N_u is the ultimate axial resistance and A is the cross-sectional area) of the five tested powder bed fusion SHS compared with conventionally produced austenitic, duplex and ferritic SHS for varying cross-section slenderness $c/(t\varepsilon)$ [63], where c is the element width, t is the thicknesses and $\varepsilon=[(235/\sigma_{0.2})\ (E/210000)]^{0.5}$), is shown in Figure 17. The stockier additively manufactured cross-sections had slightly greater normalised axial resistance, using the averaged vertical material properties, compared with conventionally formed stainless steel SHS. The most locally slender SHS had a normalised resistance slightly below the existing conventional test data, which may be the result of internal defects or high residual stresses. The EN 1993-1-4 [63] cross-section resistance predictions were calculated for the additively manufactured SHS and were found to offer suitable predictions for the non-slender cross-sections and slightly unconservative predictions for the slender cross-section, overestimating the cross-section resistance by 13%. The continuous strength method (CSM) resistances were also determined, and these were found to be more accurate in predicting the resistances of the non-slender cross-sections.



Figure 16 Deformed additively manufactured square hollow section (SHS) compression test specimens [61]

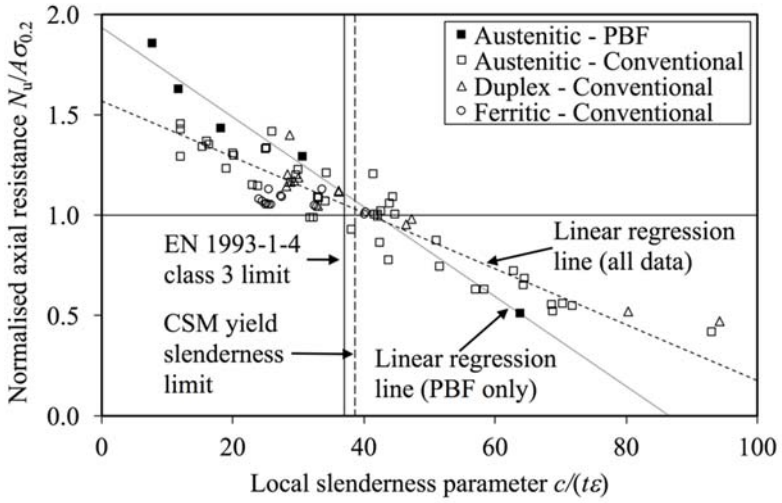


Figure 17 Normalised ultimate axial compressive resistance $N_u/A\sigma_{0.2}$ varying with local slenderness $c/(t\varepsilon)$ [61]

4.2 Directed energy deposition (DED) manufactured material and components

The effect of heat treatment and thermal history on the tensile and compressive properties of directed energy deposition manufactured Grade 316L stainless steel material has been investigated in [76]. Heat treatment was found to lower the yield and ultimate strength, but increase ductility, as with conventional annealing. The effect of the laser power and powder delivery rate on the mechanical properties of Grade 304 stainless steel has also been investigated [77].

Early research on metal additive manufacturing using three-dimensional welding was undertaken by Spencer et al. [78] who built a series of simple shapes using mild steel wire and investigated the surface finish, microstructure and residual stresses. An additive manufacturing technique that combines gas metal arc welding and CNC machining, to produce mild steel tensile coupons in varying orientations, has also been explored [79]. Anisotropic behaviour was observed, with the average ultimate strength varying by up to 15% with orientation, although this was later reduced with a higher arc current. The welded nature of WAAM

structural elements is likely to render them unsuitable for fatigue prone applications without additional post processing, such as surface finishing and heat treatment.

The use of wire and arc additive manufacturing (WAAM) in structural engineering applications has been explored as part of the preparatory work for the stainless steel MX3D bridge [51]. Tensile coupons were built from 308LSi and 316LSi stainless steel wire, with slight anisotropic material behaviour observed (a variation in the ultimate strength of 10%) from the test results; fatigue tests and buckling tests on rods were also undertaken. Further tensile coupon tests on wire and arc additive manufactured 304 stainless steel and ER70S mild steel were carried out in [80]. Tensile coupons in two perpendicular orientations were built for mild steel, with no significant difference in yield strength observed, while the stainless steel coupons were built in the same direction. Recent experimental and numerical work has been undertaken by the authors on wire and arc additive manufactured cross-sections that mimic key parts of the MX3D bridge (discussed previously in Section 2.4.3). Typical specimens, prior to testing, are shown in Figure 18. Advanced 3D laser scanning has been employed to measure the specimen geometry enabling the undulating surface topography, that results in varying wall thicknesses, to be captured. Scanning of a typical test specimen is shown in Figure 19a, the digital representation of the scanned specimen is shown in Figure 19b and the wall thickness distribution is reproduced in Figure 19c, the latter clearly indicating greater variation than seen with conventionally manufactured sections.



Figure 18 WAAM circular and square hollow section specimens prior to testing

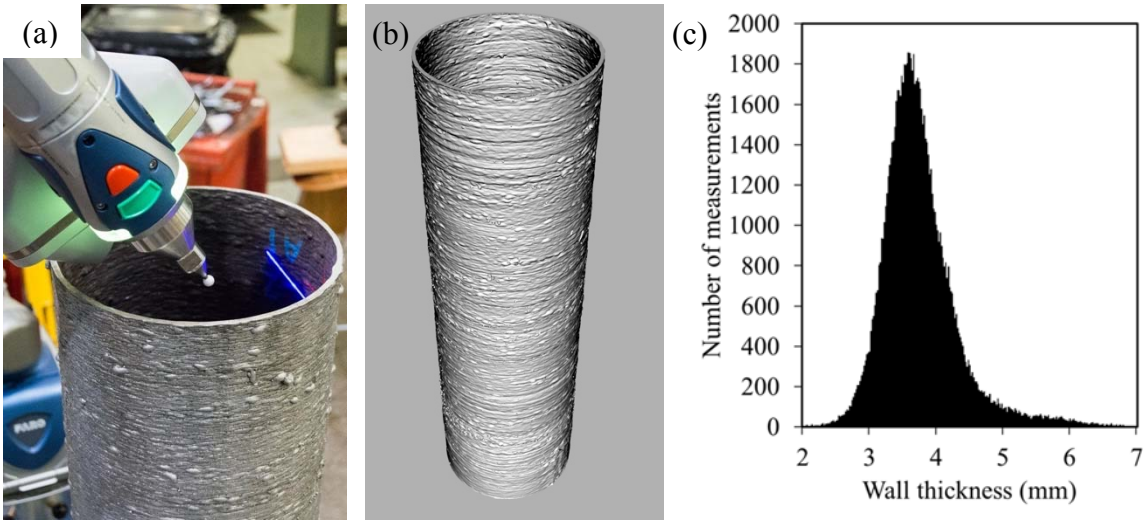


Figure 19 (a) 3D laser scanning of a WAAM circular hollow section, (b) the digital representation of the scanned specimen and (c) the measured variation in the wall thickness

4.3 Other

Research into sheet lamination has been more limited than for powder bed fusion or directed energy deposition. A variety of complex shapes, cooling channels, honeycomb structures and spherical shells with holes, with sheet metal and polymer adhesives, has been built [53]. The feasibility of electrochemical additive manufacturing (ECAM) has been established by building nickel microstructures with cantilevering overhangs [55].

5 Lessons learnt from the use of metal AM in other disciplines

While metal AM is only starting to be used in the construction industry, it is more commonplace in other engineering and science disciplines. In this section the key advances and lessons learnt from the aerospace, automotive and energy industries and the medical sector are highlighted and discussed. The automotive, medical and aerospace industries alone are anticipated to account for 84% of the AM market by 2025 [81].

5.1 Aerospace industry

Metal additive manufacturing is currently used in the aerospace industry due to its advantages over conventional manufacturing techniques. A popular metric in the aerospace industry is the buy-to-fly ratio, which is the ratio of the mass of material purchased to the mass of the final finished component. Buy-to-fly ratios between 10 and 20 are common, although it can be as higher [48]. Traditional subtractive techniques are very wasteful, whereas AM techniques waste less material and enable more optimised structural forms, resulting in a lighter final component. It has been estimated that AM could save €4.3 million for an aircraft, and €770 for a car, in lower manufacturing costs and reduced fuel consumption over the lifetime of the vehicle [5]. Within the construction industry, the emphasis on reducing waste is also highly applicable, lowering the environmental impact, as seen in the previously presented additive manufacturing construction case studies in Section 2, and ultimately reducing the overall project costs.

Additively manufactured parts are typically used for non-safety-critical components, and on military rather than commercial aircraft, due to the variability in the manufacturing process. New models of the Eurofighter Typhoon use additively manufactured components in their air-conditioning unit, as does the Airbus A380 for brackets within the passenger cabin [82].

Additive manufacturing within construction may also be more widely adopted to produce components that do not affect the overall structural stability, unless the structural integrity of the component can be reliability predicted. GE Aviation has developed a metal AM fuel nozzle (shown in Figure 20), which has reduced its part count down from 18 pieces to a single piece, reduced the mass by a quarter and led to a fivefold increase in the lifetime of the part. GE Aviation has received orders for over 8000 engines, each containing nineteen additively manufactured fuel nozzles [83]. They plan to have produced 100000 AM structural parts by 2020, with production rates of 40000 components per year using more than 400 AM machines [3]. Similarly connection details in structures can have multiple parts that are joined together, as seen in Section 2.4.2 for the redesigned lighting node, and AM can be used to consolidate the number of components required for complex structural elements.



Figure 20 GE Aviation additively manufactured fuel nozzle [83]

In 2013, SpaceX built and tested an additively manufactured nickel superalloy engine chamber. They noted that the novel manufacturing technique reduced the time from concept to firing by an order of magnitude, down to roughly three months. The engine chamber has been fired more than 80 times. The following year SpaceX launched a rocket with additively manufactured components in the engines, and the components could operate under high pressure and vibration and at low cryogenic temperatures. Building took two days rather than many months for casting and the built valves were found to have superior strength, ductility and fracture resistance over conventionally cast components [84]. Metal additive manufacturing in construction offers the potential of structural components with improved mechanical properties over traditional forming techniques and with considerable manufacturing time savings for geometrically complicated parts.

5.2 Automotive industry

Metal additive manufacturing has been trialled for use in producing stamping inserts for the automotive industry. Although the inserts required further processing after building, production was found to be cheaper than conventional methods due to the faster building time, and the inserts achieved comparable levels of performance in testing [85]. Additive manufacturing has also been explored in a motorsports context with titanium alloy hydraulic components built and tested in accordance with internal Red Bull Racing standards. The components satisfied all testing requirements, and additive manufacturing was found to allow lower weight and more optimised forms, leading to more efficient fluid flow [86]. The testing required for additive manufactured components to determine their reliability and integrity will

typically exceed that required for conventionally formed parts; this represents one of the key challenges for the construction sector, as seen in some of the previous construction case studies described in Section 2.

5.3 Energy industry

Additive manufacturing has also been used within the energy sector for repairing gas turbines. Wear and tear on the burner tip requires regular maintenance, involving cutting out the old tip and welding a prefabricated replacement. Additive manufacturing has enabled significantly faster repairs, up to 90% faster, by only needing to remove the damaged material before adding new material. Old versions of burners can also be updated with the latest improvements, resulting in further cost savings [87]. In construction, it can be foreseen that additive manufacturing techniques could be used to repair damaged or corroded structural elements or even be used to 'upgrade' a structure in-situ in response to increased loading demands.

5.4 Medical sector

Metal additive manufacturing offers significant opportunities within the biomedical field for specialist surgical instruments and prosthetic implants [49]. Conventional metallic implants have an incompatibility of stiffness with the surrounding bone, which can lead to loosening over time, causing pain and requiring surgical intervention. Additive manufacturing offers the possibility to build lightweight, porous implants, with a reduced stiffness closer to human bone, and encouraging guided tissue regeneration to lead to a longer lifetime within the body. The microstructure, shape, size and addition of internal structures, along with direct low-volume manufacturing, present customisation opportunities and biological and mechanical properties not possible with traditional techniques [88]. There are strict requirements for implants due to the need to ensure patient safety, with standards for the materials, machining methods and functionality [89]. The requirement for corrosion-resistant biocompatible metallic materials has led to titanium alloys and cobalt-chromium alloys being used to build prototype human vertebra [90], dental implants [91], hip stem implants [88] and intramedullary nails, to treat bone fractures [89]. Hollander et al. [90] noted that heat treatment was required to ensure that the implants attained the required ductility. The rough unfinished as-built surface also required sandblasting to prevent inflammation within the body, though, even considering the time for this post-processing, the manufacturing time was still significantly faster with additive manufacturing than traditional fabrication [90]. These biomedical AM applications provide some key learning points that can also be applied to construction. For example, the rough finish described above could be advantageous in composite construction to enhance the shear connection; also the production of lightweight, porous parts would allow material savings and reduced self-weight, with the latter having secondary benefits associated with reduced transportation costs and foundations, and functional grading of the material can be used to control the distribution of forces and moments around a structure, manage strength demands and enhance compatibility with adjoining elements.

6 Opportunities and challenges in construction for metal additive manufacturing

Metal additive manufacturing offers tremendous opportunities for innovation within construction; these opportunities are set out in Section 6.1. Along with these new opportunities, additive manufacturing also brings challenges, some of which are inherent to the manufacturing technique (such as variability in material and geometry) and others that relate to the current state of the technology, which may be alleviated as the manufacturing capabilities advance. These challenges are discussed in Section 6.2.

6.1 Opportunities

6.1.1 Geometric flexibility and optimisation of material properties

A key opportunity that additive manufacturing offers over traditional manufacturing processes is the geometric flexibility at both the macro and microscales, allowing for highly optimised structures and engineered materials. This is of particular importance given that approximately one quarter of all steel produced is used in construction, and that the average estimated utilisation of this steel is below 50% of the available capacity [92]. Designers are no longer limited to working with simple geometries, with non-re-entrant shapes and constant wall thicknesses. Additive manufacturing unlocks a variety of new structural cross-sections and forms, such as cross-sections and members with varying wall thicknesses around the perimeter or along the length, or hollow sections with internal strengthening features and shear keys, for enhancing composite action with infill material, that were not technologically or economically feasible with conventional methods – see Figure 21. With additive manufacturing, geometric complexity can be obtained at minimal, or in some cases no, additional manufacturing cost, whereas with conventional manufacturing there is always a direct link between design complexity and cost [4,93]. The ability to place material in the most structurally-optimum locations is an important feature of AM, with wide-ranging benefits, not least a reduction in material consumption and waste, and therefore ultimately cost. This concept is shown in Figure 22, where a continuous beam, with varying overall depth, can be replaced with a constant depth metal AM beam, with varying flange thickness. Material is placed where it is required to match the demands of the bending moment diagram, and the stockier and therefore geometrically more ductile cross-sections coincide with the points requiring the greater rotation capacities. Compatibility with existing design philosophies, having consistent outer dimensions, is maintained, with more efficient material usage than conventional manufacturing methods.

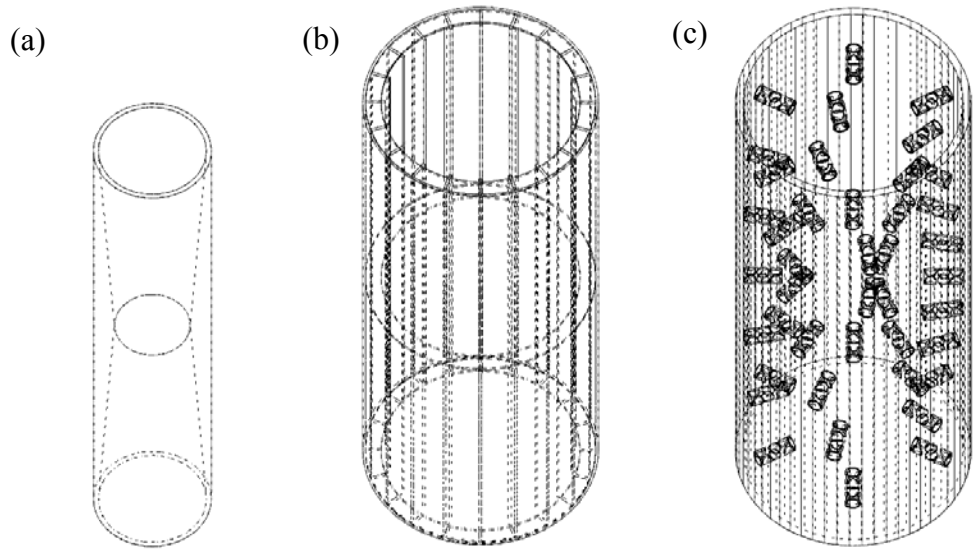


Figure 21 Examples of possible AM hollow structural members featuring (a) varying wall thickness to enhance member buckling performance, (b) internal stiffening to improve local buckling resistance and (c) perforated shear keys to enhance composite action with infill material

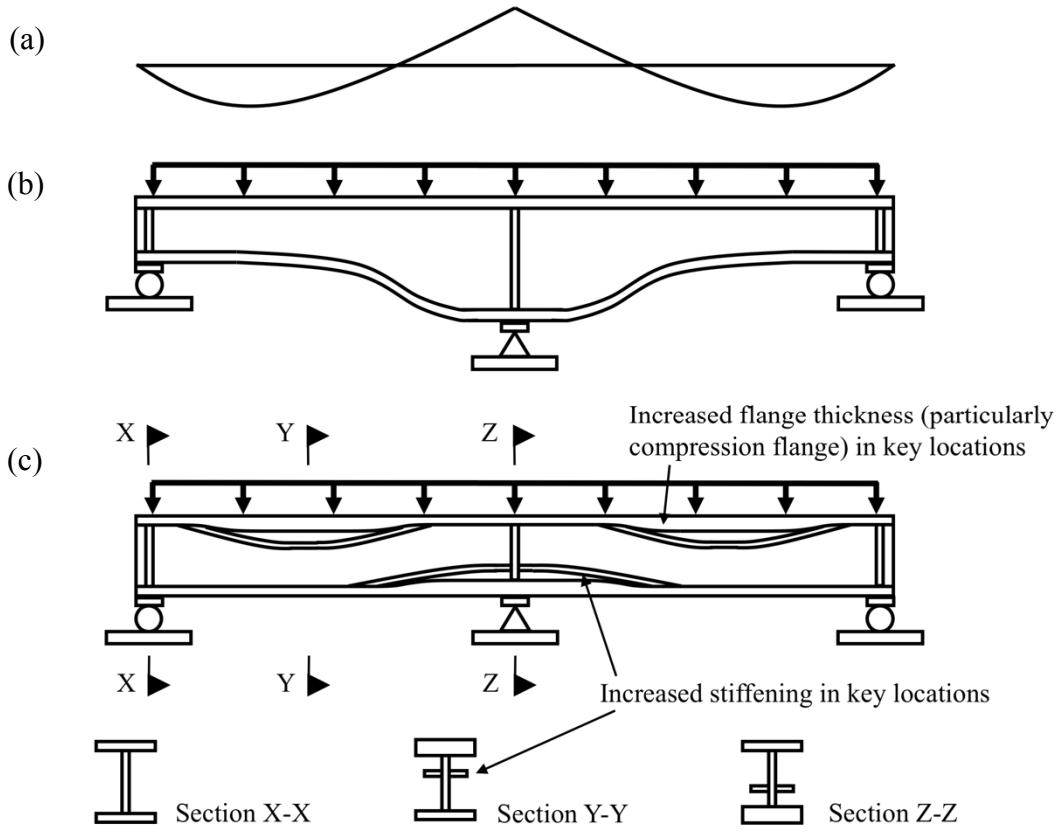


Figure 22 (a) A two-span continuous beam bending moment diagram with (b) a traditional fabricated, variable depth beam and (c) a replacement metal AM beam, with varying flange thickness and additional stiffening in key locations

At the microscale, the material properties can be modified to produce engineered materials with controlled mechanical behaviour. As explored in Section 5.4, the porosity of biomedical implants is deliberately increased in key locations to lower the material stiffness to improve compatibility with the adjoining human bone [88]. Within construction this could be used to distribute forces and moments in the most favourable way by reducing the stiffness to attract less force in certain areas, or used to produce sacrificial energy absorbing elements for structures in seismic areas – see Figure 23. Structural components could have physical properties allowing for parts to transition from being rigid to flexible along their length, i.e. functionally graded materials. The strength and ductility of the material could also be optimised around the structure by controlled cooling, e.g. utilising high strength material in regions of high forces and moments such as the mid-span of beams, but higher ductility in regions such as connections where ductility demands are high (Figure 24). Additional functionality could also be incorporated into built components, such as enhanced acoustic or thermal properties [28].

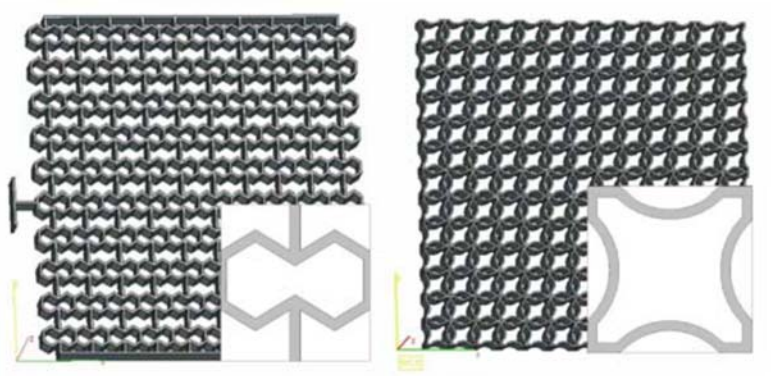


Figure 23 Negative Poison's ratio honeycomb structures [75] that could be adopted as energy absorbing elements

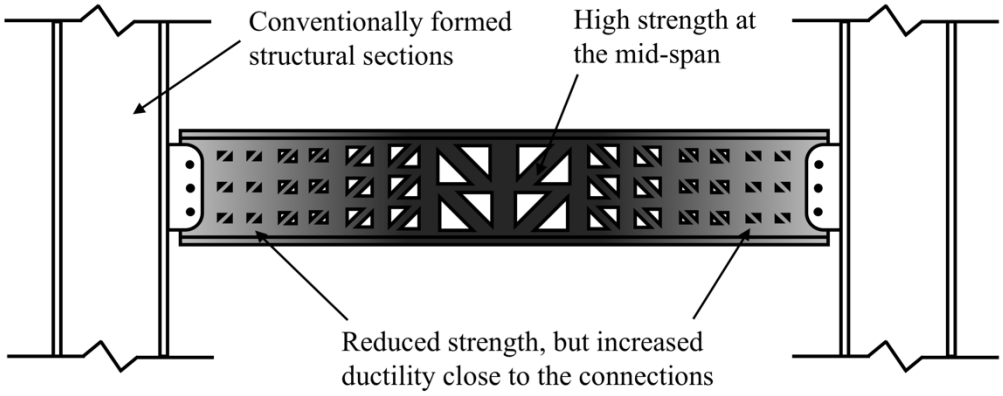


Figure 24 Possible functionally graded AM beam, as part of a hybrid structure

Residual stresses are generally regarded as an unwanted 'imperfection', typically resulting in premature yielding and a reduction in load-carrying capacity, but one person's residual stresses are another's prestressing, and if the residual stresses are arranged to be of the opposite sense to the stress arising from the applied loading they can delay yielding and have a positive influence on load-carrying capacity. The distribution of residual stresses can, to a significant extent, be controlled by adjusting the order in which the material is printed, with successive layers generally compressing those that have gone before due to shrinkage of the material as it cools. The entire residual stress pattern must of course be in overall self-equilibrium and there will be associated distortions. Care must also be taken in fatigue-prone structures. This concept has been seen previously in welded I-sections fabricated from flame cut plates, where the flange tips are in residual tension, leading to enhanced minor axis buckling resistance [94]. Similarly, prestressed cables have been employed to compress the lower flange of steel beams; under load the pre-compression must first be overcome before tensile stresses are generated, delaying yielding and enhancing load-bearing capacity [95].

The geometric and material flexibility presents the opportunity to build highly efficient, optimised structures. Topology optimisation is a computational approach that varies material placement to attain specific behaviour, such as minimum material or uniform stress distribution, under specified loading and geometric constraints [3]. AM provides the opportunity to combine computational optimisation with a physical manufacturing process capable of building the resulting optimised structure. In essence, AM allows the structure to be built for the function for which it is intended, without the usual fabrication restrictions.

Optimised structures will utilise less material, and enable more expensive materials to be competitive, which could lead to new materials being adopted in the construction sector [28].

6.1.2 Customisation

Additive manufacturing offers a degree of customisation that has not previously been attainable in a low margin industry, such as the construction sector. Small production runs are possible, with no tooling requirements in many scenarios, enabling the fulfilment of custom orders for niche markets [2]. Structural engineers could make every structural component unique with no additional manufacturing costs; the cost to produce two identical or different variants of an object is essentially the same [16,17]. Design changes could also be rapidly incorporated. This customisation will likely create additional demand for additive manufacturing, which in turn will help to lower costs. Customisation has been used, since the 1990s, as a marketing strategy in the Korean house-building sector [1].

AM can be utilised to produce elements that change form or function after the manufacturing process is complete, termed '4D printing'. Common examples provided include a thermally sensitive façade that can provide shade by changing shape and fluid pipes that can change dimensions to control the internal flow rate [28]. AM offers far greater customisation opportunities than traditional manufacturing methods.

6.1.3 Construction time

In construction, generally the longer the duration between the start of a project and the finished structure, the greater the financial cost of the project. Additive manufacturing offers several opportunities for this construction time to be shortened. Firstly, there is reduced setup time for manufacturing components with these new techniques [85]. The time to build the individual structural elements can also be reduced; for example, the build time for a structural concrete wall built using concrete printing was reduced to 65 hours compared with 100 hours for a conventional wall [2]. Other studies determined that the geometry being formed strongly affects whether AM techniques are more efficient than conventional methods, with prefabricated offsite casting being the fastest technique for a simple straight wall with a fixed 8 hour working day for both techniques [26]. Increased deposition rates do however generally result in lower placement precision and resolution, which can affect the surface finish. Typically, a better surface quality is attained from building with thinner layers, but this takes more time.

For metal additive manufacturing, faster build times can be achieved through consideration of the build orientation [2], taking into account the characteristics of the building process and by keeping the build height low [4]. AM can be expected to significantly reduce the time to fabricate complex structural elements from weeks to hours [28]. Additive manufacturing will likely initially feature predominantly in offsite manufacture and modularisation which will help to increase quality, but also allows for reduced costs, through economies of scale.

6.1.4 Hybridisation and structural strengthening or repair

Additive manufacturing is considered more likely to complement rather than replace conventional building techniques [28]. 'Hybrid solutions' where parts of the structure feature traditional building products and others are formed, perhaps the more intricate parts, using additive manufacturing have clear attractions.

Additive manufacturing techniques also offer the opportunity to repair damaged or corroded structural elements, or be used to strengthen a structure in-situ, reducing the cost of the repairs

or strengthening work. Any repair process also provides the opportunity to update the design of the structural element [81].

6.1.5 Environmental advantages

Construction uses vast resources; in the US it has been estimated to consume 36% of the total energy, 30% of raw materials and 12% of the potable water [96]. Globally, construction contributes to 30% of greenhouse gas emissions [28]. Traditional construction techniques use standardised components - for example metallic structural cross-sections or reinforcing bar, for beams, columns, floors and walls that have unique dimensions. The components must therefore be cut down to size, ultimately producing waste and increasing the economic and environmental costs [16]. Additive manufacturing provides opportunities to reduce this waste by allowing bespoke, optimised structural components to be produced for each project, reducing the amount of raw material required and unwanted material that needs to be disposed of. For metallic powder bed fusion methods, up to 98% of the remaining 'waste' powder can be recycled and reused [5]; in general, additive manufacturing techniques can lead to a 40% reduction in waste over subtractive techniques [17]. The environmental impact of an additively manufactured component has been estimated to be up to 70% lower than that of an equivalent component produced with conventional techniques [97].

Additive manufacturing also enables just-in-time manufacture, which can reduce inventory storage costs, in addition to providing structural engineers with an unbounded range of cross-sections and forms that are not restricted by uncertain demand and low inventory turnover [17]. If this manufacturing took place onsite, or closer to the final location, there could also be reduced emissions from shorter transportation distances [25,81].

6.1.6 Human factors

Labour productivity on construction projects has remained essentially the same over the past fifty years [28], in contrast to other industries. Labour costs are estimated to account for 15-50% of the total cost of construction projects [25]. Some have argued that many onsite tasks can be achieved more safely, accurately and faster using increased automation in addition to working through adverse weather and at night [25].

Additive manufacturing building processes are typically highly automated, reducing labour costs and reducing the risk of human error during the manufacturing process [5]. The 3D CAD models do however need to be of high quality and error free as there are fewer opportunities for human intervention during manufacture [3]. This increase in automation will involve a step change from conventional, more manual, construction, with automated processes currently limited to sprayed concrete, precast concrete and milling operations [16].

Additive manufacturing is also seen as an opportunity to reintroduce manufacturing capacity in regions where it has been lost, due to pressure from lower labour costs, higher taxes and easier access to raw materials elsewhere [5]. AM could also be used to build infrastructure in harsh environments where construction activities are dangerous or difficult for humans, such as in regions affected by war, natural or manmade disasters or even in extra-terrestrial environments [28].

6.2 Challenges

6.2.1 Costs

The cost difference between structures or structural elements produced using AM and traditional manufacturing will vary on a project-by-project basis, and will be influenced

significantly by the individual cost implications for the design phase, material use, human labour and equipment, all of which can differ substantially between the two building approaches [28]. While additive manufacturing offers considerable potential for material and cost savings in the future, there is currently likely to be an economic penalty in the early adoption of this technology. The construction industry is highly cost sensitive. The opportunities for major innovation are severely limited with projects predominantly awarded based on cost, with the lowest bidder winning. The cost implication of additive manufacturing in construction is still unclear, and some have commented that it is too early for it to be utilised in the construction industry [1]. For non-complex geometries, it is unclear if there are significant human cost or material savings from AM [28] – hot-rolling and cold-forming are very rapid and efficient production methods for relatively simple standardised geometries; however, low production runs are commonplace in construction and this is a clear case where AM can be cost competitive compared with conventional manufacturing [26]. Any optimisation processes will also increase costs through the additional design effort required, and a major risk is that structures become unnecessarily complex due to the opportunities presented by AM. There will be economic limits on optimisation and excessive optimisation may affect structural robustness [28] and the ability to respond to unanticipated loading. The raw material cost can also be higher than for conventional processes – for aluminium, the material cost can be ten times greater, and with powder bed fusion, the material cost can account for up to half the total cost of the printed element [3]. This is less so for WAAM processes, where the input material (i.e. the welding wire) is the same as for conventional manufacturing. There are also costs associated with failed builds that need to be considered. The cost of additive manufacturing equipment, particularly for laser or electron beam based methods, can be high and costs do not decrease with increased production runs [17]. Energy costs vary depending on the technique used; stereolithography uses as little as 100 W, whereas electron beam melting directed energy deposition can use 3 kW [5].

Additive manufacturing processes, while heavily automated, are not entirely labour-free; there can be significant pre-processing and post-processing steps to undertake, such as file repair, build machine cleaning, removal of support structures and heat and surface treatment [3,5]. While faster construction is possible with additive manufacturing over conventional techniques, this requires increased deposition rates that generally result in lower placement precision and resolution, affecting the geometric accuracy and the surface finish. Typically, a better surface quality is attained from building with thinner layers, which takes more time and therefore increases the economic cost.

6.2.2 Manufacturing process variability and limitations

A current major challenge with additive manufacturing technologies is the lack of standardised manufacturing guidelines and practices. The same 3D CAD file can produce a wide range of results with different additive manufacturing methods. This lack of standardisation can be commercially beneficial for equipment manufacturers through vendor lock-in, although it hampers more widespread adoption of additive manufacturing techniques. There is a clear requirement for material, process, calibration, testing and file format standards despite the range of materials, equipment and processes currently available [4]. Variability across builds [4] and between machines using the same process [3] will require new quality assurance measures to ensure that parts built meet appropriate strength and reliability requirements.

Parts which are additively manufactured behave differently to conventionally formed components, as seen in Section 4 from prior stainless steel AM research. The inherent material anisotropy, due to the novel manufacturing process, may be reduced with heat treatment,

although this still requires further investigation. Unlike subtractive manufacturing, where the component is at its strongest at the start of manufacturing [3], with AM the part is gaining strength throughout the building process and requires special techniques, such as support structures [5] or using unconsolidated powder [16], to resist self-weight and external loads from the printing process along with internal thermal forces and residual stresses. The surface finish of metal AM parts differs from conventional manufacturing techniques, with the layer-by-layer building process leading to a 'stair-stepping' effect and incomplete melting in powder based techniques resulting in a rough surface finish [4]. The actual geometric properties of built elements can have a broad distribution rather than the tightly-controlled values typically associated with conventional forming methods. This was seen in the variation of the wall thickness of the WAAM circular hollow sections shown in Figure 19c, requiring more advanced measurements techniques than are currently commonplace in construction. Additionally, additive manufacturing allows internal features to be built, but the presence and position need to be verified [3].

6.2.3 Design methodology and digital workflow

Additive manufacturing goes hand-in-hand with the digital revolution and data centric engineering. A new breed of highly computer literate engineers will be needed and, in order to take full advantage of AM, the geometric freedom, production and assembly needs to be considered from the start of the design process [28]. More decisions need to be made in the design phase, than with typical forming methods, due to the variability and limitations highlighted previously. The International Organization for Standardization (ISO) and American Society for Testing and Material (ASTM) has formed working groups to solve these issues, and in 2013 set the goal of developing a single set of global standards to be applied to the majority of additive manufacturing materials, processes and applications [3].

Design for Manufacturing and Assembly (DfMA), i.e. designing and optimising a component or system in conjunction with its manufacturing process to lower costs and development time, is becoming increasingly common in construction [3]. Design for Additive Manufacturing (DfAM) will be required to allow the designer to appreciate the opportunities and constraints from the capabilities of the equipment, changes in material properties during the building process, maintenance and future regulations and standards. Substantial work is still required to understand the building processes and develop suitable design workflows and methodologies [3]. An architectural design workshop resulted in designs which required significant reworking to allow them to be realised using additive manufacturing methods [27]. Designs for parts can be easily shared, which can be considered as benefit or a threat. Manufacturing could be outsourced which, intellectual property permitting and assuming reliable, repeatable building processes, allows the design process to be separated from the manufacturing process [17].

DfAM will result in an entirely digital design process. A major benefit is frictionless integration with building information modelling (BIM). BIM aims to increase collaboration and productivity by combining planning, scheduling, estimation and long term management [98]. Currently, significant effort is required to translate traditional 2D construction drawings into a 3D CAD model. This conversion is inefficient and can result in 3D models that are inaccurate and of poor quality; with AM, however, these 3D models are inherently created as part of the design process [1].

6.2.4 Design and verification of structures

Existing structural design methods will need to be updated and re-thought for the verification of metal AM construction. For example, the levels of anisotropy, geometric imperfections and

residual stresses will typically be far higher in AM (particularly WAAM) elements than in conventionally produced members. This will have an effect on many aspects of structural design, particularly in relation to instability phenomena such as member and plate buckling. Beyond traditional codified design approaches, design by advanced analysis is likely to be required to take full advantage of the geometric and material freedom. This will put greater demands on the computational ability of structural engineers and will require further development to structural design standards. An example of the verification of a structure by advanced analysis was provided in Section 2.4.3, where the complex geometry of the MX3D bridge required the development of a sophisticated geometrically and materially nonlinear finite element model as part of the structural verification.

Structural engineers, and ultimately their clients, will need to be able to fully trust the structural integrity of the built components [5]. Robotic and material advancements are outpacing structural design standards and the long-term behaviour of additively manufactured components is also unknown [1]. Structural engineers need to be able to confidently specify AM components, which is currently challenging with a wide range of uncodified materials and manufacturing processes [25]. In Europe, regulators have been accommodating towards AM construction by allowing certification of structures through testing, while in California, USA, AM construction is prohibited for public structures due to liability concerns [25]. AM construction liability is particularly complex as there are multiple stakeholders involved – the designer, contractor, manufacturer of the machine that made the part and material feedstock manufacturer [28]. For construction, a rigorous inspection and testing regime will need to be established. Significant effort is required in developing quality assurance procedures, (process monitoring, regular inspection etc.) to ensure that built parts are produced as intended by the designer, and remain reliable throughout their lifespan. In addition to the advanced finite element simulations, the MX3D bridge is undergoing significant material and cross-section testing, as described in Sections 2.4.3 and 4.2, along with non-destructive load testing on the partially and fully complete bridge; a long-term sensor network to monitor its structural performance over time is also being installed. The described verification approach has been required for the MX3D bridge, due to its pioneering nature, but advanced analysis and a suitable testing and inspection protocol are envisaged to be necessary for all metal 3D printed structural elements in the future.

6.2.5 Societal issues

The wider public is increasingly seeing robotics and increased automation as a threat to job security [25,99]. AM is entirely based upon high levels of automation and its more widespread use may prove controversial to the current construction workforce and society as a whole.

The term ‘rapid prototyping’ was originally used for the manufacturing field that has become AM and negative connotations with this term have been identified [5]. It was proposed that stigma surrounding this term could hold back wider adoption of additive manufacturing for end use components.

7 Concluding remarks

3D printing, or additive manufacturing (AM), is highly suited to high precision, low demand manufacturing in a wide range of materials, including polymers, concrete and metallic materials, and is being considered as a viable building technique within the construction sector. This paper has reviewed current metal AM techniques, existing research, early applications in construction, use in other advanced technology sectors and has explored the many opportunities and challenges ahead for wider metal AM adoption in the construction industry.

Powder bed fusion (PBF) and directed energy deposition (DED) methods are the two most suitable metal AM techniques for use in construction. PBF and powder based DED methods enable accurate building, but with cost, time and maximum dimension limitations. Wire and arc additive manufacturing (WAAM) DED enables faster and cheaper production and virtually unlimited part sizes, although with dimensional accuracy and surface finish limits. WAAM is being used in the construction of the MX3D bridge, the first structure built with metal AM.

Metal AM enables highly optimised structural forms that are too expensive and time consuming, or even impossible, to produce traditionally, and these printed elements can be combined with conventional structural sections to form hybrid structures. The underlying mechanical properties can be altered by varying the microstructure, and the internal distribution of forces and moments can be controlled through functionally graded material. Structural sections with energy absorbing properties or hollow cross-sections with internal strengthening features can be produced, and typically unwanted residual stresses can be turned into beneficial prestressing. Existing AM construction projects have shown reduced material usage compared with typical methods; high-technology industries using metal AM have demonstrated faster fabrication of complex components than conventional approaches, material strength and ductility advantages, and new repair and strengthening opportunities.

Significant challenges and demands do remain for the adoption of additive manufacturing techniques in construction. AM is expected to, initially at least, cost more than conventional manufacturing methods. New digital design workflows will need to be developed, with a mind-set change from design for production to design for function, and existing codified structural design methods will need to be updated for the different material properties and more variable geometry. Structural engineers will need to become more highly computer literate and make greater use of advanced computational analysis techniques in the design process. Metal AM building processes will need to become more standardised and new quality assurance procedures will need to be introduced to ensure that built parts are produced as intended, and that they remain reliable throughout their lifespan. It is also unclear, beyond the high-profile projects utilising AM, how these new manufacturing methods will be utilised – entire structures could be 3D printed, such as the MX3D bridge, or they may be used for hybrid solutions, combining the advantages of new and existing techniques. However, what is clear, is that additive manufacturing offers tremendous opportunities and potential for the construction industry, as these challenges are overcome.

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