A Literature Review of WAAM and Future Application in Buildings

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With rising needs for sustainable and innovative designs, the traditional process of manufacturing steel within the Architecture, Engineering, and Construction (AEC) industry must find new ways to adapt to changing demands. This literature review aims to evaluate one emerging technology – Wire Arc Additive Manufacturing (WAAM) – on its potential to bring the AEC industry to the forefront of sustainable growth through its ability to manufacture standardized metal components with improved sustainability, scalability, production time, and material efficiency compared to the traditional manufacturing process. This review observes first the historical and technological background of WAAM, before examining three case studies which assist in understanding the feasibility of integrating additive manufacturing methods into architectural design. Each case study positively indicates that WAAM has potential to become a primary metal manufacturer in the AEC industry, while acknowledging existing uses and constraints.

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INTRODUCTION

Since its invention, modern steel has been one of the primary construction materials in the AEC industry due to its fantastic strength and durability. But, as a changing climate calls for more innovative, sustainable urban landscapes, the methodology of steel and other alloy manufacturing has remained largely traditional, stagnating at nearly the same process used since its conception in 1856 by Henry Bessemer [1]. With rising needs for sustainable and innovative designs, the traditional process of manufacturing steel must too find new ways to adapt to changing demands. This literature review will explore Wire Arc Additive Manufacturing (WAAM) as one promising emerging technology for the manufacturing of architectural design expressions which may contribute towards a more sustainable, resilient built environment.

WAAM, as a metal 3D printing technology, shows revolutionary potential in the AEC industry. WAAM, compared to other Additive Manufacturing (AM) technologies, allows for significant reductions in the building industry's material consumption, labor costs, and embodied carbon, while also removing major design constraints that have previously limited the production of unique and complex building components – a necessary development for the facilitation of future novel designs. This literature review is driven to answer the research question: Can WAAM bring the architectural design and buildings industry to the forefront of sustainable and innovative growth? This question will be explored first by highlighting WAAM's current and future potential through a review of its technology, evolution, and sustainability. Then, three case studies will be observed to understand the feasibility of WAAM becoming a primary manufacturer for architectural design.

A HISTORY OF WAAM TECHNOLOGY

Wire Arc Additive Manufacturing (WAAM) is a Direct Energy Deposition (DED) metal 3D printing technology that utilizes a metal wire and a robotic arm. The metal wire is fed into a welding nozzle at the tip of the arm, which uses an electric arc to melt the metal and deposit it in layers according to a digital 3D input design[2], effectively welding layer upon layer of metal into a 3D structure.

As indicated in Figure 1, the history of 3D printing steel technology can be traced back to the 1980s. In 1983, Charles Hull defined 3D printing as machines that melt curable materials and deposit the melted material in layers until the desired shape is achieved [3]. Hull invented stereolithography, which allowed CAD data to be translated to 3D printers, and created the first 3D printer. In 1984 Carl Deckard developed an alternative AM method known as selective laser sintering (SLS). This technology

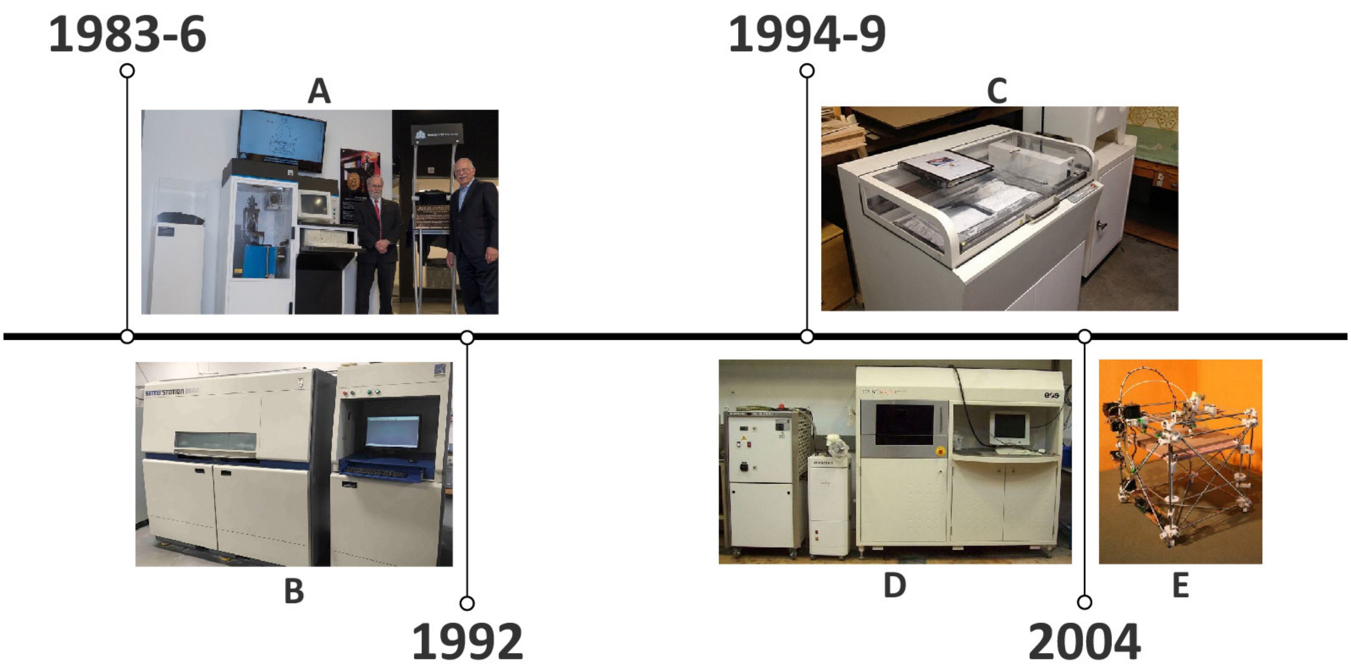

Figure 1. 3D Printing Timeline [4]

uses a high-powered laser to heat powder particles and fuse them together[5], and is implemented in the DTM SinterStation 2500 (Figure 1-B)[6]. In 1989, Fused Deposition Modeling (FDM) was invented, and would become the precedent for commonly used 3D printers today. FDM takes a continuous filament of thermoplastic material to a heated head, which deposits the melted material on a heated surface[7]. Between 1994 and 1999 several new printers joined the market, including the "RepRap" printer (Figure 1-E), which allowed 3D printing to become commercially available. In 2004, the first metal 3D printer, EOSINT M250 (Figure 1-D), was invented using the SLS system. This initial attempt to create a metal 3D printer opened the door to a wave of new approaches, including Direct Energy Deposition, Binder Jetting, and Bound Powder Extrusion, each fusing metal powder into parts within a vacuum[8]. Although the concept for Wire Arc Additive Manufacturing was originally patented in the 1920s, the proper development of DED and CAD softwares was the final push needed for WAAM to come to life[9]. With these developments alongside WAAM, metal 3D printing has proven a swiftly growing industry, with an "expected compound annual growth rate of 23.9% from 2022 to 2030" and a value of 3.52 billion USD in 2021 globally[10].

This rapid growth is funded by the major strides metal additive manufacturing has made in the healthcare, prototype, automotive, aerospace, and defense sectors[11]. Metal additive manufacturing has proven an integral technology in these industries, with a wide range of uses from "manufacturing simple objects such as armrests to complex parts such as engine components"[12]. Compared to other metal additive manufacturers, however, WAAM has found its niche in supplying affordable, "large-sized parts with medium complexity components, made with high-value materials"[13]. Currently in the aerospace industry, this includes FAA-approved WAAM components in airplanes such as the Boeing 787 Dreamliner, through the manufacturer Norsk Titanium [14]. Although AM's current application in these industries follows separate parameters from architectural component design, its successful implementation provides ample evidence for WAAM's future integration and adaptation to AEC.

THE BENEFITS OF WAAM

Many of the same qualities that make AM a preferred manufacturing technology in the aforementioned industries make WAAM a logical option as a primary manufacturer in architectural design. From the simple fact that WAAM is an additive process, material waste, energy consumption, labor costs, and construction time can be significantly reduced when producing traditional products such as beam and column connection pieces, even compared to traditional manufacturing.

Traditionally, metal building components are manufactured through subtractive assembly lines. For example, to manufacture a steel connection, flat steel plates are mass-produced, then cut into a desired size, pressed into their intended shape, and welded to form a complete steel connection. Through cutting huge plates of steel to fit the needs of components, large quantities of waste are generated. This process is also labor and energy intensive, slowing construction times while adding to a building's embodied carbon count. In comparison, since additive manufacturing builds each component by layer, only the material within the component is used in the process of making it. In one study using WAAM in the aviation industry, researchers

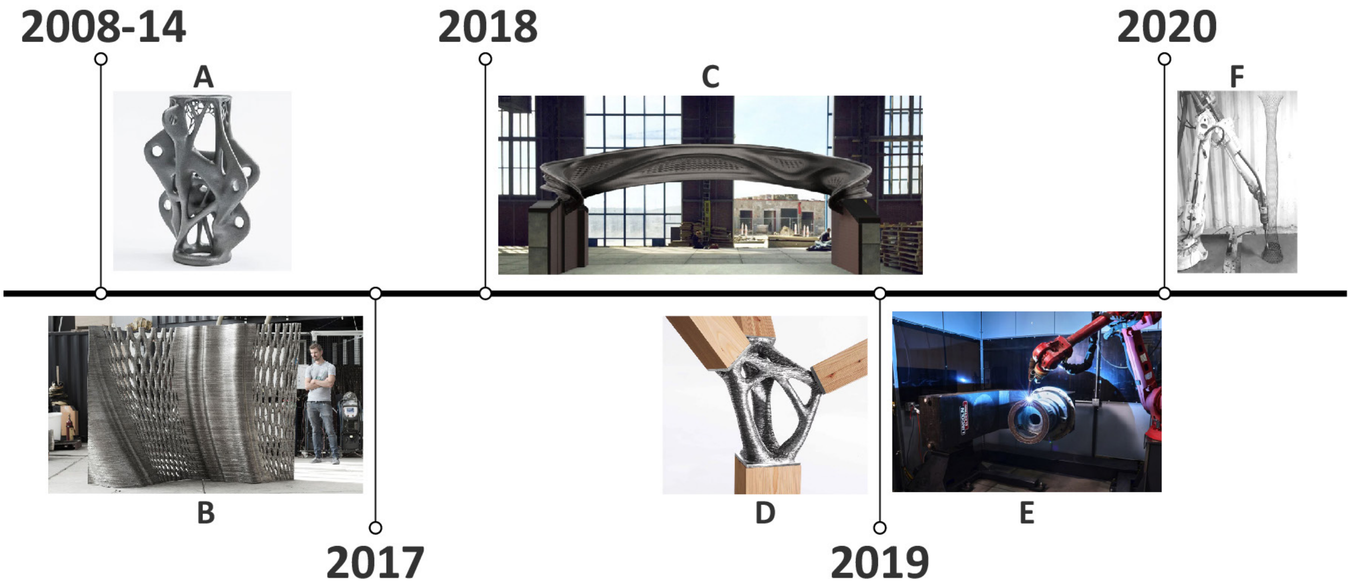

Figure 2. WAAM Timeline [15].

found a material usage reduction of up to 74% compared to the traditional process [16]. Furthermore, since additive manufacturing methods require melted/powder metal, the previous form of the filament does not matter. Thus, additive manufacturers that use powder-based metals can take in recycled and/or scrap material as filament, just as other traditional processes to further reduce embodied carbon [17]. Hence, additive manufacturing can save large amounts of embodied carbon and material usage even in manufacturing standardized components.

WAAM, compared to other AM technologies, is the primary option for the future of 3D printing in the AEC industry because of its scalability, affordability, and speed. WAAM operates with less material waste than other additive manufacturing processes, such as laser-based AM and AM utilizing metal powders as opposed to wire arcs [18]. WAAM's unique robotic arm allows it to manufacture larger components that are more appropriate for AEC scale. WAAM's process of melting a solid filament also eliminates the need for a vacuum – which is required for printers utilizing metal powders – and thus the vacuum's size restraints. In addition, the mechanical parts that compose WAAM apparatuses are predominantly standard off-the-shelf equipment, lowering capital cost of the technology while allowing the machine to be easily created, fixed, and replaced [19]. Furthermore, WAAM's arm can distribute the melted steel in a ball drop form, making the process faster and more precise than other 3D printers [20]. This faster deposition rate then also lowers the energy and production costs of manufacturing a part[21]. Its speed can reduce the production time of a product by 40-60% comparatively [22] with reductions in machinery times by 15-20% depending on the component size[23]. Because of this reduction in material usage, machinery time, and thus energy consumption, WAAM's products are generated with significantly less embodied carbon compared to traditional processes, including energy expended[24].

It should be noted that in certain applications, such as the construction of a simple straight steel wall, other technologies such as CNC milling cause less environmental impact and operate at a lower cost than WAAM [25]. However, as the example steel wall deviates into more complex internal structures such as irregular openings, WAAM quickly becomes the more viable manufacturing method as regardless of the end geometry, its material waste and deposition rate do not suffer. Even in cases of the aforementioned simple steel connections, WAAM still presents incredibly efficient production compared to other manufacturing methods.

DEVELOPING TECHNICAL ASPECTS OF WAAM

Because WAAM is a new technology, its components must still obtain certification and perform nondestructive testing in order to take on a structural role [26]. Based on research done in 2015, the extreme temperature change required in the steel melting process to produce additive layers can significantly redefine the microstructure of the product [27]. According to another study, heat treatment also causes precipitation which results in an increase in disproportion structure [28,29]. In addition, one study has found WAAM may produce micropores through the process [30], which can worsen through residual stress and micro defects, though this depends upon region. The significant temperature change can also cause tensile stress [31]. Because of the nature of its process, WAAM generates products with a rough outer

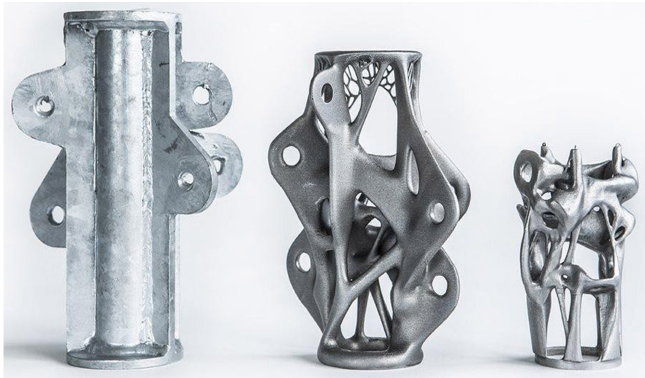

Figure 3. Tensile structure node by Arup [33]

surface that must be heat treated to achieve a smooth outer skin similar to a traditionally welded product [32], which addseven more heat to the process [34]. But despite these drawbacks, WAAM technology is still actively used in non-structural roles in the aerospace and prototype industries, while other research studies have found that WAAM-produced steel components perform with a high tolerance for vertical forces [35]. This implies that while WAAM must still undergo testing before achieving full integration into the AEC industry, its feasibility is dependent only on further studies of its properties rather than a complete redesign of the technology itself.

EMERGING PROJECTS USING WAAM

Although WAAM has not entered the architectural design environment fully, there are several case studies of WAAM's integration in design and infrastructure, primarily led by a leading start-up in WAAM technology, MX3D. Between 2008 to 2014, Arup formed the first design method for creating 3D-printed structural building elements using AM, shown in Figure 2-A. In 2014, MX3D, explored manufacturing a WAAM produced chair. In 2017, MX3D performed a WAAM testing project in collaboration with Jaarman, to computationally design a gradient screen as a part of a sculptural screen collection, shown in Figure 2-B. MX3D and Jaarman also collaborated with Arup to design and manufacture the MX3D Bridge. This bridge, (Figure 2-C) is significant as it serves as a proof of concept for the structural properties of WAAM. The diagrid column produced by MX3D and Tomaso Trombetti is another great project demonstrating how structural components can be reimagined by using WAAM. This column, shown in Figure 2-F, is composed of a series of interlocking strands, while the profile of the column bulges towards the center, adding additional strength to the column [36]. Each of these case studies are significant in helping push WAAM further into the architectural design field.

To consider WAAM's possible advantages in architectural design, three case studies will be explored in greater depth. The first case study, Arup's 2008 Tensegrity Structures, was the first project to apply AM to a structural form. The second case study, the 2019 MX3D bridge, is the first project to apply WAAM to a functioning, large scale infrastructure project. The third and final case study, the Takenaka Connector, is the first to apply WAAM capabilities to a vital architectural component, through mixing artistic form, material efficiency, and structural stability. Each case study is analyzed for its implications on WAAM technology and its indications of WAAM feasibility as a primary steel manufacturer for architectural design.

CASE STUDY I: ARUP'S TENSEGRITY STRUCTURES

The first project applying Additive Manufacturing technology to a structural, weight-bearing design component began in 2008 by Arup, with a complex, irregular tensegrity structure which required the deployment of multiple specialized connection nodes (Figure 3) to which tension wires could be attached [37]. Typical tensegrity structures are designed with standardized components that repeat throughout the structure. The node is often the most challenging component, as it must be lightweight and solve multiple connections at varying angles and forces. Arup's "urban chandelier" tensegrity structure included 1,600 unique nodes in its design [38]. Rather than simplifying the structure to a repetitive pattern, which would require standardized, manufactured nodes, the designers turned to AM as a solution for their project.

The initial attempt to produce the node using traditional methods of welding steel is the leftmost node depicted in Figure 3[39]. After the initial structural analysis, the researchers began experimenting with the metal version of SLS: Direct Metal Laser Sintering (DMLS), a metal homogeneous mass [40]. Like WAAM, the researchers found DMLS can create highly complex forms without adding complexity to the manufacturing process, and thus pursued a more structurally efficient and unique node form[41]. Since the load on each node comes at predetermined points, they ran computational analysis to optimize the node design. The middle image in Figure 3 is an example of their first node produced using DMLS. This iteration reduces the amount of material by creating a branching structure that holds the wire connection points together [42]. While the middle node in Figure 3 successfully reduces the material used, the rightmost node in Figure 3 – the third iteration – further increases the component's material efficiency by optimizing the structure and using computation to re-design the connection points built into the node. The second and third iterations are examples of the variation in form that a materially-efficient, optimized connector can reach using DMLS and computation [43]. Through this research project, Arup became the first to "experiment with the 'printing' of structural building elements in metal." [44]

This case study shows that the application of DMLS and additive manufacturing is significantly beneficial in increasing material efficiency, both through minimizing waste in the production process and through the new ability to design uniquely to loads themselves. This case study demonstrates that while AM is significantly more sustainable compared to the traditional steel manufacturing process, it also opens new doors for a completely

Figure 4. 3D-Printed Stainless-Steel Bridge in Amsterdam [45]

Figure 5. Connector for Takenaka by MX3D [48]

novel style of architectural component design. While this process used a separate 3D printing technology from WAAM, it proves the benefits and feasibility of mass customization in the architectural design industry through computational design and additive manufacturing.

CASE STUDY 2: ARUP + MX3D'S BRIDGE

The MX3D Bridge – an entirely 3D-printed full-scale steel bridge across an Amsterdam canal – is the first application of WAAM technology to an approved large-scale infrastructure project. The project, seen in Figure 4, began in 2015 and was installed in 2021, after close collaboration between architects (Joris Jaarman Lab), engineers (Arup), and contractors (MX3D). To start the unprecedented project, the team adapted the typical infrastructural design workflow to computationally design the structure, while investigating the structural properties of WAAM-produced steel. Advanced computer simulations and significant repeated testing informed each other simultaneously to achieve the final design: a topologically optimized 12.5 m long bridge made up of over 1,100 km of stainless steel filament, which is over 4,500 kg of stainless steel [46]. After the design was determined, material properties were tested before production. The printing process itself took six months, with six WAAM robotic arms working to manufacture the bridge in four parts. Because the long-term properties of WAAM steel is unknown, the MX3D Bridge now also has a "Digital Twin," a digital replica of the bridge that is fed live data of the structural integrity of the bridge from sensors onsite. Through this, the project is constantly monitored for signs of structural deficiencies, while also providing live data about the long-term effects of WAAM steel.

This bridge is a groundbreaking project for WAAM as it is the first large-scale design to rely entirely on WAAM technology. While the bridge was broken into four parts and then welded together, the project nevertheless proves that WAAM is highly capable of projects to the scale of the AEC industry. Similar to the MX3D Tensegrity Structures, the bridge also demonstrates the new possibility of realizing materially efficient forms, through the topological optimization of architecture-driven geometry [47.]

Furthermore, the MX3D Bridge is significant as it was built and defined before the material properties of WAAM were fully understood [49], meaning while there are many more tests to be completed before WAAM can be completely integrated into the architectural design industry, it is an evidently feasible technology. Further projects merging WAAM into the architectural industry can significantly help bring this new technology to the forefront of sustainable and innovative growth.

CASE STUDY 3: TAKENAKA CONNECTOR

A manufactured product for an unbuilt project, the WAAM-produced Takenaka connector (Figures 5) demonstrates the true practicality of WAAM in the architectural components industry. As artistic and highly unique as the Arup Tensegrity Structures are, and as structurally defined and analyzed as the MX3D bridge is, the Takenaka connector is the closest WAAM has come to true application into the architectural design industry. The connector, fabricated by MX3D in 2019 in collaboration with the Japanese AEC firm, Takenaka, is a node which connects non-uniformly angled non-orthogonal timber structural beams at important junction points. With such structural irregularity, creating connectors through traditional methods was unfeasible. The Takenaka connector enables the architectural design's complex geometry, not only through its ability to receive beam members at variable angles, but also because of its hollow structure. The steel connector is filled with mortar, which doubles its compressive strength while maintaining its light weight [50]. WAAM technology thus allowed for the production of a unique and highly rationalized connector [51] that could perform in a structural buildings role.

The collaboration arrived at the final form by using a computational process to solve for an ideal connector through consideration of the angle and load of each linear member. This workflow created a highly efficient form, as it was liberated from the orthogonal constraints of traditional connector manufacturing. MX3D could maintain control over the design, production, timeline, and cost by using an entirely digital design process. A key benefit is the material efficiency of the created organic forms. This computational process also opens the door to experimenting with more sustainable materials. The timber linear reduced embodied carbon counts compared to other commonly used materials, only possible through the unique connector holding the project together.

DISCUSSION

Through reviewing the available research, and three major case studies throughout the evolution of WAAM, it is evident that WAAM has the significant capability to revolutionize architectural design as we know it – to adapt to the world's needed increase in sustainable and innovative design.

Through assessing the design workflows and literature presented, however, there are still major adaptations both the architecture and WAAM industries must consider to make the full application of WAAM technology in architectural design a reality. As seen in all three case studies, to take full advantage of WAAM's ability to mass-customize, designers turned to computational processes to maximize material efficiency. Further development of computational processes that interact directly with WAAM technology and structural information would be beneficial for further integration into the design workflow. While many designers today use computational design methods, this is significant in combining structural design and manufacturing processes into the architectural design workflow from early design phases. As learned from the MX3D Bridge, "future WAAM structures must be engineering focussed," as "WAAM's novelty necessitated 'design by testing' with significant time and cost implications." [52] Properly integrating WAAM's capabilities into the architectural design space would also call for a stronger collaboration between architectural designers, structural engineers, and WAAM manufacturers in order to maximize the benefits that accompany WAAM in the AEC industry.

Another vital aspect for WAAM meeting its potential in the architectural design space is for more manufacturers to take on WAAM technology. Currently, only a few companies in the world utilize WAAM technology to fabricate components, including Lincoln Electric Company in the US and MX3D in Europe. Increasing the number of manufacturers that can perform WAAM – and consequently the number of printed projects that come with them – would be beneficial in providing more collaborative opportunities, data, improvements, and thus more options to create fully integrated WAAM-based architectural designs. Increasing scale increases accessibility and affordability.

As seen in each of the three presented case studies along with the literature reviewed, further research on the application of WAAM in the architectural design space is essential to fill primary technical gaps in knowledge regarding the aging and property alterations of extreme-heat-exposed steel during production. As seen in MX3D and Arup's bridge, although these technical gaps are not fully understood, projects can still progress and contribute further data and understanding to WAAM-based infrastructural development. Thus, further testing, research, and attempts to apply WAAM technology to architectural design in a real-world application, is vital for the future of WAAM in architecture.

CONCLUSION AND OUTLOOK

WAAM is a vital step for furthering sustainable and materially efficient architecture in the future. While simply manufacturing a typical steel component through WAAM – rather than the traditional manufacturing process – significantly reduces material waste, WAAM eliminates the need for standardized forms in construction. This technology allows maximum material efficiency and embodied carbon savings through creating structurally rationalized and unique architectural components. Arup's Tensegrity Structures, as the first case study of AM in structural design, demonstrate that metal additive manufacturing can reduce both material waste through production and material use through form, once liberated from the constraints of traditional steel processes. In the second case study, MX3D and Arup's WAAM-produced Stainless Steel Bridge demonstrates that WAAM is fully capable of application to large-scale constructions. Furthermore, as an in-use work of infrastructure, it demonstrates the feasibility of applying WAAM to the broader architectural-design industry, as well as the significance of collaboration between designer, engineer, and manufacturer. Finally, in the third case study, the prototype Takenaka Connector is the first to truly apply WAAM to the architectural buildings component and design space. This project demonstrates even more potential for the future of WAAM in the architectural buildings industry, as it computationally forms a structurally rationalized, sustainable component that can integrate specific and sustainable materials. In conclusion, once WAAM is directly applied to architectural design in the mainstream industry, this technology will significantly decrease the industry's embodied carbon and construction costs, allowing the industry to be at the forefront of sustainability and innovation.

WAAM-based architectural components, if adopted into mainstream constructions, have the potential to alter the built environment as we know it. Should complex connection pieces similar to the Takenaka connection become widely available, non-rectilinear geometric designs could become as affordable and trusted as traditional orthogonal buildings. For example, a typical housing block of modular rectilinear units is, at present, preferred compared to a complex hexagonal construction. The structural support system for the latter would require custom connections capable of bearing loads at regular but atypical angles – an expense difficult to justify. But, if this design was achievable at no increased cost or construction time, the question flips from why to why not? Previously unique geometries may become ubiquitous. Buildings would evolve, and with them, entire urban environments.

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