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Digital Metal: Additive Manufacturing for Cast Metal Joints in Architecture

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Cast metal can be applied in architecture wherever strong parts with three dimensionally differentiated geometry are needed. However, the shape of metal parts is limited by our ability to fabricate the necessary mold, which can be very labor intensive. Current advances in 3D printing metal parts can bypass mold making. However, the application of this method for architectural components has challenges such as: small build volumes, long print times, limited kind of metal material that can be printed and high cost.

This research proposes an indirect use of 3D printing as a way to fabricate full-scale, customized, three-dimensional and structural metal parts in architecture. It uses 3D printing to fabricate sand-molds for casting metal in any conceivable shape. Here, we benefit from the geometric freedom of 3D printing and the flexibility of metal casting. With the use of 3D-printed sand-molds we can overcome these challenges without sacrificing geometric complexity or surface detailing.

To assess the proposed method in an architectural context, a 20 sqm footprint and 6-meter-tall space-frame structure was designed and built from 182 non-repetitive lightweight cast joints. All connectors were digitally designed and fabricated using 3D-printed molds which allowed to define and place material strategically where needed. Therefore, reducing material use (compared to a joint built from massive standard parts) as well as fabrication time. The constraints of metal casting were encoded in the algorithm that generates the geometry of the connectors and their molds, which then ensured fluidity of the molten metal throughout all the cavities, good dimensional-accuracy after shrinkage of metal as it cools, and good surface finishes.

3D printing allowed the integration of a gating system that guided the molten metal to the mold cavity from early design stage, thus considerably reduced tolerances and fabrication time. As a result, the fabrication of all cast joints took only 14 days which in average is 80 times faster than typical production where a complex metal part takes two weeks to a month to be produced. These results showcase that through 3D-printing sand-mold, cast metal can play a new role in bespoke architectural constructions. This approach can unlock an entirely new vocabulary of shapes for metal structures, previously unavailable with traditional mold making systems.

1. Background: Cast connections

1.1 Cast metal nodes in architecture

Cast metal has been commonly used in architecture in bridges, facades, connections, beams, and columns. Historical examples are the cast iron arches and columns in the interiors of the Sainte-Geneviève Library and the National Library of France in Paris, designed by the architect Henri Labrouste. Cast metal can find its application in architecture wherever strong parts with three-dimensional geometry are needed (Figure 1). Casting allows fabrication of strong, freeform, intricate, integral parts with design features such as undercuts, overhangs, internal structures and the three-dimensional differentiation of wall thickness, that cannot be obtained by other fabrication methods. These advantages of casting metal have been embraced by architects, as it allows for design freedom.

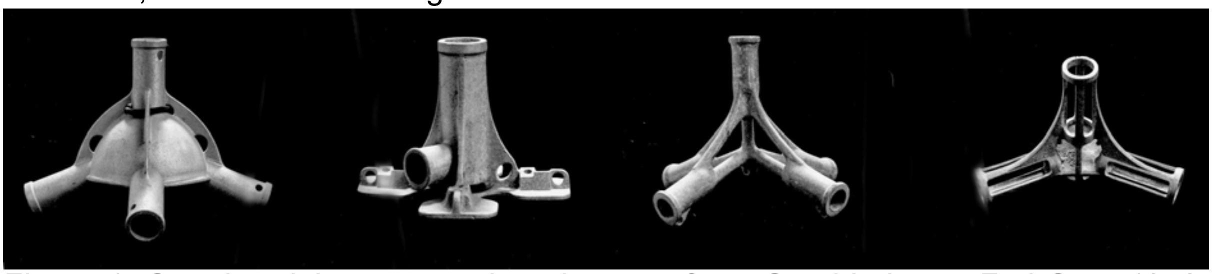

Figure 1: Cast iron joints connecting elements for a Sarabhai tent, Frei Otto, 1973, 50x38x40cm.

Today we see an increased use of “architecturally exposed” (Brack, 2011 & 2015) steel cast connections in conjunction with cable and glass structures, space frame structures, and tubular structures (Boake, 2016). Examples are large cast steel connectors of the Georges Pompidou Center in Paris (Gerberette) and architecturally exposed structural cast nodes in the Transbay Transit Center in San Francisco. When using casting, the wall-thickness can be adjusted to the flow of forces, bespoke cast connections can connect members in various angles.

However, the degree of geometric complexity achievable in a metal cast joint is still constrained by our ability to fabricate the necessary mold. Conventional sand-casting fabrication of mold involves making a pattern — a replica of the object to be cast—that would be placed in sand. Then the pattern and sand is incorporated to a gating system. This traditional way of making mold, especially the fabrication of the pattern, is very labor and time intensive, thus turns custom castings and production of nodes in small volumes very expensive.

“*The typical sand casting production process, [...] involves a significant investment in the production of hard tooling (i.e., patterns) to be able to produce the sand molds used in the production of complex shape metal castings...*” (Lynch, et al. 2017)

1.2. Additive manufacturing of metal joints

Current advances in additive manufacturing of metal can bypass mold making and offer the ability to produce bespoke nodes with complex geometry without molds. An example is the 3D printed steel node by Arup that was topologically optimized to reduce 75% of material (Galjaard et al. 2015).

However, while today multiple technologies of metal 3D-printing exist, each have major shortcomings for the application in building industry, where usually a larger amount of bespoke large metal parts is needed within a short production time.

The most common method is Powder bed fusion (such as SLM, EBM, and DMLS), in which each powder bed layer is selectively fused through energy, like laser or electron beam. This method is commonly used for manufacturing small, low volume, complex metallic parts (Bhavar, 2014). Major drawbacks of employing this technology for building industry are the small build volumes, long print times, limited metal material that can be printed, and high cost.

Printing methods for larger metal parts, such as robotic gas metal arc welding based additive manufacturing —where the stainless-steel rods of 5 to 7 mm in diameter are printed through welding layer by layer — are recently developed. However, this technique requires expensive postprocessing to reach a high-quality surface finishing and is still limited in the printable forms. For example greater production angles lead to larger geometrical inaccuracies and ductile material behavior (Joosten, 2015).

In general, the available additive manufacturing methods for metal are too expensive for the application in architecture.

2. Digital Metal Research: Additive manufacturing of molds and casting metal

To overcome these challenges, this research employs AM to fabricate the molds for metal casting rather than fabricating the metal part directly. Here, we can take benefit from the geometric freedom offered by 3D printing and the flexibility of metal casting. When combining 3D printed sand mold with casting, we can efficiently create large bespoke metal elements, and we are not limited to a few alloy but we can cast practically any kind of metal.

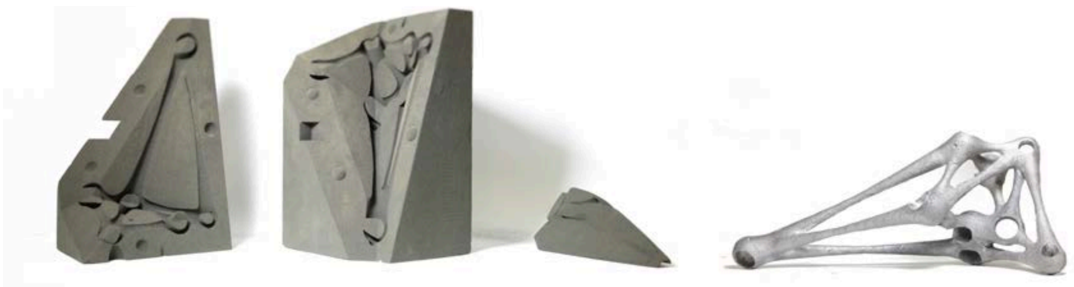

Figure 2: Segmented mold and cast node. Photographer: Ma Xije

While there are a few different types of AM technologies, binder-jetting technology, where a liquid agent is selectively dropped on thin layers of sand to bind it, is the most suitable one to fabricate sand-molds or cores[1]. Binder-jetting technology offers a unique combination of geometric freedom, resolution of parts, print-bed dimension and printing time. In recent years, we have seen a growing interest in integration of Binder Jet AM technology into the metal casting industry to produce molds and cores (Lynch et al. 2017) for small cast parts. However, It has not yet found its application for the fabrication of structural or ornamental architectural elements.

To explore the potential and challenges of this method in architecture, an experimental space-frame with bespoke metal nodes cast in 3D printed molds was designed and fabricated. To evaluate this fabrication process, we then compared it with directly 3D printing these nodes from metal.

[1] Resin types deposition method is used as a mold or core, e.g. for metal casting applications (Hochsmann and Ederer, 2000).

3. Experiment: Bespoke temporary space-frame structure

3.1. Overall Design

Liquid Pavilion is a 5 (h) x 12 (l) x 8 (w) meter space-frame structure that is designed and built from 182 non-repetitive lightweight cast aluminum nodes combined with standard aluminum tube (Figures 2 & 3). The design of pavilion involved the generation of the overall geometry of the space-frame structure base on a network of lines using a custom computational approach. The assembly-logic of the structure consisted of seven large pre-assembled parts which were stitched together on site with predefined stitching aluminum tubes. This facilitated a fast disassembly, transportation and reassembly on a second site.

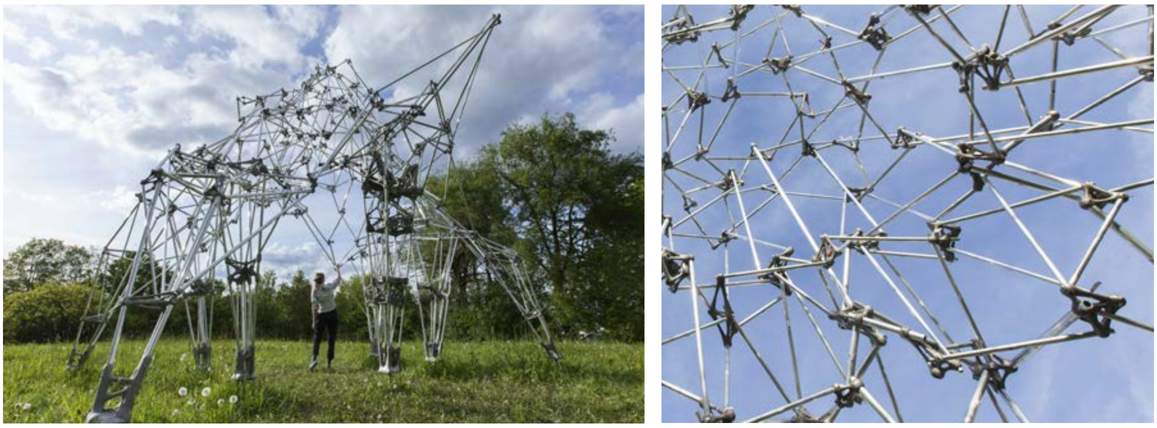

Figure 3: Liquid Pavilion, space frame structure, and close up of nodes connecting aluminum tubes in variety of angle and position. Photographer: Demetris Shammas.

3.2. System of nodes and computational design

Due to the irregular shape of the structure and the diversity of spatial arrangements of aluminum tubes (there are more than 900 variations in angle and position of the attached aluminum tubes), all nodes have a unique form. A custom computational model automatically generated all details of those nodes.

The nodes were designed to connect aluminum tubes from multiple directions in a tangential way avoiding intersections in a single point. A custom script was developed to shift the position of lines in space accordingly. This geometric shift facilitates the assembly and can deal with large tolerances of the length of the aluminum tubes. A node was generated automatically at the intersection points of any group of spatial lines. The detail of the passage of aluminum tubes using a user-defined diameter was integrated by the custom software. The topology of each node was adopted to receive these the aluminum tubes precisely and were optimized locally to reduce material use (Figure 3). The complexity of the space frame required to tag aluminum tubes and nodes to allow for differentiation and ensure correct spatial location during the assembly process. The nodes are labelled with a computational tagging system that contains a node number, connections with neighboring labelled aluminum tubes and the orientation in space imprinted into the physical node. The 182 generated nodes range in dimension between 17 X 17 X 9 cm (0.5kg) up to 100 x 58 x 82 cm (54 kg) and can connect between 5 and 25 rods depending on the complexity (Figure 4). 10 extra-strong nodes were designed as support for the structure.

The fabrication of those unique nodes in a short period of time would mean an enormous challenge for conventional casting. Therefore, this project helps to examine the feasibility of the proposed fabrication method for real world application.

Figure 4: Variation of small sized parametric nodes. Photographer: Ma Xije

3.3. Computational design of mold and casting system for the nodes

The generation of the molds for 182 geometrically different nodes was automated through a set of algorithms that take the geometry of nodes as input (Figure 7). The computational model was setup to include casting constraints and optimization parameters for the mold making. The gating system which includes all passageways through which the molten metal flows was encoded into parametric model of mold. The gating system is composed of pouring basin, sprue, runner, gates and risers (Figure 5). A central gate system, on which a number of molds were composed, was designed to cast a number of joints in one process (Figure 6).

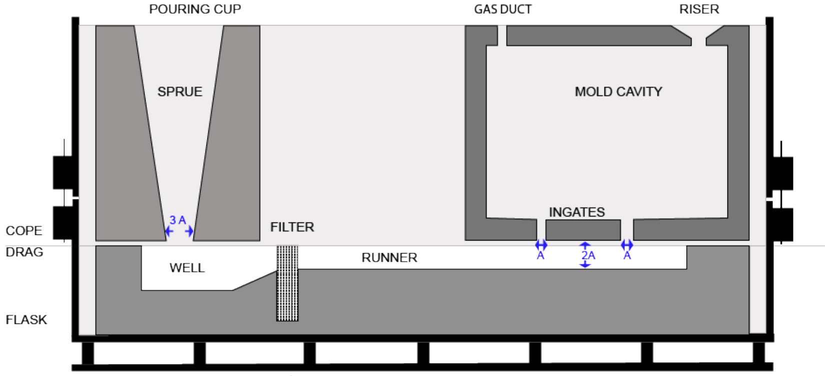

Figure 5: Diagrammatic section of conventional mold and its gating system

During prototyping defects occurring due to improper design of gating system were identified: oxidation of metal, mold erosion, shrinkage of metal, porosities, misruns, cold shuts and penetration of liquid metal into mold walls. Knowledge gained during prototyping phase informed the development of the mold system continuously. Minimum dimensions, a ratio between sprue, runner and ingates of 3:2:1 (Figure 5) as well as the shrinkage of metal identified (1%) were embedded into the computational model to minimize failure such as disconnected parts. All corners within the mold were rounded to avoid clogging.

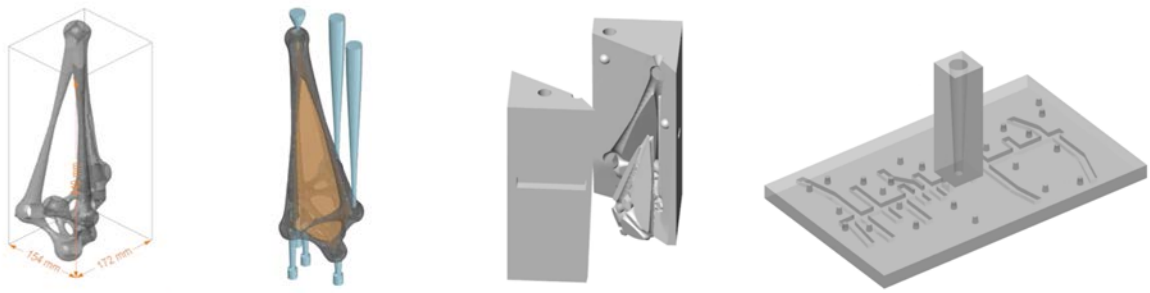

Figure 6: Computational design of mold and casting system: a) automatic rotation of a node, b) automatic generation of the core and casting ducts (gate, riser, and runner), c) automatic generation of the mold by Boolean subtraction of the node, d) a central gate system that allows casting of multiple nodes in one go. Images produced by students of MAS DFAB 2016-2017.

In order to optimize the use of each print box and material use the orientation of nodes in the mold was parametrically optimized to nest the nodes cased on casting orientation, connection with the gating system and filling of the print box (Figure 6). Transferring digital data of molds to 3D print was just a push of a button.

3.4. Fabrication of molds and nodes

The fabrication process starts with using Binder Jetting technology to 3D print the mold parts. Binder is injected layer by layer onto the sand and binds it to form the final mold. The supporting loose sand allows a large geometric freedom including hollow and cantilevering features. After the printing process, the loose sand is carefully removed with air pressure (Figure 7) and recycled. The segmentation of the molds ensures that sand can be fully removed.

The mold parts are assembled to form the mold for each cast joint and then placed on top of the gating system that is feeding all molds with aluminum (Figure 7). Sand mold are then heated to 300°C prior to the casting process. The liquid aluminum is cast into the pouring cup at the temperature range of 700°C to 800°C (Figure 7). Casting temperature and the kind of aluminum alloy are highly relevant for a successful cast[2]. As the aluminum travels through the gating system, it cools down and its viscosity changes. Therefore, the time that aluminum takes to travel throughout the mold is very important factor for a successful cast. To ensure successful casting, the constraints of the distance for smooth flow of molten aluminum was integrated into the parametric model of the mold. Once the aluminum is visible at the riser, we knew that casting was successful and liquid metal has filled the mold entirely. After cooling, the sand molds are removed with mechanical force on a vibration platform (Figure 7). What remains is an array of metal joints connected to ingate system (Figure 7). This ingate system is removed with a metal saw as part of the postprocessing. All ingate material is fully recycled. The loose sand from the 3D printing can be recycled too.

The fabrication of all custom molds was achievable within a week. 182 molds were produced using only five print boxes, each box with a print volume of 1.8x1.0x0.7m and arranged along 27 central gating systems for casting. The printing time of each box was less than 12 hours. Unpacking took ca.4 hours per box. Assembly of the mold segments on the central gate system was quick as 3D printing allowed automatic tagging of numbers on the printed parts. Casting itself had to be very quick (in less than 2 minutes) and followed the conventional procedure. Solidification of aluminum took less than 3 hours per cast and demolding was a few minute works. Post processing was the only time-consuming part of the process. The removal of solidify gating system from each joint was relatively time and labor intensive. The production of this amount of bespoke metal parts in two and a half weeks could not be achieved by 3D metal printing nor by conventional mold making process.

[2] The alloy used for this experiment was AlSi10Mg 239.

Figure 7: a) Unpacking of 3D printed sand molds, b) Assembly of multiple molds on a gating system c) 3D printed mold with casting systems, d) Casting process e) Demolding using vibration platform of gating system, f) an array of metal nodes with ingate system.

4. Result and comparison to direct 3D metal printing

4.1. Comparison of fabrication time, cost and precision

It is a challenge to compare fabrication processes without a specific target. The above described project served as a base for comparing the approach of indirect 3D printing to direct metal printing using SLM and DMLS for production of bespoke metal joints in architecture. A survey was conducted to estimate the cost, fabrication time and feasibility of fabricating the above mentioned 182 nodes using SLM and DMLS. Eight companies were provided with a node of each kind (small, medium, and large sizes).

Most of the companies had their metal printers loaded with bronze and steel, and it would take them three days to exchange the powder to aluminum. The print box of available DMLS printers were not large enough to print any of medium sized joints, so a node had to be segmented into two or three parts and be printed in different sessions. Printing of a single small node from the moment of sending the data to receiving the part would usually require ca. 7-14 days including all fabrication steps (Figure 8).

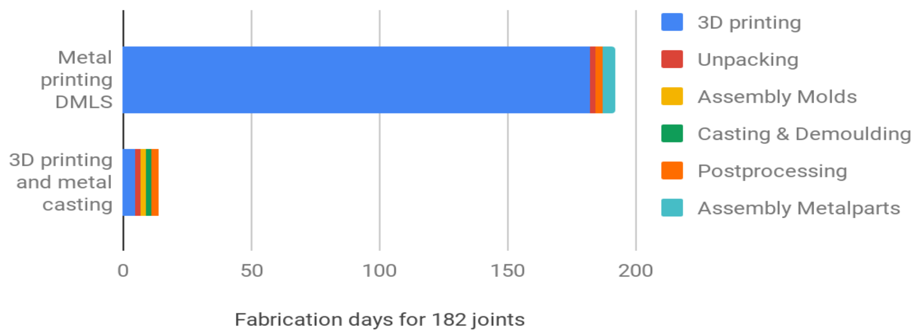

Figure 8: Fabrication time of 182 joints using 3D printing and metal casting compared with direct metal printing using DMLS. Times from DMLS are estimates from a survey among 8 metal printing companies and are based on the use of a single 0.4x0.4x0.4m DMLS printer.

	Direct metal printing with DMLS	3D printing molds for metal casting
Fabrication steps	● 3D printing ● Unpacking ● Post-processing of metal parts (Removal of support structures, Grinding) ● Assembly of larger parts from multiple printed parts	● 3D printing ● Unpacking ● Assembly of molds ● Casting ● Demolding ● Post-processing of metal parts (Removal of gating system, Drilling, Grinding)
Printing time	>1-2 days for 0.4x0.4x0.4m print-box	12h for 2x1x1m print-box
Printing cost	Machine-costs, material and energy are the main cost-driver: Price is calculated per volume of solidified material. Prices are in range of 5-8 USD per cm3 (0.01liter) 500-800 USD / Liter printed metal without post-processing	Sand and binder agent are cheap. Costs are dominated by machine cost. Therefore, the price is calculated by bounding box of 3D prints. Max. 20 US Dollar / Liter bounding box. (Prices vary per company) Aluminum: 1.2 USD / kg (found 30.07.2018)
Machine cost	over 1 Mio. USD	over 1 Mio. USD
Geometric constraints	Highest possible geometric freedom. Very thin parts possible. Challenge are the deformations occurring while printing due to the heat created in the printing box. Depending on the target geometry, support structures need to be printed.	Cast metal has to be able to reach every part of the mold, which constraints the mold's cavity to a minimum thickness. Complex forms might require molds composed from multiple elements. Every mold has to be cleaned from loose sand, which adds some constraints on the geometry. The printed sand has a limited structural strength, which adds constraints to the minimum thickness of printed mold features.
Dimensional constraints	0.4x0.4x0.4m print bed (average)	Up to 4x2x1m print bed Binderjet printers are available in large dimensions. Molds for even larger metals parts can be assembled from multiple prints.
Quality	High quality metal parts can be achieved, range of printable metals is limited.	Quality of conventional metal casting. All castable metals possible.
Precision	0.02 – 0.08mm layer height	> 0.2mm layer height

Table 1: Comparison between direct metal printing and printing molds for metal casting

4.2 Three-dimensional geometric differentiation on multiple scales

An extreme example of the fabricated metal parts was the central membrane connecting over 15 tubes. This large (1x0.6x0.8m, 54 kg of aluminum) metal part has a complex three-dimensional topology (Figure 9 left) while having highly detailed surface with millimeter-precise details (Figure 9 right). Undercuts and overhangs were easily achievable without sacrificing surface finishing. Although being all one-of-a-kind cast elements, the fabricated nodes were precise enough to allow a fast assembly of the pavilion and no node had to be reproduced.

Figure 9: Large connective membrane: overall geometry (left) and highly detailed surface (right). Photographer: Ma Xije

5. Conclusion

The discussed digital fabrication approaches for bespoke metal parts are targeting very different applications in architecture and it is important to strategically decide when to use what. Powder-bed metal printing is best in producing highly precise, lightweight small metal parts in low volume / lot size. Casting metal in 3D printed molds has enormous advantages when high volume custom parts or parts with a larger dimension are needed. Here, the indirect use of 3D printing is much faster, cheaper and feasible than direct 3D printing and is well qualified for architectural applications.

An important aspect for future research is to facilitate the design of molds for any given shape, and to automatically orient parts in an optimal way, integrate details such as the feeding of the metal and minimize the necessary post-production. Such specific molding strategies can dramatically reduce the required amount of post-processing. To further increase the degree of automation of the discussed process, unpacking and post-processing, which are currently done manually could be in future automated by robots.

Linking the ancient fabrication method of casting to state of the art 3D printing opens the door for a revival of bespoke metal parts in architecture. Coupling this fabrication approach with computational design, we can unlock an entirely new vocabulary of shapes for metal structures, previously unavailable with traditional mold making systems. This allows us to structurally optimize metal components, reduce the amount of material needed as elements can be differentiated in all three dimensions. We can design and produce unimaginable, new and radically expressive aesthetic.

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References

Bhavar, V., Kattire, P., Patil, V., Khot, S., Gujar, K. and Singh, R., 2014, September. A review on powder bed fusion technology of metal additive manufacturing. In *4th International Conference and Exhibition on Additive Manufacturing Technologies-AM-2014, September* (pp. 1-2).

Boake, T., 2016. Innovation in Architectural Steel. *Structures and Architecture: Beyond their Limits*, p.2.

Boake, T . M. 2015. “”Architecturally Exposed Structural steel: specifications, connections, Details.” Berlin: Birkhauser.

Brack, M., 2011. The Art of Exposing Structural Steel. *Modern Steel Construction*, *51*(12), pp.26-31.

Galjaard, S., Hofman, S., Perry, N. and Ren, S., 2015, August. Optimizing structural building elements in metal by using additive manufacturing. In *Proceedings of IASS Annual Symposia* (Vol. 2015, No. 2, pp. 1-12). International Association for Shell and Spatial Structures (IASS).

Giedion, S., Georgiadis, S. and Berry, J.D., 1995. *Building in France, building in iron, building in ferroconcrete*. Santa Monica, CA: Getty Center for the History of Art and the Humanities.

Giedion, S., 2008. *Space, time and architecture: the growth of a new tradition*. Harvard University Press.

Hochsmann, R. and Ederer, I., Generis GmbH, 2000. *Method for manufacturing of parts by a deposition technique*. U.S. Patent 6,147,138.

Joosten, S.K., 2015. Printing a stainless steel bridge: An exploration of structural properties of stainless steel additive manufactures for civil engineering purposes, Master Thesis document.

Lynch, P.C., Beniwal, C. and Wilck IV, J.H., 2017. Integration of Binder Jet Additive Manufacturing Technology into the Metal Casting Industry. In IIE Annual Conference. Proceedings (pp. 1721-1726). Institute of Industrial and Systems Engineers (IISE).

Vrachliotis, G., Kleinmanns, J., Kunz, M., 2017. Frei Otto: Thinking by Modeling (pp. 128-133).