3D PRINTING SAND MOLDS FOR CASTING BESPOKE METAL CONNECTIONS

Digital Metal: Additive Manufacturing for Cast Metal Joints in Architecture

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Abstract. Metal joints play a relevant role in space frame constructions, being responsible for large amount of the overall material and fabrication cost. Space frames which are constructed with standardized metal joints are constrained to repetitive structures and topologies. For customized space frames, the fabrication of individual metal joints still remains a challenge. Traditional fabrication methods such as sand casting are labour intensive, while direct 3D metal printing is too expensive and slow for the large volumes needed in architecture.This research investigates the use of Binder Jetting technology to 3D print sand molds for casting bespoke metal joints in architecture. Using this approach, a large number of custom metal joints can be fabricated economically in short time. By automating the generation of the joint geometry and the corresponding mold system, an efficient digital process chain from design to fabrication is established. Several design studies for cast metal joints are presented. The approach is successfully tested on the example of a full scale space frame structure incorporating almost two hundred custom aluminum joints.

Keywords. 3D printing; binder jetting; sand casting; metal joints; metal casting; space frame; digital fabrication; computational design; lightweight; customization.

1. Background

1.1. THE ROLE AND RELEVANCE OF BESPOKE JOINTS IN SPACE FRAMES

Joints play an important functional and aesthetic role in space frame constructions. They are crucial to connect, strengthen and stiffen the structure, and responsible for around 20 to 30% of its total weight (Lan, 2005). The design of the joints defines how many members can be connected, and what forces can be transferred through the structure, which has a direct impact on the possible topology and geometry of the space frame.

The production cost of joints has been one of the most important factors affecting the final economy of the finished structure. To reduce costs, usually

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joints are designed as as standardized elements, which consequently limits the overall topology and the form of space frame structures. However, whenever a space frame structure is optimized for a specific context or loadcase and requires an adapted topology, or when the space frame should follow a freeform geometry, bespoke joints are required.

1.2. FABRICATION OF BESPOKE METAL CONNECTIONS

For joints with complex 3-dimensional geometry and high structural demands, metal casting is traditionally the prefered option. Casting allows fabrication for high strength, freeform, intricate, integral joints with design features such as undercuts, overhangs, internal structures and the three-dimensional differentiation of their wall thickness. Cast steel structural connections have been commonly used in architecturally exposed structural steel. A prominent example is the gerberette element of the Pompidou Centre in Paris, France, which is considered to be the first architecturally exposed structural cast steel component in a European building.

1.2.1. Traditional sand casting

Sand casting is a common fabrication process used for casting metal connections. The degree of geometric complexity achievable in a cast metal joints is constrained by the ability to fabricate the necessary sand mold. Conventional sand-casting involves making a sand mold from a full scale pattern - a replica of the object to be cast. A pattern is usually made of wood, foam, metal, plastics or other materials and is produced by hand or using a CNC mill. The finished pattern is then covered and packed by chemically treated sand and is removed once the sand is cured and stiffened. Due to the necessity to remove the pattern from the stiffed sand, the sand mold is fabricated as two halfs. If the metal part has cavities or hollow features, additional sand-cores can be added to each mold. This hollow and stiff sand mold is then manually connected to a casting system known as gating system. The pattern can be used repetitively for reproducing the same mold.

1.2.2. Metal 3D printing

Today multiple technologies of metal 3D printing for the moldless fabrication of bespoke elements with complex geometry exist. An example is the 3D printed steel node by Arup that was topologically optimized to reduce 75% of material (Galjaard et al. 2015).

A technology commonly used is Powder Bed Fusion (such as SLM, EBM, and DMLS), in which each powder bed layer is selectively fused through laser or electron beam. While this technology is used for manufacturing of small volumes of complex metal parts (Bhavar, 2014) it’s application for building industry has still major limitations: small build volumes, long print times, limited printable metal materials and high cost.

The recently developed technology of robotic gas metal arc welding allows additive manufacturing of large scale parts. Here, metal is printed through welding layer by layer. However, this technique requires expensive postprocessing to reach a high-quality surface finish and is still limited to certain printable forms.

2. 3D printing sand molds for metal joints in architecture

Rather than fabricating the metal part directly, this research uses AM to fabricate the sand molds for metal cast joints (Figure 1). Here, one can benefit from the geometric freedom offered by 3D printing and the flexibility of molten metal to take the shape of the mold.

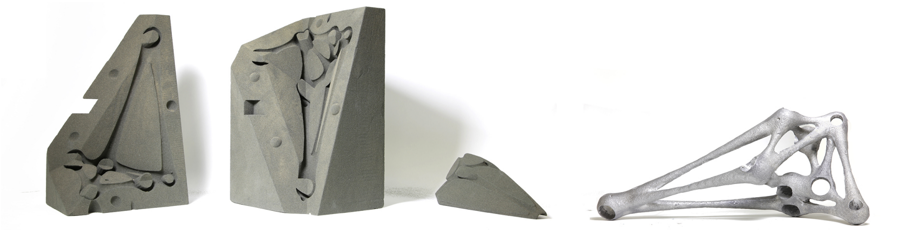

Figure 1. 3D printed segments of a sand mold and a cast aluminium node. Photographer: Ma Xije.

Among various AM-technologies, the most suitable one to fabricate sand-molds or sand-cores is Binder Jetting. Here sand is layed out layer by layer and a liquid agent is selectively dropped on each layer to bind the sand where needed. During the printing, the loose sand supports the printed part which enables the fabrication of porous or cantilevering parts. This unused sand can be recycled after the printing.

Binder Jetting is attractive because it offers a unique combination of geometric freedom, resolution of parts, print-bed dimension and printing time. This indirect use of 3D printing is much faster and cheaper than direct 3D printing for the production of large parts in large volumes (Meibodi et. al., 2018). In recent years, we have seen a growing interest in application of this technology in the car industry (Lynch et al. 2017). However, the potential of this technology has not yet been explored for the fabrication of structural or ornamental architectural elements.

2.1. DESIGN STUDIES OF CAST JOINTS

To explore the potential and challenges of this method for architecturally exposed and bespoke cast joints, a series of joint systems for connecting tubular members were developed by students of the MAS Postgraduate course Digital Fabrication (MAS DFAB). Joint and mold design go hand in hand. Several design goals were driving the design studies of cast joints:

- To facilitate the assembly and disassembly of space frames from hollow metal tubes and cast joints. The joints need to provide a degree of freedom in order to allow assembly of certain geometric constellations (For example in a tetrahedron constellation, inserting the last members is problematic due to the geometric impossibility to fit the closing member between the joints)
- To reduce the amount and weight of metal in each joint by optimizing it regarding the flow of forces. (ex. in accordance with the bending moments

of the structure).

- To rationalise the molds needed for casting by reducing dimension and amount of mold segments needed.
- To reduce the amount of post-processing needed. This means the seam of molds, and casting details should be at locations which are not visible or not sensitive to precision.

Based on these design goals, four parametric joint systems were designed and series of them were cast using 3D printed sand molds (Figure 2).

Figure 2. Design studies of joints by the MAS DFAB Students 2017/18 in the context of the Digital Metal Course. Photographer: Axel Crettenand.

A first design iteration of the joint (Figure 2a) provides a functional minimal compact geometry that connects the center lines of the members in one point. However, it can not connect a larger amount of members and it is not possible to close a tetrahedron due to the collision of the last member with the first joint.

The design of the second iteration (Figure 2b) addresses the assembly problem by adding details at the connection point and the members (sliding sideways). It is also designed to connect a larger number of members in space through different angles at a single point.

The third joint (Figure 2c) is more spread out and allows for sliding the members from various directions.

The fourth joint typology is designed to connect aluminum tubes that do not meet at one point. This offset provides more design freedom and facilitates assembly from multiple directions. It also allows hierarchical connections where members can pass continuously through the joint and others ends at the joint.

While the mold for the first, second and third joint topology is composed of two or maximum three parts without a core, the mold for the fourth joint topology is made of the inner core and outer sides of the mold.

2.2. PARAMETRIC MOLD SYSTEM

A critical aspect of casting joints is the design of the mold and its gating system, which controls the flow the molten metal. The gating system is composed of several functional details, starting with the pouring cup and the sprue in which the molten metal is cast. Departing from the sprue, the runner and ingates distribute the material to the mold cavity. The riser indicates when the mold is filled enough and creates a buffer of extra material to compensate the shrinking of metal through cooling (Figure 3).

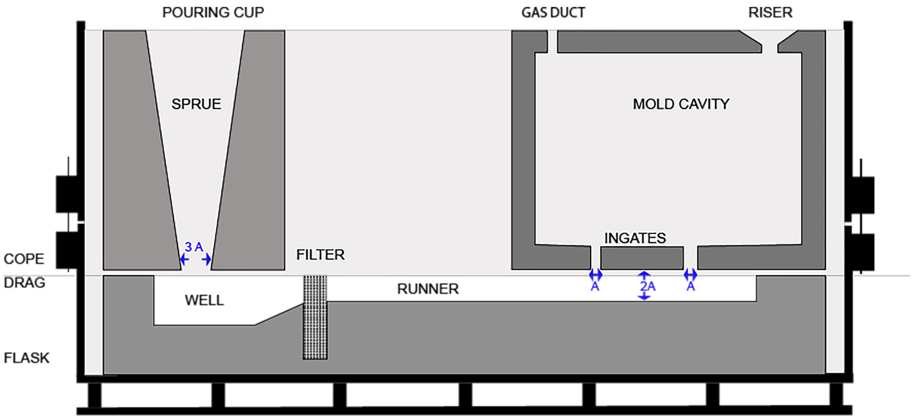

Figure 3. Diagrammatic section of gating system.

The location and dimension of these details needs to be strategically designed in order to control the flow of the material and minimize the post-processing of cast elements. After the casting, the gating system remains as solid part of the cast and needs to be cut off from the final cast (Figure 4). These modeling steps are usually done manually with a CAD software by experts in foundries and is very time consuming.

Figure 4. The image shows a FDM-printed of a joint design (left) and the final cast joint before post-processing (right). The gating system needs to be removed from the joint, thus the articulation of the interface is important. Photographer: Axel Crettenand.

Our approach is to rationalise the fabrication process of an entire family of bespoke joints by a parametric mold design system. Therefore, custom algorithms are developed to automatically generate molds for each individual joint, integrating also the relevant casting details of the gating system (Figure 5). Instead of fabricating a gating system for casting each joint, a central gating system feeds a number of molds simultaneously and allows to cast a number of joints at once. To reduce the amount of post-processing, the script includes the strategic placement of the seams as well as the locks that hold the mold parts together in position.

In order to optimize the use of each print box and material used for 3D printing the mold, the orientation of nodes in the mold is parametrically optimized to nest the joints based on the casting orientation and the connection with the gating system (Figure 5). The digital data for 3D printing can be directly derived out of the model.

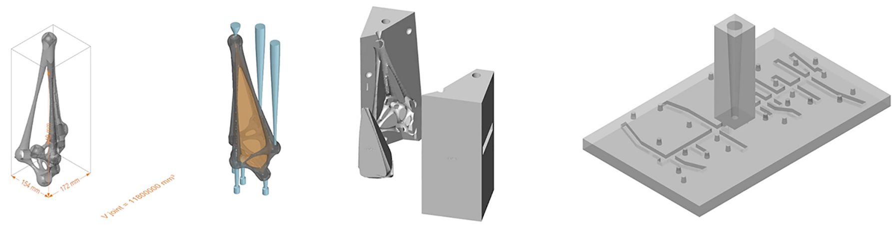

Figure 5. Computational design of mold and casting system: a) automatic rotation of a node to minimize the bounding box, b) automatic generation of the core and casting ducts (gate, riser, and runner), c) automatic generation of the mold by boolean subtraction of the node, d) a central gating system that allows casting of multiple nodes in one go. Visualisations:students of MAS DFAB 2016-2017.

The knowledge gained during prototyping phase informs the development of the mold system continuously. Minimum dimensions, the best ratio between sprue, runner and ingates (3:2:1) as well as the specific shrinkage of used metal identified (1%) is embedded into the computational model to minimize failure such as disconnected parts. All corners within the mold were rounded to avoid clogging.

2.3. THE FABRICATION OF MOLD AND CASTING JOINTS

The fabrication process consists of following sequences (Figure 6):

- 3D printing of mold
- Unpacking of printed molds
- Assembly of mold parts on the shared gating system,
- Preheating of molds to 300°C
- Casting liquid aluminum (700-800°C) into the pouring caps
- Cooling
- Removal of sand molds with mechanical force on a vibration platform

What remains is an array of metal joints connected to ingate system which is then removed with a metal saw as part of the postprocessing. All ingate metal can be fully recycled.

Figure 6. 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.

Casting temperature and the type of aluminum alloy are highly relevant for a successful cast. As the aluminum travels through the gating system, it cools down and its viscosity changes- cooling starts on the outside surface and moved inward. Therefore, the time that aluminum takes to travel through the mold is an important factor for a successful cast.

Here the parametric model allowed for integration of constraints of the distances and dimensions relevant to a smooth flow of molten aluminum to the mold design. If channels are too narrow, or if the metal cools down too early, then not every part of the mold is reached by the aluminium. In order to identify minimal dimensions and minimizing shrinking, several prototypes with varying gating system were tested.

Another challenge of the casting is that the molten aluminum is leaking through the seams of the mold, demanding excessive post processing work. To reduce the leakage, the seams are reduced to a minimum number and placed strategically. Alignment and locking details are added to hold the parts of the mold precisely in place.

3. Case study: a bespoke space frame structure

The feasibility of the described approach is evaluated through design and fabrication of a 5 (h) x 12 (l) x 8 (w) meters space-frame structure, Liquid Metal Pavilion. The structure is designed and built from 182 non-repetitive lightweight cast aluminum nodes combined with standard aluminum tubes (Figures 7). 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. All individual joints and their molds were automatically generated including all details.

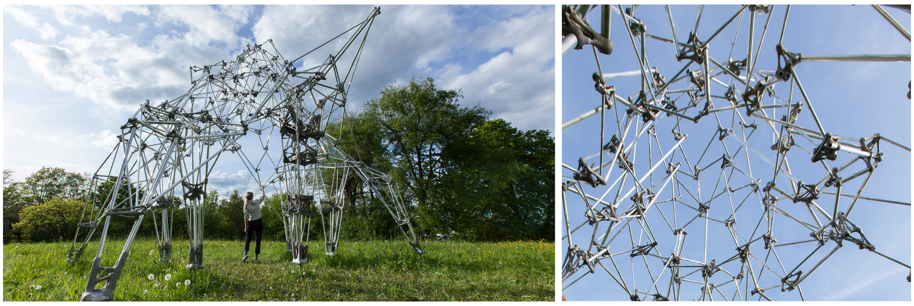

Figure 7. Liquid Metal Pavilion, space frame structure (left) and close up of nodes connecting aluminum tubes in variety of angle and position (right). Photographer: Demetris Shammas.

The fabrication of 182 custom molds was achieved within a week. All molds were produced using only five print boxes, each box with a print volume of 1.8 x 1.0 x 0.7m. The printing time of each box was less than 12 hours. Unpacking took ca. 4 hours per box. 182 molds were cast along only 27 central gating systems. Assembly of the mold segments on the central gate system was quick as 3D printing allowed automatic labeling of the printed parts. Casting itself followed the conventional procedure and could be done within minutes. Solidification of aluminum took less than 3 hours per cast and demolding was a few minutes works. Post processing, 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 a conventional mold making process. A detailed comparison between direct metal 3D printing and 3D printed molds for metal casting in terms of fabrication time and cost can be found in a related publication (Meibodi et. al., 2018)

4. Conclusion

Computational design approach enabled the automatic generation of parametric joint geometries and of the required molds including their gating system. This fast design-to-fabrication pipeline allowed to optimize the digital model by casting and testing multiple physical prototypes.

The experimental pavilion demonstrated that the cast joints are strong and precise enough for real world applications in architecture. The production through 3D printing sand mold is much faster and cheaper than state of the art direct metal printing strategies.

A drawback of this approach is the post-processing which still involves manual labor which could be further reduced by an improved integration of casting details in the design of the joints. However, similar post-processing steps are needed with most metal printing strategies.

Combining the traditional process of casting with 3D printing offers new possibility for three dimensionally articulated metal joints in an unseen architectural language. Similar to direct 3D printing, the discussed approach also allows to calibrate thickness of the part precisely according to the load-case and flow of forces.

The geometric freedom of cast metal opens the door for redefining the tectonic relationship between joints and members, as shown in the Liquid Metal Pavilion.

Using the discussed fabrication method, joints can become sculptural part of the construction and provide a larger design freedom for space frame structures.

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