Mass-customization of Joints for Non-Standard Structures through Additive Manufacturing

The Trefoil and the TriArch projects

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Due to recent advancements, additive manufacturing technologies (AM) have finally addressed the scale and materiality in architecture. The exploration of its capabilities has balanced between the idea of printing entire structures and buildings, and that of printing just a set of selected parts that will integrate and affect the final construction. In the context of the latter approach, this paper presents a research work developed by the Digital Fabrication Laboratory (DFL) at FAUP, which is focused in the design and fabrication of non-standard structures. By discussing the relevance of non-standardization in architecture, the paper describes and illustrates two projects that explore the mass production of customized joints through computational design methods and AM technologies - the TREFOIL and the TRI-ARCH structures. By focusing the attention just in the smallest component of a structure, the paper argues about the short-term potential of the real impact of AM technologies in the design thinking and materialization of architectural structures.

Keywords: Non-standard structures, Additive Manufacturing, 3D Printing, Computational Design, Mass Customization

INTRODUCTION

Non-Standard Structures

The integrated use of computational design and digital fabrication technologies has enabled a greater freedom in architecture, by facilitating the control and materialization of geometric complexity and design customization. Today, many of the most innovative buildings feature unique forms, structures and material solutions, showing the possibility to exceed the limits of standardization (Kolarevic et al 2008).

The emergence of such trend can be traced back to the 1990’s in the discourse of architects like Bernard Cache (1995) and his notion of “objectile”. But the impact of such conceptual and technological opportunities in the built environment was framed by the end of 2003 in the “Architectures Non Stan-
“Architectures NonStandard” exhibition that took place in the Pompidou Center (Figure 1a). Curated by Frederic Migayrou, this event announced and examined the growing of non-standard modes of production in architecture, design and urbanism (Migayrou 2003).

One year later, in 2005, the Yale School of Architecture hosted the Symposium called “Non-Standard Structures: Irregular Geometries, Hybrid Members and Chaotic Assemblies of a New Organic Order”. Driven by a similar concern, the organizers were, this time, more focused in the impact of algorithmic strategies in the design and production of customized structures (Figure 1b). Besides the presentation of interesting built works, this event was refreshing as it pointed out how digital technologies were setting new conditions for architecture and engineering collaboration. Through a renewed synergy across disciplines, the exploration of non-standard logics could be used for seeking more efficient and optimized designs, rather than for expressing sole aesthetic ambitions. The design of an efficient structure could thus clearly benefit from mass-customization. Moving beyond standardization, new digital technologies could enable the design and production of the individual -optimum- geometry of each component, to address the particular structural requirements for its position in space.

Additive Manufacturing Technologies
Since those events, technology evolved incredibly fast. Ten years later, digital design and manufacturing technologies have become more integrated, diversified, powerful and accessible. On the design side, common software environments, like McNeel’s Rhinoceros or Autodesk’s Revit, have included more and more computational, analysis and fabrication tools. On the manufacturing side, digitally driven technologies relevant for building construction have expanded, giving rise, among other technologies, to the increasing exploration and development of additive manufacturing (AM) (Gibson 2016).

While initially associated with the production of small size physical models, AM is now addressing the scale and materiality of architectural buildings (Malé-Alemany 2013). Like it happened in other disciplines (e.g. product, fashion, medicine...), these technologies are now opening the possibility for efficiently address geometric complexity and customization in construction, while avoiding, or dramatically reducing, material waste and the use of molds. When attempting to evaluate its (potential) impact in architecture, it shouldn’t be done just in terms of productivity. For the present paper, it is decisive to examine how AM can inspire and support new ways of thinking about design, in order to realize the degree of disruption and innovation in the discipline of architecture (Carpo 2017).

Mass-Customization of Structural Joints
Since 2013, the Digital Fabrication Laboratory (DFL) at the Faculty of Architecture of the University of Porto (FAUP) has been investigating the design and fabrication of non-standard structures minimizing the need for geometric rationalization methods. Given that such structures require variable members (i.e. frames, beams) and joints, they are a key topic for the exploration of computational design and digital fabrication processes. In this study, the DFL has centered its focus in the problem of the joint design, as the key component for setting the global shape and performance of a structure. The idea is that by employing maximum customization in the smallest components of a structure, even if it carries an extra cost, some significant efficiency and economy in the

Figure 1
In the left (a), the poster of the “Architectures NonStandard” exhibition and, on the right (b), the poster the NonStandard Structures.
Such argument was drawn from previous experiments conducted by the 1st author José Pedro Sousa at the Massachusetts Institute of Technology (MIT) in 2003, during a taught by Larry Sass on the design of customized frame system for a glass facade. In one prototyping experiment, the laser cut of all the acrylic parts for the frames was very efficient and fast while the CNC milling of a single 3D joint was dramatically slower (Figure 2). This same perception was proved in another prototype, this time, using CNC water-jet cut steel frames and CNC milled joints (Figure 3). Such experience was highly revealing. On the one hand, it proved the efficiency of CNC cutting processes to afford mass customization in fabrication. A similar cutting process solved the fabrication of the variable finger-shaped nodes for the roof surface of the British Museum’s Great Court, designed by Foster and Partners in 2000 (Veltkamp 2007, 54). On the other hand, it made difficult to envision the employment of variable joints to solve non-standard three-dimensional spatial structures.

Those limitations are being challenged today by current AM technologies. One of the most interesting examples come from the engineers at Arup, who are looking for combining the use of computational design and 3D printing to redefine the structural joint. Their goal is to optimize the individual design of each joint according to the structural requirements of each specific location and, then, directly 3D print all of them in steel. According to Salomé Galjaard, team leader at Arup, it has “tremendous implications for reducing costs and cutting waste. But most importantly, this approach potentially enables a very sophisticated design, without the need to simplify the design in a later stage to lower costs” (Haltermann 2015). As a result, she estimates a reduction of more than 40% of the overall weight of a structure, which is a significant achievement in terms of material efficiency.

The consideration of AM processes seems to shift the main attention to the design side, where computational design skills are decisive to integrate design generation, parametric variation, structural analysis and digital fabrication in a flexible, but automated, process. In this context, and as argued before, the research at the DFL is not looking for 3D printing whole structures. While structural members can be fabricated using conventional efficient CNC processes, the DFL has been interested in using AM in the mass fabrication of customized joints, taking advantage of its flexibility, precision and sustainability. Following, the authors describe the two research projects developed so far - the TREFOIL and the TRIARCH structures-, which served to test and examine the combination of computational design methods and 3D printing processes in the production of non-standard structures.

**THE TREFOIL STRUCTURE (2013-14)**

The TREFOIL structure was the first comprehensive research work on the topic, and it was developed at the scale of the model. Its motif was the design of an irregular truss-type of structure with finger-shaped
Figure 4
(a) In the top row, the generative design process of the TREFOIL structure, from a mathematical shape to a structural system of non-standard members and joints. (b) In the middle row, a close-up of the information contained and provided by the computational model. (c): In the bottom row, the associative connection between the joint models in space and their nested arrangement in the plane for fabrication (left), and the final 3D printed joints, still with some visible supporting structures.
joints. Based on a trefoil knot surface, computational design was used to generate, visualize and evaluate different densities and arrangements of a linear grid, and to convert it into a series of structural finger joints and tubular members (Figure 4a). Comprising 120 different members and 320 different joints, the final solution set the ideal scenario for challenging digital fabrication strategies (Figure 4b).

The fabrication of the Trefoil structure used two different processes: AM for the joints, and cutting for the members. The parametric design model of the structure included algorithms to prepare and label the structural components for both fabrication processes. The joints were rotated in space and aligned in the best position for minimizing the need for printing supporting structures. All the joint models were also nested in a grid to optimize the available space in the 3D printer, which run for five times to produce all the elements (Figure 4c).

The TRI-ARCH structure (2017)
The TRI-ARCH structure aimed at advancing the previous research by developing a 1:1 scale installation using a real building material - iron plates with 1mm thickness. Unlike the TREFOIL project, the TRI-ARCH was designed with a structural performative principle. By conducting a form finding process with Kangaroo plugin for Grasshopper in Rhinoceros, the surface of a three-legged vault was generated and iteratively refined and subdivided. Then, the vertices of the cells were copied towards the inside, by following the normal to the original surface. The displacement was made shorter according to the height of the structure in order to reduce its weight in the top. The resulting matrix of points was used to define the surfaces of an alveolar structure made out of 106 unique panels meeting at different angles (Figure 6a). Because this modelling process generated some twisted surfaces, an algorithm was applied for flattening them. Once achieved that planar condition, the computational model calculated the design of 144 parametric joints with a Y-shape with variable orientations, and two holes for bolt insertion (Figure 6b). While the iron panels were fabricated through CNC laser cutting, the Y-joints were 3D printed in ABS using FDM.

The TRI-ARCH structure was thought to be unveiled in the CONCRETA 2017 Construction Fair in Porto. On the first day of the exhibition, the visitors could see the joints being printed on site, while the steel plates were being cut in an external company. On the second day, the visitors saw the DFL team assembling the structure, starting by the three legs...
and ending by placing the crown part (Figure 7). On the third and fourth days, the visitors saw and experienced the TRI-ARCH installation. The choreography of this production in public created expectancy in the visitors and triggered very positive reactions. In the end, the new visitors were attracted by the unusual shape of the structure and were surprised when realized how such tiny and variable elements produced through 3D printing were indeed the key to control a structure with such scale and formal complexity.

Figure 6  
(a) In the top row, the form finding process that led to the surface and structural configuration of the TRI-ARCH structure.  
(b) In the bottom row, the planarization of the panels and the integrated design of the joints.

Figure 7  
3D printing the joints and assembling the TRI-ARCH structure in the DFL’s exhibition space during the Concreta 2017 Fair in Porto.
Figure 8
The TRI-ARCH structure assembled in the DFL’s exhibition space during the Concreta 2017 Fair in Porto.
CONCLUSION
The potential and contribution of AM technologies in architecture oscillates between two poles. On the one hand, the interest in large-scale production (e.g. 3D printing entire houses), which requires the development and use of complex machines to handle the building scale and the large amount of material involved. On the other hand, using more standard equipment, the interest in using AM in the production of small-scale components to affect the design of larger structures. Despite the disruptive potential of the former trend, the authors are not yet convinced by the development of the technology and the quality of existing applications at that level so far. Most of them, like the 3D printed houses developed by Winsun company in Shanghai, does not reveal formal, structural and finishing qualities that could prove the benefit of employing AM technologies. Despite this observation, the authors do not want to deny their intrinsic value as research works that are absolutely necessary to reach the day when they become fully functional and affordable. However, in a different way, the selective use of AM to produce just a set of parts to interact with existing construction methods and materials, seems to be more efficient and pragmatic strategy to introduce applied innovation in architectural design and construction in the short term. This is precisely the scenario framing the research work presented in this paper, which is very close to real and integral application in practice.

Regarding the specifics of the projects presented here, the computational design approach proved to be able to manage the design and data complexity related with non-standard structures. In other words, without the current level of technology in the design side, such explorations would not be feasible. The 3D printed fabrication of the joints was also a very efficient process to solve the mass production of such amount of customized three-dimensional components. Dealing with a larger scale and real construction materials, the TRI-ARCH installation raised the two next research directions: connecting the thickness of the joints to the structural requirements of each one (material optimization), and exploring the 3D printing of metal components. Such design and technological framework affords to bring together architectural imagination and performance in new, and sustainable, ways.

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