FLEXI-NODE

An Adaptive, Programmable Mold to Digitally Fabricate Grid Structures’ Joints

ABSTRACT
This paper is part of an ongoing research project on flexible molds for use in concrete fabrication. It continues and advances the concept of adjustable molds by creating a flexible system to produce a variety of concrete grid-joints. This reusable and adaptive mold streamlines the process of fabricating inherently diverse nodal joints without the need for cost-intensive mass-customization methods. The paper also proposes a novel way to cope with some of the significant drawbacks of similar mold techniques that have been explored and found wanting in similar projects. The technique used for the mold in the current research is inspired by a flexible mechanism that has been implemented in other manufacturing contexts, such as expansion joints and bendable straws. The outcomes of the project are a platform called “Flexi-node” and relevant software components that allow users to computationally design and fabricate a great variety of concrete joints for grid structures, using just one mold, with minimum material waste and no distortion from hydrostatic pressure.

Keywords: flexible molds, nodal joints, computational design, concrete fabrication, mass customization, grid structures
INTRODUCTION

Space-grid construction techniques are generally used in large spanning structures. Steel grids are the most common; however, concrete space-grids can provide an excellent alternative. The Delhi Exhibition Halls, constructed in India in 1982, are notable examples of concrete space-grid architecture (Chilton 2000). Nodal joints have a key role in the design of these space-grids—the joints largely determine the final form of the structure, dictate the required erection process, and account for a large portion of the construction cost. Thus, the means of efficiently and effectively fabricating modular joints for concrete space-grid applications is an important topic of investigation.

Standardized methods of mass-production for concrete joints typically require the use of one-off molds or rigid formworks, which limit the diversity and variation of the end product. This is a widespread problem; all conventional casting techniques used in construction fields have this tendency to produce modular and uniform results. In contrast, fabricating non-standard geometries for the joints through regular rigid molds requires a massive investment of material and human labor, resulting in a time-consuming and expensive process (Echenagucia 2018). This is a significant concern for architects, as the difficulty in fabricating unique and diverse construction components is one of the primary factors that limits the innovativeness and creativity of architectural designers.

In recent years, researchers in construction and architecture fields have been attempting to tackle this problem by integrating mass-customization techniques into the design and fabrication process of the built environment. One approach, generally referred to as “digital fabrication with concrete,” uses various 3D-printing processes to create custom formworks for concrete casting (Asprone 2018). Another common method is the use of industrial robotic arms as a means of fabrication. Although there have been some notable successes using these approaches, the resulting processes are still under development and are not ready for widespread application (Dritsas 2018).

In the current research, we addressed the issue of fabricating non-standard concrete node geometries through the use of an adaptive casting platform, without the assistance of industrial robotic arms. Our approach was to develop a specialized, adaptable mold for casting the joints. We integrated the adaptive physical structure of the mold with software control components that can allow users to computationally design and then fabricate a large variety of unique concrete joints. To demonstrate the use of the system and provide a real-world proof-of-concept, we used an adaptable mold in the construction of a pavilion, with concrete cast joints, wooden linear elements, and steel connection parts.

BACKGROUND

Early experiments with space-grid construction techniques were carried out by Alexander Graham Bell, eventually leading to several commercial systems using prefab components (e.g., MERO KK, ABBA Space, and NODUS). The German architect Konrad Wachsmann pushed this approach forward by designing a “universal joint” for aircraft hanger construction, which could connect up to twenty liner elements at one node. The overall value of space-grid design is that it offers more choices for architects and builders in positioning structural supporting columns, leading to greater flexibility in the design of the final structure (Chilton 2000). In addition, a similar approach called “diagrids” tends to use less materials compared to conventional building-frame systems (Moon 2007).

Three interconnected techniques have played a role in the current move toward improved space-grid structures: adaptive fabrication, flexible formworks, and adjustable molds. The first of these, adaptive fabrication, is a challenge to the current paradigm of standardized production for molded construction materials. A large array of “mass-customization” approaches in architecture are currently being developed, based on technologies such as additive manufacturing and CNC machining. State-of-the-art approaches, including robotic incremental sheet-metal forming techniques (Kalo 2014; Nicholas 2016), creating mass-customized molds using hot-cutting tools (Søndergaard 2018; Clifford 2014), developments in concrete formwork 3D-printing (Gaudillière et al. 2018), and material deposition on custom, non-planar surfaces (Ayres 2018; Battaglia 2018), all demonstrate the potential of integrating robotic arms as part of the fabrication method. The main purpose of these techniques is to avoid the use of conventional molds and thereby enhance customization.

However, construction cost is one of the most important considerations in designing space-grid structures, and this financial component tends to limit the value of many adaptive fabrication approaches. The need for advanced tools, training, materials, and robotic arms that are used in these approaches leads to much higher expenses compared to traditional molding and casting techniques.
While new horizons in adaptive manufacturing are opening exciting possibilities for architectural designers, the current authors would argue that not all customized projects need to be constructed through the use of expensive industrial robots and 3D-printing systems. Nevertheless, several of the developments in this area had a great influence on the current research.

Lloret and colleagues (2015) proposed a Smart Dynamic Casting (SDC) system that uses slipforming, a technique traditionally applied for on-site fabrication of large-scale components used in silos and high-rise buildings. In the slipforming process a formwork—considerably smaller than the structure being produced—moves vertically while being filled with concrete at a velocity set to match the hydration rate of the concrete. The material inside the formwork is shaped by a dynamically controlled mechanical actuation system that enables the fabrication of vertical reinforced concrete elements with significant cross-sectional change (Lloret et al. 2015). By adopting this type of adaptive formwork system along with a sophisticated approach to the use of admixtures in concrete processing, the SDC system enabled the production of bespoke concrete elements (reinforced structural columns and façade mullions) while eliminating the need for labor-intensive, non-standard formwork systems. The SDC approach seems very promising, and should be considered as a complementary technology to the adaptable molding system for joint elements developed in the current research.

Another relevant study combined metal 3D-printing technology with a topology optimization technique to fabricate diverse nodal joints (Ren 2015). Additive manufacturing was used to overcome conventional fabrication drawbacks and create a large variety of metal nodes. This project helped to inspire the current work on finding new approaches to concrete joint manufacturing. By using a flexible mold rather than a 3D-printing process, our aim was to attain the same degree of customization without the need for robotic arms or other expensive technology.

The second area of study that has informed the current project is research into flexible formworks. Typically made of heavy-duty fabric, these forms tend to deflect under the pressure of fresh concrete. Researchers have investigated a variety of ways to implement flexible formworks as a means of producing adaptive, non-standard concrete geometries, particularly for shell structures (Veenendaal, West, and Block 2011; Culver and Sarafian 2018).

Although this approach has certainly been shown to add adaptivity in the fabrication process, the main drawback results from the hydrostatic pressure of the concrete, which is liable to produce deformation and distortion in the cast part. To help combat this problem, researchers have used cement paste-coating techniques, pneumatic formworks, and a variety of other methods generally resulting in shell-like or hollow components (Popescu 2016/2018; Kromoser 2016; Costanzi et al. 2018).

One of the most inspiring research projects in the area of flexible formworks was called “Rotoform,” developed by the Digital Design Unit at the University of Darmstadt, Germany. This technique combined fabric formworks with a rotational molding technique to produce nodal joints (Tessmann, Mehdizadeh, and Scherer 2018). A specially formulated concrete mix was poured into the latex formwork, which was then gently rotated until a thin layer of concrete hardened into the desired configuration. Like most rotational techniques this approach produced a hollow joint, which can be useful in some applications but does not have the same strength as a solid cast component.

Finally, researchers over several decades have attempted to address the customization problem through the creation of adjustable molds, an approach that is most closely related to the current project. Notable early work in this area included conceptual designs created by Renzo Piano (1996). Efforts toward developing adjustable molds seek to combine the benefits of fast manufacturing, low production cost, and little material waste with the advantages of a customizable product (Lee and Kim 2012; Schipper 2015). Most investigations into adjustable molds have used a method called the “pin-table,” which applies linear actuators to control the position of each pin and thus change the shape of the mold. One recent experiment moved beyond the pin-table technique, instead using a CNC machine to control the configuration of the mold (Loh, Leggett, and Prohasky 2018).

The current project combines the adjustable mold concept with an integrated digital controlling technology, oriented specifically toward concrete joint fabrication. This allows users to create numerous complex and precise joint geometries for modular construction, with potentially broad impacts for the field of affordable construction automation.
METHOD
Concrete Casting in an Adjustable Programmable Mold

Grid-structure joints are all superficially similar in appearance, but in their application they require multiple variations, such as different angles between the crossing arms. This means that a traditional casting process requires frequently changing the mold to produce the needed configurations. For this reason, these joints are an ideal candidate for developing a flexible mold. Our solution was to create a mold consisting of a fixed core plus flexible arms, which allows a wide range of possible joint variations. To establish the accurate position for each arm of the joint, design data is transmitted from the Rhino-Grasshopper software package, via an Arduino board, to stepper motors running a novel spherical positioning mechanism in the flexible mold.

The “Flexi-node” design consists of a rigid fixture containing a mobile inner core, surrounded by four flexible arms. One of the end-caps of the arms is designed to serve as the casting hole (Figure 2). The use of a double-skin core facilitates the process of opening the mold to dismiss the product and prepare for next casting. In other words, once the initial phase of concrete hardening has passed, the mobile inner core of the mold can be removed and replaced with another mobile core, so that the primary fixture can be used for another casting in a relatively brief period of time. This approach also helps to avoid any potential damages to the main platform and positioning mechanism when opening the mold.

The primary, rigid parts of the mold are reusable, but in its current iteration the flexible parts must be torn off of the final product and recycled. We are currently using ready-made flexible arm pieces consisting of a thin layer of fiber and aluminum. In the future, however, we hope to shift to a flexible tube that can be 3D-printed from TPU filament, which will be able to withstand the hydrostatic pressure of concrete while also being removable without damage (and thus able to be reused). This aspect of the project is still under development (Figure 3).

2 The design of flexi-node includes: (1) a solid core, (2) fixture, (3) flexible arms, (4) end caps, (5) casting hole, and (6) rods and nuts.

3 Future versions of the mold will employ a customized, reusable flexible arm.

4 Achieving the desired curvature of the arm (a) required the ability to change the alignment of the positioning mechanism; conventional XYZ positioning without rotation (b) would not produce the desired curvature.
POSITIONING MECHANISM
One of the central challenges for the design of Flexi-node was the mechanism for accurately and independently positioning each arm of the joint. Our goal was to create a computer-driven positioning system that could seamlessly integrate with Grasshopper design software. We first investigated a conventional XYZ Cartesian positioning mechanism, but discovered many unforeseen problems when using that approach. One concern was simply the number of stepper motors needed for the mold—with three axes of motion for each arm, a total of 12 motors were required; this was a significant cost concern and it proved to be a challenge for the Arduino controller. Even more significantly, due to the rotation of the mold’s arms as they flex, the alignment of the positioning mechanism had to constantly change, which threatened to vastly increase the complexity of the device (Figure 4).

To address this issue and create a more streamlined positioning device, we changed to a custom-designed spherical mechanism. In addition to achieving the proper rotational alignment, this design also had the benefit of reducing the total number of motors and thereby limiting costs and complexity. Our design for the arm-positioning device is shown in Figure 5. In this approach, the end cap of each arm is fixed in a holder that can move along a 120-degree circular path. This provides one axis of spherical rotation. A secondary gearbox allows the entire holder mechanism to be rotated in a perpendicular direction, thereby allowing a full range of spherical coordinates (at a fixed radius). This device proved to be very successful in achieving the desired patterns of arm curvature. When the end of the arm is appropriately positioned, it is fixed in place with locking screws, which help to prevent the weight of the concrete from shifting the device. As noted earlier, one of the arm holders also serves as the casting hole.

FILLING THE MOLD USING A ROTATIONAL PLATFORM
We considered several scenarios for the filling phase, including casting, rotational molding, and injection. Due to the physical features of flexi-node—most notably, the variable positions of arms—a simple casting process would not consistently fill all areas. Rotational molding is a time-consuming process and typically produces a hollow product, which is not appropriate for structural uses. Finally, concrete-pumping and injection are complicated and expensive procedures that would reduce the desired simplicity and efficiency of our design.

To address this dilemma, we used a combination of rotational molding and casting. The key is to move the arm that contains the casting hole into a position where it is higher than all other parts of the mold, which will then allow a conventional casting process to fill all areas. In other words, the rotation frame was only moved once for each design, and was locked into place prior to filling. This process is shown in Figure 6.

COMPUTATIONAL DESIGN PROCESS
Using a custom algorithm written in the Python programming language, we created a component called ‘Manual Flexi-node’ for Grasshopper. This program receives inputs for the angle of each arm in a concrete joint, and then
Our custom positioning mechanism holds the end of the arm (1) in place and allows it to be positioned anywhere within a 120-degree spherical coordinate system. It includes a casting hole (2), primary guiding shaft (3), primary stepper motor and gear (4, 5), secondary stepper motor and gear (6), and locking screws for each of the motors (7, 8).

6 Manufacturing with Flexi-node: (a) the mold is attached to a rotational frame, (b) the frame is positioned so that the casting hole is higher than all other parts of the mold, and then (c) the mold is filled and the casting hole is capped, without further rotation.

produces a parametric model of the joint that can be used to program the flexible mold. In its basic iteration, the human user manually sets the desired arm-angles (Figure 7). To take this customization a step further, we also created a software component that receives a designed surface as an input, and then automatically calculates the joint angles that are needed for the design. This program applies a diamond-pattern or square-pattern grid to the surface and then produces a list of the needed joints and their arm angles. An example of a pavilion design using this approach is shown in Figure 8.

TESTING AND STRUCTURAL SPECIFICATIONS

Concrete is well-known to be weak in tensile strength, and our results were no exception. During testing, the connection between the arms and the central body of the joints proved to be particularly problematic. To assist with this, we incorporated reinforcement into the joints, using Ø 8 mm embedded deformed rebar with end hooks. We also embedded bolts into the end cap of each arm, which produces further strength and allows the joints to be readily connected to the linear elements of the structure. These reinforcements (Figure 9) allowed the joints to serve a load-bearing function and to withstand tension and torsion as well as compression.

One of the most important steps in conventional concrete casting is applying vibration to the mold. This ensures that the concrete fills all of the corners of the mold and settles firmly into place. Adequate vibration has a significant effect on the strength of the cast component, and it contributes to avoiding surface blemishes. However, the use of vibration created significant problems for Flexi-node, as it degraded the accuracy of our positioning mechanism. Moreover, implementing an embedded vibration mechanism would result in a more complex and cost-intensive system. To solve this problem, the concrete mix that we used for testing was based on Self-Consolidating Concrete (SCC), with an added polycarboxylate ether superplasticizer to improve the workability without increasing the water content. This mix eliminated any potential congestion in the mold or in the casting funnel, thereby allowing us to cast the joint without the use of a vibration mechanism. The fine aggregate included in the mixture consisted of limestone with a maximum size of 4.75 mm, which is in accordance with the recommendations of the American Society for Testing and Materials (ASTM-C33). We tested three alternative mixes with slightly different proportions, the specifications of which are listed in Table 1.

Since cast joints are not independent structural elements, we were not able to conduct structural tests directly on each joint. Instead, we carried out compressive strength tests and three-point flexure tests on our concrete mix designs, and then applied these results using finite-element-analysis software modeling. The concrete testing was conducted on 10x10x10 cm cast blocks (for compressive strength testing) and 4x4x16 cm blocks (for flexure testing). The specimens were left in a curing tank at a temperature of 23±2 C° and then tested after 1, 3, and 7 days. The compression strength tests showed an overwhelming advantage for our concrete mixture #3, and so flexure testing was only carried out for this final mixture. The results of these tests are shown in Table 2.
The structural simulations were carried out in the ANSYS software package (Figure 10), using the pavilion model shown in Figure 8. Material parameters for the concrete joints and the linear elements were entered based on the results of our testing, including a density of 2247 kg/cm³, Young’s Modulus of 25.1 GPa, Poisson’s Ratio of 0.2, bulk modulus of 13.9 GPa, shear modulus of 10.5 GPa, tensile ultimate strength of 3.31 MPa, and compressive ultimate strength of 35 MPa (Table 3). We also included parameters for the reinforcing rebar in the joints, using structural steel with density of 7850 kg/cm³, Young’s modulus of 210 GPa, Poisson’s ratio of 0.3, bulk modulus of 175 GPa, shear modulus of 80.7 GPa, tensile and compressive yield strength of 4000 Kg/cm², and tensile and compressive ultimate strength of 6000 Kg/cm² (Table 4).

The connection of linear elements to the joints was regarded as rigid/fixed (in practice, they would be bolted connections). The reaction of the structure was modeled under standard-gravity load (9.8 m/s²). The maximum resulting displacement was approximately 1.2 mm, the maximum stress for concrete parts was 8.4 MPa, and the maximum stress for the steel parts was 9.6 MPa. By comparing the concrete stress value from the simulation...
Table 1. Three concrete mixtures were used when testing Flexi-node joints

<table>
<thead>
<tr>
<th></th>
<th>Cement (kg/m³)</th>
<th>Fine Aggregate (kg/m³)</th>
<th>W/C (ratio)</th>
<th>Superplasticizer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 1</td>
<td>500</td>
<td>1356</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Mix 2</td>
<td>500</td>
<td>1533</td>
<td>0.35</td>
<td>1%</td>
</tr>
<tr>
<td>Mix 3</td>
<td>500</td>
<td>1486</td>
<td>0.39</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

Table 2. Compressive strength and flexure strength testing of the concrete mixtures; flexure testing was only carried out for Mix 3

<table>
<thead>
<tr>
<th></th>
<th>Compressive Strength (MPa)</th>
<th>Flexure Strength (MPa)</th>
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<tbody>
<tr>
<td></td>
<td>DAY 1</td>
<td>DAY 2</td>
</tr>
<tr>
<td>Mix 1</td>
<td>N/A</td>
<td>9.5</td>
</tr>
<tr>
<td>Mix 2</td>
<td>16.2</td>
<td>27.6</td>
</tr>
<tr>
<td>Mix 3</td>
<td>25.4</td>
<td>34.8</td>
</tr>
</tbody>
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with the concrete strength driven from the test results, we figured out that the pavilion would completely be stable under normal gravitational conditions, with the safety factor of 4.2 \((35 ÷ 8.4 = 4.2)\).

**PROTOTYPE**

To demonstrate the proof-of-concept and to get a better sense of what construction looks like with Flexi-node, we continued with the process of fabricating a portion of our test pavilion. This involved casting a variety of concrete joints in accordance with the software outcomes, creating wooden linear pieces to connect the joints, and then assembling them in our workshop. Figure 11 shows some of the diversity of the pavilion joints, and the outcome when they were connected together:

In building this prototype, we learned that newly cast joints are not ready to be utilized instantly as load-bearing components, and that we needed to cure them for at least one week prior to assembly. Curing concrete has a significant impact on the ultimate strength reflecting the generally recognized standard of 28 days as the strength criterion. Additionally, in order to obtain a more stable structure, fixing the first row of the linear elements to the
ground is of vital importance, last but not least, on large scale construction, deploying a falsework beneath the structure facilitates the assembly process.

CONCLUSION AND FUTURE WORK
We envisage that Flexi-node can make an important contribution to practical construction techniques. Using this approach allows us to fabricate variety of specialized joints for grid-structures while minimizing cost and material waste. Flexi-node offers inexpensive, fully formed, and solid construction components that are feasible for large-scale structural use.

It does not suffer from deformations caused by hydrostatic pressure, which have tended to plague other types of flexible fabric castings. The inclusion of rebar reinforcements can further enhance the strength of the joints. In addition, the integration of the mold with sophisticated software controls allows for ease of use and quick implementation of the required arm angles. In real-scale construction, the Flexi-node approach can be used for load-bearing facades, single-layer grid structures, and free-form space frames. By scaling the mold and replacing the flexible tubes with custom reusable tubes, it will be possible to cast larger joints, for example diagrid joints. Designing and manufacturing these custom, reusable, and larger tubes is a central part of our ongoing research.

Future improvements to Flexi-node will be focused on refining the arm-positioning mechanism, developing reusable arm-pieces, and expanding the capacities of the controlling software to allow for even more innovative applications, such as double or multilayer grid structures. We are interested in implementing a closed-loop control system that will analyze feedback from the arm’s position to help ensure the greatest possible precision for component angles. We also want to branch out to develop molds with variable numbers of arms. This will allow the system to produce, for example, joints with three connections or six connections, rather than being limited to four. Last but not least, we intend to test alternative materials such as Ultra High Performance Concrete (UHPC) for use with Flexi-node, which may assist with reducing the fabrication time and further enhancing the structural performance of the joints.
REFERENCES

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**IMAGE CREDITS**
All drawings and images by the authors.

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