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Jammed architectural structures: Towards large-scale reversible construction

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Abstract

This paper takes a first step in characterizing a novel field of research – Jammed Architectural Structures – where load-bearing architectural structures are automatically aggregated from bulk material. Initiated by the group of Gramazio Kohler Research at ETH Zürich and the Self-Assembly Lab at Massachusetts Institute of Technology, this digital fabrication approach fosters a combination of cutting-edge robotic fabrication technology and low-grade building material, shifting the focus from precise assembly of known parts towards controlled aggregation of granular material such as gravel or rocks. Since the structures in this process are produced without additional formwork, are fully reversible, and are produced from local or recycled materials, this pursuit offers a radical new approach to sustainable, economical and structurally sound building construction. The resulting morphologies allow for a convergence of novel aesthetic and structural capabilities, enabling a locally differentiated aggregation of material under digital guidance, and featuring high geometrical flexibility and minimal material waste. This paper considers 1) fundamental research parameters such as design computation and fabrication methods, 2) first results of physical experimentation, and 3) the architectural implications of this research for a unified, material-driven digital design and fabrication process. Full-scale experimentation demonstrates that it is possible to erect building-sized structures that are larger than the work-envelope of the digital fabrication setup.

Keywords: Architectural research, computational design, robotic fabrication, jammed structures, granular construction, additive manufacturing

1 Introduction

Robots are extremely useful to the field of architecture [1]. Not only can they lead to significant time and cost savings in fabrication, but their ability to connect digital design data directly to the fabrication process enables the construction of non-standard structures at full-scale [2, 3].

"Jammed" materials – defined as amorphous solids that are structurally disordered and which possess a yield stress [4] – lend themselves well to robotic aggregation methods. During a "jamming transition", granular materials can change from a non-solid, liquid-like state into a solid (jammed) state. This transition to solidity is reversible and occurs under certain constraining force conditions [5], such as the density of granular structures and shear force. These constrains can be controlled by a hybrid constructive system using rigid compressive and soft tensile materials (see chapter 3).

Therefore, jammed materials are significantly different from other constructive materials – they are reversible, immediately structural (do not require any curing time), and self-organising – and are thus of great interest to architects. This paper describes a new form of "granular construction" that uses robotic fabrication methods to build jammed architectural structures (see Fig. 1) that are 1) efficient in terms of capacity (formal and functional), 2) reversible without additional formwork or other means of manual construction, and 3) aggregated from local or recycled materials into complex geometries.

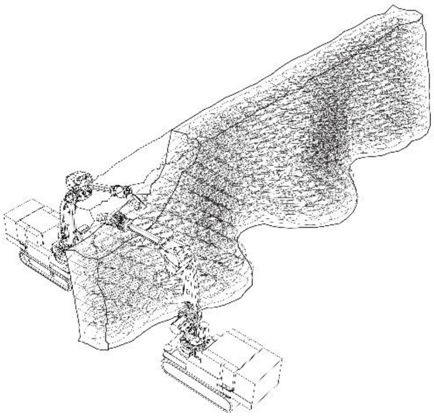

Fig. 1 *Conceptual model of a jammed building structure aggregated by two robotic systems. One robot manipulates the dry granular bulk material, while the other robot positions tensile materials so that forces are integrally transferred into the depth of the structure in a three-dimensional manner. Gramazio Kohler Research, ETH Zürich, 2014.*

Robotic fabrication of jammed architectural structures is in its infancy, and presents many theoretical, practical and methodological challenges, including the need for advanced digital design processes, computational physics simulation and modelling, as well as the corresponding adaptive fabrication strategies for controlling industrial robots.

In order to address these challenges, the group of Gramazio Kohler Research at ETH Zürich [6] and the Self-Assembly Lab at MIT [7] collaborated to create a first experimental setup for the robotic fabrication of jammed architectural structures. This endeavour resulted in several architectural prototypes that were digitally fabricated by up to two robotic arms. These jammed structure prototypes required many innovations, including the development of new material systems, hardware (end-effectors), new computational systems, and multi-robotic motion planning (see Figure 2). While it remains to be seen whether this approach will emerge as a viable building technology, first experiments successfully illustrate how digital fabrication makes granular matter tangible to large-scale construction, fully reversible, and addressable by robotic machinery.

Custom fabrication setups have become a standard approach for digital fabrication, for example six axis robotic arms mounted on movable platforms, or horizontal axis and vertical axis setups coupled with custom made end-effectors [8]. The machinery is controlled by algorithms that can be programmed to generate digital blueprints. These blueprints are adapted to the initial design requirements and can react to external inputs, such as the behaviour of the structure during the build-up. This direct synthesis between jamming processes and manufacturing automation allows for highly sustainable and effective structures built from local materials – without any additional formwork or construction support. The resulting architectural structures require little to no external energy for the jamming transformation and can be realized at full architectural scale, directly at the construction site. Then, at the end of their useful lifespan, they can be fully released into loose, reusable aggregates. A variety of novel load-bearing construction types (see Fig. 2 and Fig. 3) that are less dependent on costly materials and/or component prefabrication as well as transportation and material waste can thus evolve.

Because the granular material is robotically manipulated, this method allows the aggregation to be structurally optimised under the explicit guidance of a digital design and simulation. In the future this will enable architects to design load-bearing structures that meet specific structural performance criteria, and develop efficient construction processes – even when the design, material behaviour and building information are highly complex. Each one of the main characteristics points towards the potential for new forms of spatial load-bearing structures that are not currently possible with standard construction.

Fig. 2 *Close up of wall element with opening. This structure demonstrates the possibility of creating architectural primitives with jammed, low-grade, granular materials. In this structure, the string was placed by hand according to a template. Gramazio Kohler Research, ETH Zürich, 2014.*

Fig. 3 A structurally sound wall element made with jammed, low-grade, granular materials. Gramazio Kohler Research, ETH Zürich, 2014.

In the next section (Section 2) we present the technological context of our work. Section 3 presents a scheme for research into robotic fabrication of jammed architectural structures, as well as initial experimentation, including material systems, design, construction processes and features of robotic machinery. Section 4 discusses the challenges of this approach and suggests strategies for addressing them. Our conclusions are presented in Section 5.

2 Context

Research on robotic fabrication in construction dates back to the early 1990s [9-11]. The original motivation behind this research was to improve the productivity and economy of building construction, mainly by using the machines' ability to handle an increased payload in contrast to humans. Although highly advanced, these developments did not find their way into the market because they were not flexible enough to adapt to different design scenarios [12]. The past decade has seen a shift from construction automation to robotic fabrication, and the exploration of novel additive manufacturing processes. Universities such as Harvard GSD (2008) [13], Carnegie Mellon (2009) [14], University of Stuttgart (2010) [15] and MIT (2012) [16] have set up architectural research facilities for custom digital fabrication with industrial robots. Following ETH Zürich (2005) [17], they have fostered architectural case studies and prototypical structures, elevating non-standard robotic manufacturing to the role of a design and construction tool (see Fig. 4), and resulting in highly versatile and customizable construction systems [18].

Fig. 4 Detail view of a dry-stacked automatically fabricated brick wall [19] together with a robotic setup equipped with a custom end-effector. Gramazio Kohler Research, ETH Zürich, 2006.

Concurrent to these advances in architectural robotic construction is a growing interest in granular aggregations [20-22]. When linked with innovative robotic machinery [23], they satisfy the requirements for control, customization, economy and fast construction [24]. These systems are statically indeterminate [25-28], are composed of a multitude of elements, and require advanced design and manipulation processes. Therefore granular aggregation lends itself perfectly to the increasingly powerful digital planning and fabrication tools that are becoming available [29]. For example, the Institute for Computational Design (University of Stuttgart) investigated using robotically aggregating granular components to assemble non-standard architectural structures from self-interlocking parts [30]. The recently launched STIK pavilion [31] project at the Advanced Design Studies (University of Tokyo) focuses on highly intricate designs aggregated from bulk material through manually held robotic gluing and deposition machinery.

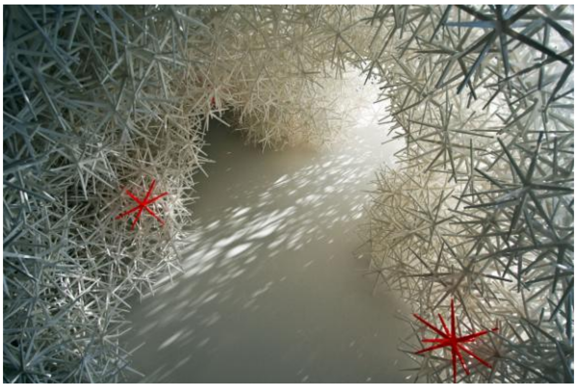

Fig. 5 *Aggregate Architectures, Karola Dierichs, Institute for Computational Design (Prof. A. Menges), University of Stuttgart, 2010 – current. Image with permission from K. Dierichs. First published: Dierichs, K., Menges, A.: Aggregate Structures: Material and Machine Computation of Designed Granular Substances. Architectural Design 82, Issue 2, pp 74-81. Wiley & Sons, London (2012)*

Fig. 6 *STIK pavilion, DFL/Advanced Design Studies (Prof. Y. Obuchi), The University of Tokyo, 2014. Image by Hayato Wakabayashi*

Nonetheless, most research in this field is aggregate-centric, focusing on design of single aggregates and/or use of non-structural aggregates. None currently makes use of coupling adaptive robotic fabrication and material science to gain insight into digital manufacturing with bulk materials that are fully reversible and loadbearing, and suitable for the scale of architecture. It is therefore of major importance to amalgamate knowledge from material science, computational design and digital fabrication in order to explore novel building processes that implement principles of jamming on a tectonic scale [32].

3 Research components and experimentation

Research on robotic fabrication of jammed architectural structures is based on two main components: 1) jammed material systems, and 2) adaptive robotic fabrication. The essential feature of this approach is to introduce the unique integration of different material and robotic systems, so their overall capabilities and limitations regarding the physical building performance can be identified. Important parameters range from particular aggregates, reinforcements, and assembly techniques to digital design parameterisation, digital fabrication processes, robotic arms and end-effectors. An essential goal in this research is to foster design methodologies that are informed by material, construction and fabrication criteria, and are able to adapt to multiple functional requirements.

3.1 Jammed material systems

Beginning with a range of different granular materials, several possible aggregation methods were manually investigated. These techniques included layering granular materials with two-dimensional elements, and using slender members and chains that naturally interlock when compressed (see Fig. 7).

The experimental setup consisted of two pistons able to load column-shaped material samples (up to 1000 mm x 150 mm) with up to 100 kg of weight. First a circular mould was placed on top of the bottom piston, and then the material system was manually placed in the mould and the top piston was put in place. Next, the column-shaped test was loaded and the mould released. These early explorative experiments indicated that the boundary fragility and the ability of the aggregates to deform are what determine the structure's overall stability. The selection criteria for the jammed material were: the buckling length of jammed material column, the load capacity, stiffness, congruent behaviour, and suitability for upscaling to an architectural scale. Some interesting material capacities were found. For example, small pieces of foam behaved as a solid under axial compression. Successful aggregations were also made out of metal chains, screws, iron rods and mixes of them. These, however, had their downsides: they were not congruent, they often buckled in unpredictable places, they were not optimal for robotic manipulation, and they consisted of high quality materials that might be put to better use.

Fig. 7 *Experiments with a wide range of different jammed material systems. Gramazio Kohler Research, ETH Zürich, 2014.*

The most suitable aggregate structures were those with the strongest edge conditions; these were aggregate structures reinforced with a second, tensional material. We also found the most suitable aggregates to be those with the hardest and most form-stable particles, such as crushed rock and standard concrete aggregates.

Unfortunately it proved to be almost impossible to repeat these manual experiments due to the natural disorder of granular matter (which makes it dependent on the build-up history) and the imprecision of the manually placed reinforcement. However, robotic manufacturing addresses these issues perfectly, as the technique allows precise control over the manipulation and placement of the aggregate and the reinforcement material.

Tensional materials such as textiles, fibres, and string elements were used in the experiments to prevent the structures from buckling. We explored two types of tensile reinforcement systems: 1) textiles that were cut into the shape of the cross section of the test segment and then layered with gravel; and 2) fibres and string elements that were placed in a continuous circular pattern surrounding the aggregates. The string element reinforcement proved to be stiffer than the layering textile reinforcement due to the direct interaction between the particles. Experiments showed that string reinforcement is highly adequate for this task: it allows for multiple degrees of freedom in placing, it does not require permanent alteration of the tensile reinforcement, and it results in a stiff jammed material system.

3.2 Adaptive robotic fabrication

The first robotic fabrication methods were designed to reduce variation between experiments. Three different digital fabrication methods were developed: rock-printing (Fig. 8), slip casting of jammed structures (Fig. 9) and a combination of the two – referred to as “multi-robotic fabrication” (Fig. 10-13).

3.2.1 Rock printing

Rock printing is based on a process similar to 3D printing [34] where loose aggregates were placed in a thin layer within a fixed printing bed and the string was robotically placed according to a digital blue-print. Then a second layer of aggregate was placed, and the process repeated until the whole structure was fabricated. When the containing walls of the print bed were removed, the aggregates that were not held in place by the string reinforcement automatically fell off, freeing the printed structure. The loose material acted as a support material during the build-up.

Critical to the success of the experiment was the ability to efficiently investigate different string patterns for the jammed structures. Initial string patterns were explored by contouring a 3D computational model and using the contour as guide for generating a digital blueprint and tool path for the string dispenser. These outline structures proved successful as long as the patterns were circular and the radius kept within certain measures. However, experiments with square and complex geometry outlines were harder to aggregate successfully. This is because it was necessary to keep the edge string under tension (to prevent the structure from collapsing); as such, the more circular and symmetric the pattern was, the better it performed. Based on this experience, we investigated string patterns developed by populating the contours with interconnected loops. This method proved very promising and is now part of ongoing research. Rock printing, however, is restricted to the work-envelope (print bed) of the machine and requires a mould system that is larger than the intended structure.

***Fig. 8** Rock print, demonstrating how the jammed aggregates can be shaped into geometrically and structurally sound designs. Gramazio Kohler Research, ETH Zürich, 2014.*

3.2.2 Slip casting

Because rock prints must be cast into moulds, a separate method was developed to investigate the possibility of aggregating structures on top of already aggregated structures, i.e. to 3D print on top of already printed material. In this respect, slip casting [35] is similar to rock printing except that the printing bed is replaced by a mould that moves upwards and rests on already jammed structures. A thin layer of aggregate was placed in the slip mould and then string was robotically placed. This procedure was repeated until the mould filled up, and then it was moved straight up to the next position.

Early experiments using this method tended to be unsuccessful because the aggregate structures got stuck inside the slip cast and fell apart. We exchanged the straight cylinder mould for a conical shaped mould with a slightly larger base, and were able to successfully slip casts. Different radiuses were explored and showed behaviour similar to the rock print experiments. Square moulds were also tested and failed when the string pattern was placed along the outline, once again behaving similarly to the rock prints. Slip casting columns (with a circular cross section) inside the square mould worked as well, but required a taller mould to prevent the support material (the excess material between the mould and the outside of the string pattern) from leaking out of the mould. The top part of the mould must have a complete aggregate layer so that the string can be held in the correct place while the next layer of aggregate is applied. Slip casting of jammed aggregate structures proved useful mainly for straight or slightly undulating, and were repeatable and suitable for comparing different aggregates, strings, layer thicknesses and proportions between string and gravel. This fabrication method was later used for the first larger scale experiments (see Fig. 16).

Fig. 9 Slip casted structures for comparing behaviour of jammed structures depending on layer thicknesses and amount of string reinforcement. Gramazio Kohler Research, ETH Zürich, 2014.

3.2.3 Multi-robotic fabrication

We developed a first approach to scalable jammed construction in architecture based on a combination of rock printing and slip casting. This section describes our experimental setup.

The aim was to create larger structures, with a focus on walls. We started by slip casting rows of columns. Due to their own weight, the columns settled and expanded radially while they were being printed, and so in the end, their bases blended into one another. These structures were very repetitive and did not provide much geometrical freedom.

In the second iteration of the experiment, we explored a different printing method. Instead of slip casting straight standing columns, the robots slip casted on an angle (varying between 30 and 45 degrees) so that each cast rested on the previous one (Fig. 10). This resulted in stronger structures and made it possible to fabricate overhangs, however the column segments remained clearly visible and the structure still lacked global stability.

In the final experiments we modified the string pattern by changing the cross-section of the columns from perfect circles to ellipsoids (with the wider direction perpendicular to the direction of the wall) in order to create a larger contact surface between the leaning columns. In this way we managed to increase the stability of the structure and change its behaviour from a segmented structure to a solid one.

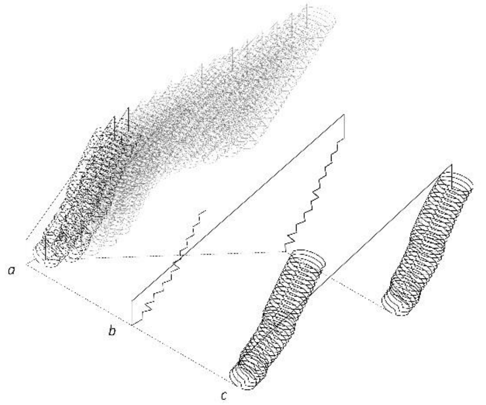

Fig. 10 Diagram showing a digital blueprint for a multi-robotic aggregation of jammed architectural structures based on ellipsoids (with the wider direction perpendicular to the direction of the wall) to

create a larger contact surface between the leaning columns. a) Overlay of the toolpaths (digital blueprints) for the mould and string dispensing tools. b) Exploded diagram showing the toolpath for the mould tool drawn by connecting the robot's waypoints. c) Exploded diagram showing the string pattern (the toolpath of the string dispensing tool). Gramazio Kohler Research, ETH Zürich, 2014.

The robotic setup consisted of two six-axis robotic arms [36], customized end-effectors, and a movable building platform. It also included a range of internally developed digital tools and interfaces to control the robotic movement. The first robotic arm was equipped with a custom-built slip-form, and the second robot with using an automated extrusion head, which was used to precisely place the flexible 3 mm textile string used as reinforcement for the material aggregation. We developed a custom design-to-fabrication workflow where the process compensated for the non-rigid behaviour of aggregate structures. The mould end-effector was mounted with springs on one of the six-axis robotic arms to allow some flexibility while moving, and to enable the aggregated material to be reconfigured. The string extruding end-effector mounted on the other of the two six-axis robotic arms was equipped with a long nozzle that was flexible enough to avoid collisions with aggregates, yet stiff enough to prevent wobble and imprecision.

Since the gravel placement was not automated, the amount of gravel needed for each layer was adjusted manually according to the behaviour of the previous layer. During the build-up, the first robot moved the slip-form into place and the second robot positioned the first string layer according to a computationally specified pattern. Thereafter, the first robot moved with the slip-form to guide the first layer of gravel deposition, while the second robot interweaved the next string layer. The mould tool ensured that aggregates were manually placed at the correct point in space. The amount of aggregate was adapted to ensure a constant layer thickness as well as overall correct aggregation volume. The layering was repeated until the robots were beyond the reach of the building platform, and then the platform was moved back to an optimal position within the robots' work-envelope to enable continued fabrication. In future setups, this could be accomplished using movable robots [37]. The fabrication method – to seamlessly aggregate structures on top of already aggregated structures – enables the fabrication of structures that are much larger than both the reach of the robotic arms and the robotic arms themselves.

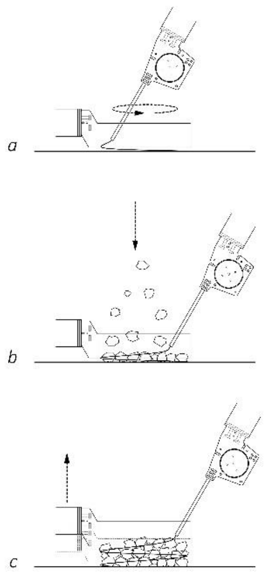

Fig. 11 a) String-extruding robot places string according to a digital blueprint inside the mould held by the second robot. b) Crushed gneiss is placed in the mould according to the digital blueprint. c) After repeating steps a. and b. according to the digital blueprint, the second robot moves the mould to the next position. Gramazio Kohler Research, ETH Zürich, 2014.

This technique of layer-based build up proved to be robust, flexible, and controllable through computational design, and could be used for a wide range of geometries, such as columns, arches and double-curved wall elements. We generated a digital blueprint in a conventional CAD environment [38] where the string patterns and the mould positions were defined, as well as the sequence in which these were executed. In addition to this, a custom-built programming interface was used to manage the overall construction process by interpreting the blueprint, and issuing control commands to the robots (see Fig. 12).

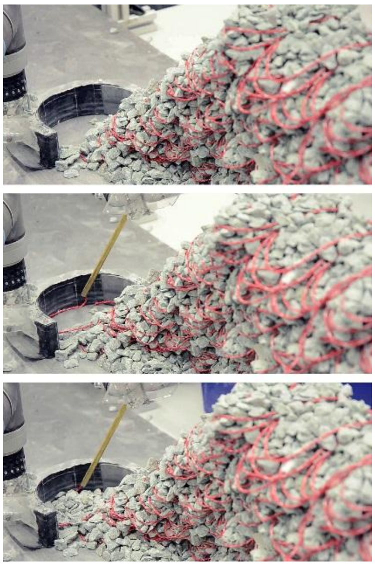

Fig. 12 Sequence of the fabrication process showing two six-axis industrial robotic arms equipped with customized end-effectors that cooperatively manipulate crushed gneiss and position textile strings according to a digitally generated weaving pattern. This is used for the robotic extrusion of textile strings that provide the lateral tensile support needed for preventing the buckling of the force chains and to stabilise the boundary fragility of the jammed structure (picture interval approx. 30 s.). Gramazio Kohler Research, ETH Zürich, 2014.

Finally, we produced a 1:5 wall prototype (Fig. 13), measuring 1415 x 345 x 137 mm, with a local slenderness ratio of 1:4. The structure was six times larger than the overlapping work-envelope of the two robotic arms. The wall prototype was double curved, featured overhangs of 75 mm, and comprised ca 125 kg of (gneiss) gravel [39] and 184 meters of textile string (see Figure 7). This material (composed of graded aggregates featuring 5-15 mm grain sizes with sharp edges and high frictional resistance) considerably enhanced mechanical interlocking and therefore the overall aggregation. Moreover, the particles lent themselves very well to the jammed aggregation of building elements at a 1:5 scale. As a reinforcement system, we introduced low-grade string (Bächi-Cord 3 mm polyester string mixed with recycled textile fibres), which (thanks to its inherent flexibility) can handle the edge condition of the material during build-up and redirect the evolving tension forces throughout the whole material structure.

Fig. 13 The resulting robotic aggregation (1:5 scale) features considerable geometric capabilities – suitable to building construction purposes – and demonstrates that jammed architectural structures have the potential to be robust tectonic elements. Gramazio Kohler Research, ETH Zürich, 2014.

Fig. 14 *Close up of a jammed structure, showing the string preventing the buckling of the force chains at the edge condition. Gramazio Kohler Research, ETH Zürich, 2014*

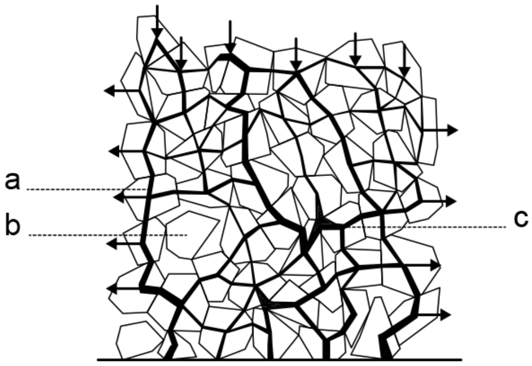

Fig. 15 2D representation of force chain network with solely repulsive interactions between packed granulates in the jammed state. a). Force network particle. b). Spectator particle. c). Force chain network. This diagram is built upon a preliminary version elaborated by the group of Prof. Hans J. Herrmann.

3.2 Empirical findings for adaptive robotic fabrication of jammed material systems

Experimental results show that the concept of robotic fabrication of jammed architectural structures has significant potential. More specifically, physical experiments revealed that the boundary fragility of the resulting structures clearly determines their overall stability. For example, upon increasing vertical load, the outer force chains buckle outwards, resulting in large restructuring events. Hence, the proper mechanical stabilization strategy of the boundary force chains represents one of the main criteria of such granular structures. The study showed that different materials (for example flat two-dimensional objects like geotextiles, and membranes shaped as the cross section, or tensile one-dimensional objects such as fibres and membrane strips) can be used to provide the lateral tensile forces needed to prevent the outer force chains from buckling (see Fig. 14) and to obtain a laminated reinforced granular column. Furthermore, the study demonstrated that it is possible to robotically fabricate a jammed aggregate structure in more than one way. The different fabrication methods show that material behaviour is consistent across methods, allowing us to derive "rules of thumb" regarding pattern, aggregates, reinforcement and geometry.

String pattern – The string pattern must be in tension to be able to hold the force chains on the surface of the aggregate structures. As such, circular patterns are the most efficient. For graded, 5-15 mm aggregates with radial tensional elements, diameters between 70-150 mm create the most stable structures. It is possible to create complex geometries with tensile reinforced aggregates by placing the reinforcement in a circular fashion following the contour of the intended geometry (see 3.2.1). We found that the layer thickness is optimal when equal to the average size of the aggregates (10 mm for 5-15 graded aggregates, and 20 -25 for 15-30 graded aggregates). Doubling each string layer makes it possible to maintain larger distances between the reinforcement layers due to the increased chance for optimal interactions between the tensional reinforcement and the aggregates.

Aggregates – The aggregates we experimented with ranged from round, natural stone, crushed rock (gneiss) and glass foam aggregates. Aggregates with sharper edges and harder surfaces generally yielded stronger and easier to fabricate structures. By mixing 3 parts 5-15 mm graded aggregate with 1 part 15-30 mm graded aggregate, it is possible to aggregate structures with larger distances between the reinforcement layers. However, this results in a rougher surface texture. Packing has a big influence of the behaviour of tensile reinforced jammed materials: the more homogenous the packing, the stronger the structure.

Tensile reinforcement – To successfully aggregate jammed structures it is important that the string deposition is precise; the ability to precisely place the string depends on the qualities of the string itself. A soft string is necessary for placing string in smaller freeform patterns. While the exact forces on the tensional elements must still be investigated, experimentation has proven that jammed structures can handle loads more than 20 times higher than the tensional strength of the string. The diameter of the tensional element seems to have a smaller impact on the behaviour than does the friction between the aggregates and the string. Another important parameter is the elasticity of the tensional reinforcement, and experiments tend to show that a more rigid string results in stronger structures.

Geometry and design parameters – Tensile reinforced jammed materials have a certain resolution that is defined both by the size of the aggregates and the radius of the string pattern. Tensile reinforced aggregate structures handle compressional forces very well and tensional forces less well. Experiments showed that it is possible to build overhangs with ca 20 degrees of inclination. By placing the tensional elements in a 3D dimensional way (instead of the current layering method, where the elements are placed along a two dimensional axis) the tensional capacities of jammed structures could be drastically improved.

The first physical experiments and prototypes demonstrate multiple possibilities for robotically fabricating jammed architectural structures, suggest essential design criteria, and reveal fundamental experimental challenges (summarized in Section 4). Against this background, the combination of robotic fabrication, computational design and material research have become an essential concept of this effort. Despite the complexity of the task, we purposely chose to examine in depth the specific characteristics of this combination, in order to unlock a new and interdisciplinary research direction for architecture.

4 Future challenges in developing jammed architectural structures

In order to be able to digitally aggregate low-grade granular material into load-bearing, geometrically predetermined structures, all build-up steps must be integrated into one unified robotic fabrication system. This is fundamental to preserving the integrity of digital information and enabling efficient construction processes, and is an inherently challenging problem. It is therefore difficult to obtain a universal principle model of such an approach. It is possible, however, to isolate important characteristics, evaluate fidelity and describe new construction methods and architectural structures.

4.1 Digital control and fabrication precision

Tremendous advances in digital technologies and their capabilities in architecture have come from the overlap between computational design and digital manufacturing. However, when exploring the link between performative design and robotic fabrication, the differing characteristics of architectural material systems and robotic fabrication are a prominent issue. Three principal factors determine the integration of material and robotic fabrication: 1) tolerances influencing the manufacturing processes; 2) the need for interfaces that provide a seamless digital information chain; and 3) knowledge of different research methodologies and disciplines. These factors influence the research process and determine how comprehensively the research can be undertaken. However, overall process and material tolerances represent the main challenges. For example, at the building scale neither the (granular) construction material, nor its robotic handling and positioning process are precise enough. In turn, deviations in the build-up emerge through their accumulation, causing major problems throughout the assembly process. This limitation requires the implementation of sensor-based feedback mechanisms to register the actual geometry of the built structure, and adjust the digital blueprint and the pre-computed motion path of the machine to the material reality [40, 41]. Consequently, the reinforcement (string) deposition must also be tolerant to discrepancies between the physical reality and the digital model to allow a range of geometric tolerances to be accommodated. Simultaneously, the real-time assessment of the build-up via closed loop feedback systems represents an important step towards the implementation of fully adaptive robotic fabrication routines for building smart and material-efficient assemblies [42].

4.2 Robotic tooling and build-up sequence

Multiple robotic arms can cooperate to perform a desired action collectively. In addition to direct collaboration, their work capacity is also scalable to a large degree – a trait that digitally controlled robotic arms share with many other digitally driven technologies [43]. In fact, industrial robots can cooperate in many ways: they can collaborate during the build-up process or cooperatively share specific manipulation tasks (as described in Section 4). Consequently, though these experiments show that multi-robot aggregations can be used in efficient and robust jammed construction systems, comprehensive investigation will be required to make this a practical reality. First, this includes cooperation between different robotic arms, trajectory planning and fault handling. Second, there is a need to develop physical manipulation systems that allow robotic arms to dispense the material at a targeted point in space. This depends largely on the machines' capabilities and on the degree of freedom of the chosen build-up sequence. Suitable solutions for this are mechanical end-effectors that feature moveable formwork elements. Furthermore, developing a specialised dispensing system would be a worthwhile endeavour, as complex tools are (in most cases) not presently robust enough to carry larger payloads and/or to manipulate heavy material into load-bearing conditions. Physical manipulation systems must also place reinforcement material in order to maintain stability during build-up. The placement (and reinforcement) of material must not only be pre-determined, but also adaptable to real-world building performance, and to interaction between machinery and periphery. Hence, the design of a particular jammed architectural structure is directly linked to the design of its fabrication process and the tools employed. Consequently, the infrastructure setup and material logistics heavily influence the build-up of such structures, and hence their aggregation performance.

5 Conclusion

In conclusion, the vision of jammed architectural structures radically expands the traditional spectrum of design and construction. Most of all, this endeavour places material logic and behaviour at the centre of the process – from the design and construction through to the object's final form – and enables a paradigm shift from standardized construction systems to low-grade material aggregations. Here, synchronization with material events and processes (such as settling) is essential to leveraging new architectural and structural potentials. Thus, robotic fabrication of jammed architectural structures injects information into the whole process of building. From the initial parameterization of the design to the automated aggregation of building layers and the deposition of reinforcement, the method opens up new ways of thinking about architectural design and materialization.

Robotic fabrication of jammed structures also drastically challenges the way we conceive of and design buildings. The ability to entirely reconfigure materials in different forms makes it possible, with no or little material cost, to change and rebuild both permanent and temporary structures. There is at present little research on this topic, and no prior experiments have been conducted in the field of architecture. Going far beyond manual assembly techniques of dry masonry, this endeavour presents a unique combination of state-of-the-art architectural knowledge, digital fabrication technology, and building material science, and introduces an entirely new, sustainable, economical and structurally sound construction method that fundamentally challenges the way architecture can be designed, constructed and fabricated.

Fig. 16 *Picture showing a jammed column (2100 mm with 180 mm diameter) produced with a six axis KUKA KR 150 L110 robot mounted on a linear axis, and equipped with a custom mould end-effector. Gramazio Kohler Research, ETH Zürich, 2015.*

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