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Roll-Locks: A Fabrication to Self-Assembly Design-Framework for Reusable Discrete Concrete Elements

Abstract: *Roll-Lock* is a research project in which building elements are informed for motion and future reuse. This paper gives technical insight into systematically investigating lightweight, hollow, and kinetic concrete elements' geometrical and physical properties. The massive-looking yet lightweight, hollow, robotically materialized concrete elements are designed to join together, but not permanently. A single person can move and assemble them with their dry-joint, interlocking connection and charged center of mass (CoM) (Fig. 1). The elements are programmed for guided self-assembly, disassembly, and re-assembly through embedded geometrical and physical attributes (Fig. 2). The reconfiguration allows for a more circular approach and reuse of concrete elements in the architectural context. Furthermore, this research seeks to provide novel strategies to save building material resources by rotoforming (Tessmann and Mehdizadeh 2020), thereby minimizing material consumption and significantly reducing the weight of hollow concrete elements (Fig. 4).

Keywords: design for reuse, digital concrete, RotoForm, programmable material, sequential dynamic casting, interlocking assembly, sequential assembly

Fig. 1: Human interaction with the 1:1 hollow concrete element for guided self-assembly.

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1 Introduction

Current construction technologies extensively rely on non-reversible mechanical fasteners or adhesives. Even precast elements are mostly connected with mortar and grout (Elliott 2002), preventing non-destructive disassembly and reversibility. In this paper, we offer a design to materialization framework that allows for reconfiguration and (re)assembly with interlocking hollow elements. We regard reconfiguration as a crucial strategy for the long-term use of building elements and reusability. Most importantly, it allows for more circularity in design and construction. We investigate geometrical and physical principles that enable and ease humans' lifting, rolling, assembling, and disassembling of building elements without any heavy equipment. Thus, reversibility reduces material consumption, allowing new forms of interaction between human and architectural elements. The presented work is based on the robotic fabrication method RotoForm (Tessmann and Mehdizadeh 2019), which saves material of both concrete and formwork by producing hollow elements.

Fig. 2: Human interaction: The process of assembly, disassembly, and lifting of the concrete element through rotational interlocking and manipulated center of mass.

2 Research background

2.1 Self-assembly

The research on self-assembly is relevant for this paper because it includes strategies of inscribing assembly information into the geometry of parts instead of using the architectural strategy of plans, drawings, and details as abstract and formalized assembly instructions for human or machine agents. The studies of Georges Popescu (Popescu n.d.) at MIT on digital materials and digital fabrication describe the programmability of parts with their simplicity and discrete logic. All parts of a self-assembly system are geometrically simple, should be able to have at least two states (e. g., on/off or attached/detached), and should be able to respond to the instruction sequence. Based on Popescu's research Skylar Tibbits suggests in his master thesis, "Logic Matter", parts for self-assembly and guided self-assembly are enabled through assembly information inscribed in their geometry and embedded digital logic (Tibbits 2012). Tibbits describes the following requirements for self-assembly systems.: 1) a simple assembly sequence, 2) programable parts, 3) force and energy for activation, and 4) redundancy. The research "growing machines" (Griffith 2004) at MIT explores the idea of self-assembly and guided self-assembly through self-replicating machines (Penrose and Penrose 1957) and identifies a discrete system that consists of different programable parts; rather than arrays of similar components. He describes the hierarchy of assemblies in biological models as a technique for building complex matter assemblies.

2.2 Interlocking

Research on interlocking originates from various fields, such as computer graphics, material science, and structural engineering. Computer graphics research defines interlocking in two categories: either the voxel-based approach assembling parts along orthogonal vectors in a particular sequence (Song et al. 2015), or the catalog-based approach, in which small pieces form a puzzle difficult to solve since the assembly must follow specific rules. While the combinatorial complexity of the puzzle's piece arrangements is exceptionally high (Xin et al. 2011). Luo proposes a digital framework, "Chopper" (Luo et al. 2012), for partitioning large geometries into interlocking parts with male/female joinery systems. Wang et al. introduce a method to cluster voxel-based geometries for a broader range of assemblies with many different shapes (Wang et al. 2018). In summary, the computer graphics community focuses on chopping the geometry into smaller buildable (printable) pieces – a top-down approach for solving the fabrication issue of large parts.

The geometrical concept of topological interlocking can be traced back to the baroque era of stereotomy (Fallacara 2009) and resurfaced through research in material science (Dyskin et al. 2003). The application potentials of the topological interlocking in the field of computational have been explored by Tessmann (2012), Gata et al. (2019), and Weizmann et al. (2017). The researcher sought to increase the geometrical repertory of topological interlockings and integrated generative and analytical capacities into a computational design framework. The flexural performance of interlocking flat vaults made from topologically interlocking concrete blocks demonstrates good performance compared to the monolithic concrete plates (Rezaee Javan et al. 2017). Moreover, Baghdadi et al. (2023) developed analytical digital models to evaluate the structural strength of dry joint interlocking interfaces between the concrete elements. The geometrical interface as a dry join possibility has been applied and explored by Oval et al. (2023) as well as Rippmann et al. (2018) as a dry joint connection between concrete, discrete elements. The architectural practice AAU-Anastas has built a couple of architectural projects using interlocking elements as flat and curved vaults.

2.3 Robotic fabrication and digital concrete

Over the last decade, a vast range of research in computational design and robotic fabrication sought to change the conventions in construction. Robotic and concrete researchers propose novel materialization methods for formwork fabrication (Wangler et al. 2019) and concrete deployment. Besides 3D printing of concrete, a technology that made the leap from research labs to construction sites (Tessmann et al. 2022), material-robot systems for concrete processing offer great potential for exploration and innovation. This research field explores a more substantial involvement of robotic kinematics in material placement, such as slip casting (Shahab et al. 2013) or rotoforming (Tessmann and Mehdizadeh 2019). Material-intensive formwork systems are replaced by robotic movement during concrete processing. Rotoforming is used in this research to materialize the building elements.

The technology utilizes the concrete flow and robotic trajectory to materialize hollow concrete elements with variable cavities inside the elements. A minimum amount of liquid concrete is poured in a form gently rotated by a machine. The material is just enough to form a thin hollow shell as the rotation makes it flow along the formwork. RotoForm allows casting in several layers of concrete with different thicknesses from outside to inside. The differentiated material and weight distribution inside the hollow elements shift the elements' center of mass (CoM).

2.4 Assembly through weight

As architectural elements are mostly meant to be static as part of a larger tectonic system, another research field focusing on dynamic objects needs to be explored. Bächer et al. developed an algorithm that generates spinning objects by optimizing rotational dynamics properties. A solid 3D model with a random, asymmetric shape and a desired axis of rotation forms the input. The algorithm then modifies the mass distribution such that the principal directions of the moment of inertia align with the target rotation frame (Bächer et al. 2014). The 3D-printed objects ideally rotate around a vertical axis while being asymmetric in their outer shape. Invisible inner cavities achieve mass symmetry.

The design research project "Walking assembly" by matter design (Brandon Clifford) addresses different aspects which are also present in this research, such as assembling the concrete Blocks through weight distribution (Swingle et al. 2020). Differently, Clifford manipulates the CoM by gradually changing the concrete density. Clifford also presents studies on Geometry and force design, which allows humans to lift and move megalithic heavy Concrete objects without cranes (Clifford 2016). A design to build a framework concerning the weight distribution in the global assembly by (Wibranek et al. 2020) illustrates the ability to assemble modular building components without the need for support structures.

3 Method

This proposal aims for objects that can roll into various assembly configurations. All elements are based on a 3D voxel grid. The catalog of elements is shown in Fig. 3.

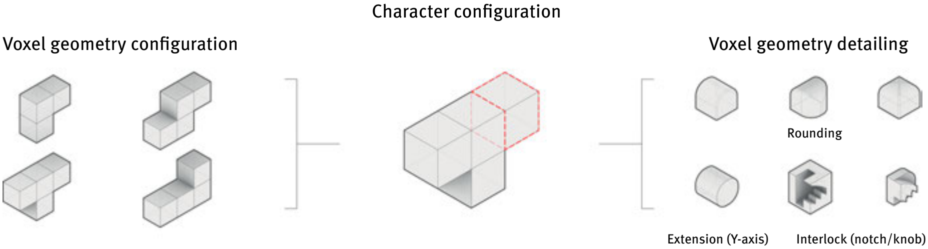

Fig. 3: The topology catalog of elements; Left: the chosen voxel-based shapes (L, T, and S), Right: the replacement voxels.

Every voxel of an element can be formed differently to gain rotational or interlocking properties (Fig. 3 right). The digital workflow in this design to simulation and fabrication process starts with developing forms that enable rotational movement. Motion and geometry are closely linked. The joints that enable rotational interlocking are derived from the rotational trajectories of the objects (Fig. 4). The interlocking performance is subsequently tested in rigid body simulations as well as the placement of the CoM through designing internal cavities and varying wall thickness. Finally, the robotic fabrication data that controls the material distribution during rotoforming is generated. We conducted several iterations of numerical and experimental experiments and produced a series of physical prototypes before evaluating the results. The following paragraphs describe the relationship between the different topics.

3.1 Motion path and rotational interlocking

The target is to generate shapes that roll and interlock into a solid connection (Gilibert et al. 2022). We characterize all part's motion paths and interlocking procedures with three transitional and three rotational degrees of freedom. The voxelated shape of

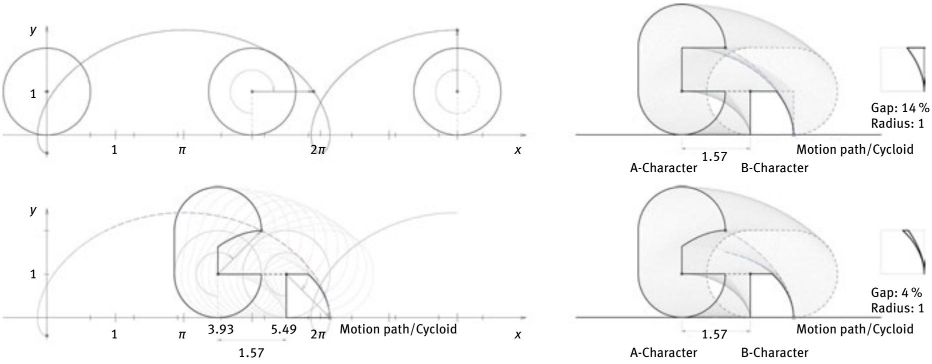

Fig. 4: A cycloid, form finding and research to increase the contact area in the locked state.

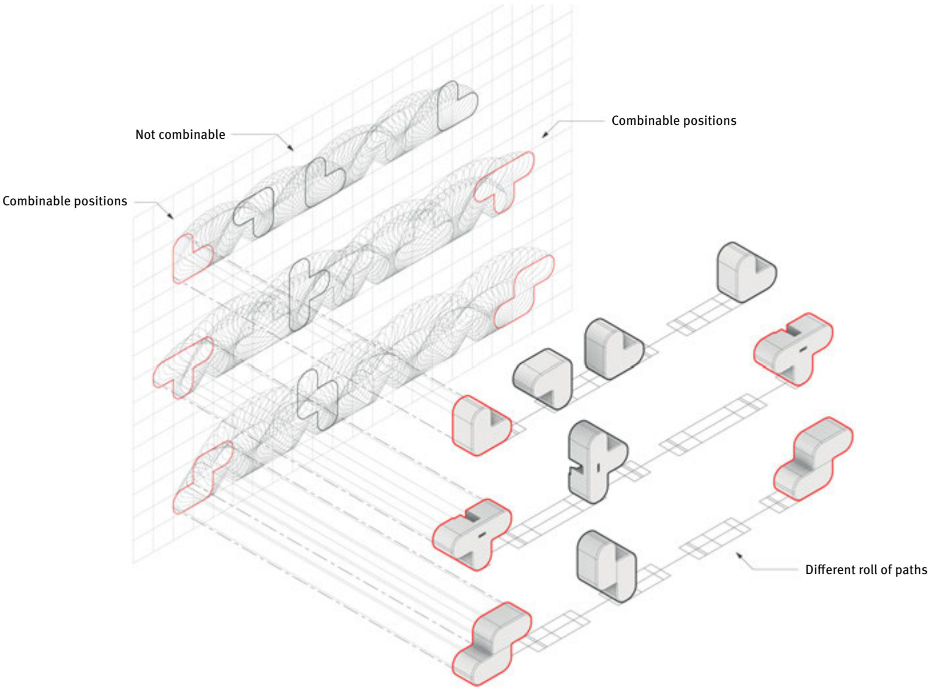

Fig. 5: Moving (rolling) paths regard to the shape of elements in 2D projection address the initial and target position for assembly.

elements and the rotational interlocking system allows for solid connections in all transitional directions (X, Y, Z) (Fig. 6).

To define a (rolling) motion path in relation to rotational interlocking, we use the geometrical principle of the cycloid. "A cycloid is a curve traced by a point on the circumference of a circle which rolls without slipping along a straight line" (Barra

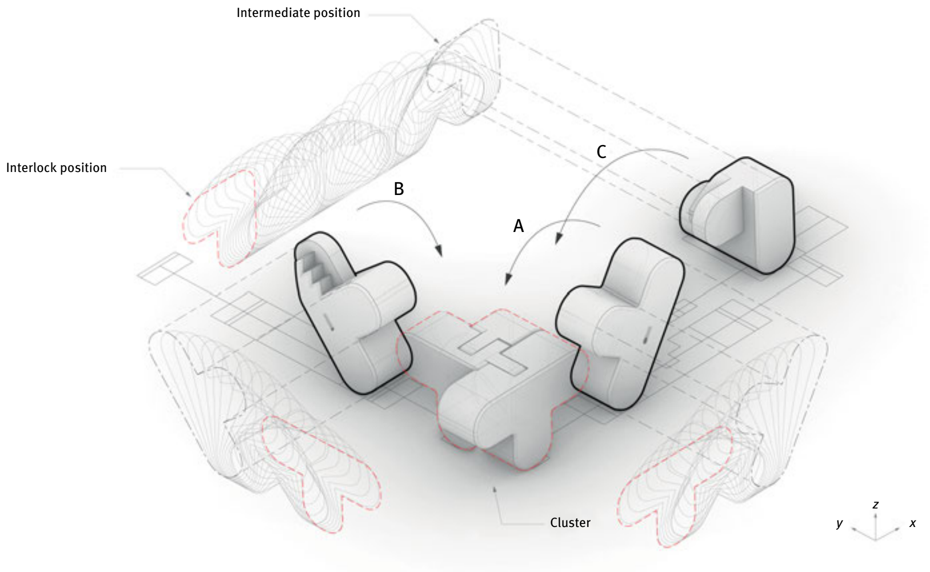

Fig. 6: Assembly sequence of the lowest hierarchy with three elements (T, T, L).

1975). A generative digital model (form finding algorithm) based on the cycloid allows for defining all the possible motion paths of the convex shapes based on their curvature (Fig. 4 left, Fig. 5). The generated motion paths define the shape of interlocking joints made from notches and knobs (male/female connection). In order to increase the contact area in the locked state between two elements, the form-finding algorithm minimizes the geometrical deviation of curvature between the male and female parts (Fig. 4 right). The number of rotational interlocking joints in the physical prototypes is increased with different radii to increase the contact pressure on the side surfaces.

3.2 Motion and assembly sequences

This scope focuses on geometry as a tool for generating assembly sequences. Designing the recursive assembly refers to the issue of finding the sequence for full (dis)assembly of all the parts. Throughout this research, we have developed and tested two main approaches to recursive assembly sequences with different shape types: a) clustering assembly, b) sequential assembly. The assembly sequence of both approaches consists of interlocking voxelated shapes with a single-key property. When the assembly is completed, all the elements in each cluster are notched and locked in all transitional directions. Disassembly is only possible through the rotational motion of the single key element. We use the mathematical method of Non-Directional Blocking Graphs.

(NDBG) proposed by (Gilibert et al. 2022) to define the assembly sequence concerning the interlocking.

3.2.1 Clustering assembly approach

This approach determines a catalog of discretized building elements in three Tetris-like shapes (L, T, and S). In order to decrease the complexity of assembly, each shape is defined with three to five voxels. Every voxel can incorporate a notch/knob joint or become a curved voxel according to the desired function of motion or interlock (Fig. 4.). Thus, each element consists of a regular, notch, and curved voxels in different orders. This catalog-based geometry generation allows for a wide range of roll-lock scenarios (Fig. 7).

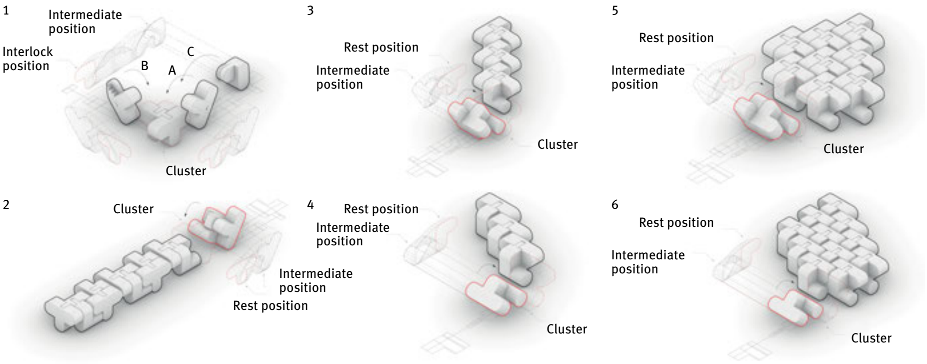

Fig. 7: The catalog of hierarchy models for one-directional (linear strings) and two-directional orders (weaved surfaces).

3.2.2 Sequential assembly approach

A second generation of rolling assembly elements is based on a sequential assembly logic through which elements join together in a specific order one after each other. With every new element added to the assembly, new rotational directions are unlocked while others are deactivated. The sequential assembly of different shapes is locked and released by one single key responsible for immobilizing all possible translation directions (Wangler et al. 2019). Each element has two states: attached and detached (on/off). The curved corners of the elements allow for rolling movement in certain positions. The topology of the element and the assembly sequence control the interlocking. The elements are different. The assemblies are designed to be finally locked in a solid composition by adding the last keyelement (Fig. 8). The sequential (dis)assembly has only one single fixed order. In a digital simulation, weights could be assigned to (solid/hollow status) to test the motion behavior (Fig. 10). (See also Sec. 3.4.)

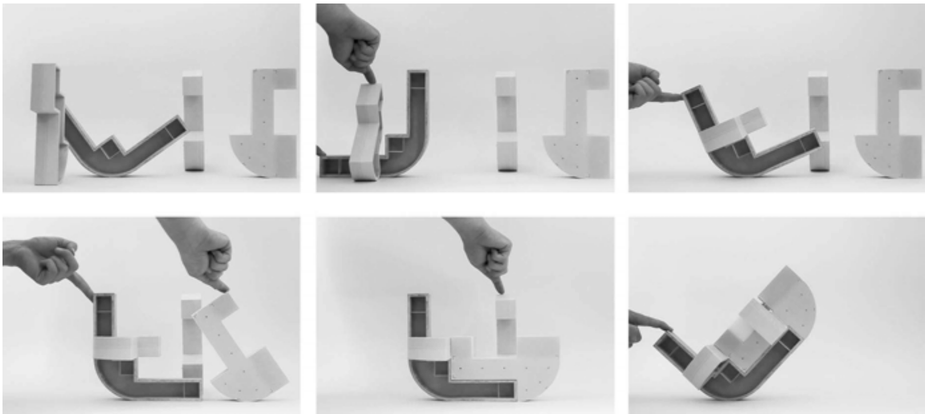

Fig. 8: The assembly sequence of elements. After adding the key element, the topological-interlocking principle holds all the parts together during the motion.

3.3 RotoForm, robotic sequential casting

The rotoforming process is iterative for several material layers, the material quantities and qualities allow for a differentiation of the layers. Using a six-axis robotic arm as a RotoForm-machine, the robotic trajectory and rotation velocity enable varying thickness of a layer in different positions (Mehdizadeh et al. 2022) (Fig. 9). We use these two parameters for programming the material (weight) distribution inside the hollow elements. Subsequently, we can manipulate the CoM (Mehdizadeh 2023) and activate the kinetic behavior of the elements through this technique.

3.4 Weight distribution inside Hollow elements

Initial activation energy is required for the guided self-assembly with hollow-concrete elements. This proposal conceives the activation energy applied by a human agent, as it is meant to offer physical affordance for reconfiguring architectural assemblage through its users. To minimize the initial activation energy for assembly, we aim for a specific position of CoM and optimize the weight distribution inside the elements. For the digital optimization algorithm, we voxelize the designed element and define each of the voxels in two categories, solid and hollow, and assign a certain weight to each

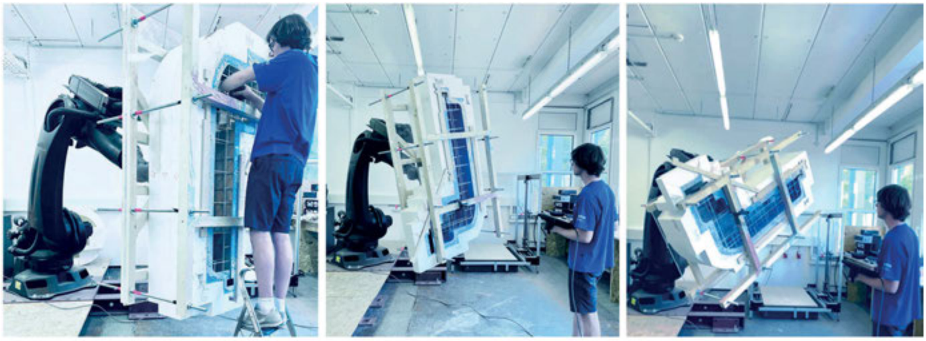

Fig. 9: Robotic sequential casting (RotoForm) of 1:1 hollow concrete element. Left: adding the calculated amunt of casting material to the formwork. Right: the robotic arm rotates the formwork to distribute the material alng the desired trajectory.

voxel. Increasing the resolution of voxels in the digital simulation model increases the simulation accuracy. The average Vector in the middle of the touching surface on the ground is the equilibrium axis (EA). To have a stable element status (in equilibrium), the total weight amount multiplied by its distances to EA should be equal on both sides of the EA. The optimization algorithm aims for the equilibrium of the element in the desired position and assigns the weight to voxels to reach the goal. After the optimization phase, we run a rigid-body simulation to track the motion of elements from any position to the stable status using Nvidia-PhysX inside the CAD environment. Rhino/Grasshopper.

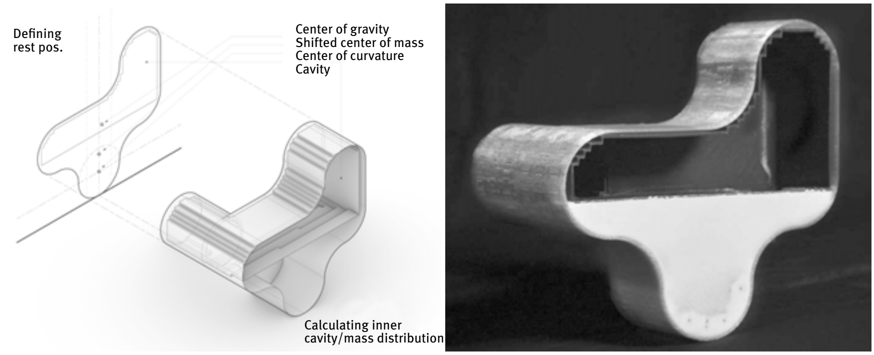

Fig. 10: Left: voxel-based optimization of weight inside the elements, right: physical prototype with 3D printed cavity.

4 Results

The continuous digital workflow from assembly motion design to robotic fabrication, allows for fabrication-aware design. Recursive interlocking architectural assemblies could become a principle for reversible, dry-joint, and circular constructions. The rotational interlocking mathematical model is the optimal solution for dry joinery of the elements that assemble through rolling (not the transitional directions) and results in a solid connection between the elements (Fig. 11). Rotoforming allows materializing the prototypes in 1:1. To evaluate the results; we used a four-dimensional survey method to track the motion of the physical prototypes and compare them with the digital simulation (Mehdizadeh 2023).

The comparison between the motion track data and rigid-body simulation illustrates the following points:

(a) Rotoforming with a robotic arm allows for precise positioning of the CoM inside the concrete elements.
(b) Manipulating the CoM allows for programming the motion behavior of elements as in simulation.
(c) Adjusting the global equilibrium of assembly clusters allows for levering and moving more elementsonce they are attached.

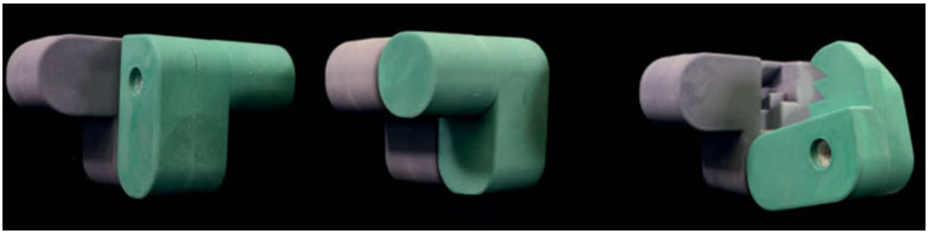

Fig. 11: Physical Prototypes of Hollow element with a rotational interlocking system in 1:10 Scale.

5 Conclusion

The research "Animate Concrete" contributes to circular approaches in design and "design for reuse" by providing a design framework for guided self-assembly and reassembly (Fig. 2). Moreover, using the robotic sequential casting method (RotoForm) reduces material consumption significantly. This study demonstrates the potential of embedding kinetic behavior and assembly information in hollow concrete elements by manipulating the physical and geometrical attributes of elements. This study shows that large-scale hollow concrete elements with particular weight distribution can be easily moved, lifted, and mobilized through a gentle touch of a human. The simulation results address the great potential of applying Nvidia-PhysX on different digital programs within the CAD environment Rhino/Grasshopper to increase the calculation efficiency. Designing assembly motion is uncommon in architecture and construction, as architects and structural engineers have rigid and stable tectonics.

6 Future works and outlook

Future studies will integrate structural analysis to analyze the load-bearing capacity of reinforced hollow concrete elements and the dry-joint solid connection between the concrete elements. The hollow concrete elements are slightly sliding on the ground when moving them. This issue decreases the accuracy of assemblies and should be solved in the following steps. Therefore, Digital material characterization and a finite element model analysis are necessary for the high-precise simulation of contact-rich and friction-fit connections. A study on environmental impact, reusability and a life cycle analysis (LCA) model for assessing the hollow concrete elements is our targeted next step.

A significant finding in this research was the ability to adjust the cluster's global CoM, which enables it to leverage the assembly's weight and move larger assemblies from horizontal to vertical status (Fig. 8. bottom right) (much like self-erection Tower cranes) (Dehlsen and Mikhail 2005). We illustrate this possibility as our next stage to lift gigantic assemblies through the same technique (Fig. 12).

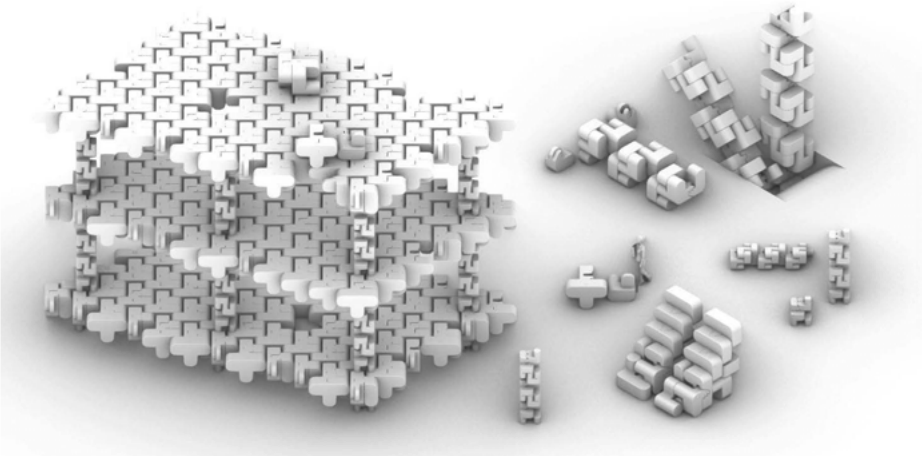

Fig. 12: A visionary visualization of various assemblies as a building system.

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