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Design-to-Fabrication of Hyperbolic Arch Module Using Recycled Concrete Rubble and Robotic Assembly

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Abstract

Recycled concrete rubble from demolition waste offers considerable potential to reduce construction-related carbon emissions, divert mineral waste from landfill, and advance circular material practices. However, its direct structural reuse remains limited by material heterogeneity, uncertain mechanical performance, and the absence of construction methods capable of accommodating irregular geometries. Consequently, most concrete waste is downcycled into aggregate through energy-intensive processing. This paper presents an integrated design-to-fabrication framework for the automated assembly of the first full-scale module of a reconfigurable hyperbolic arch system using recycled concrete rubble, robotic placement, and a reusable sand-based support substrate. The study is based on a 1:1 target hyperbolic arch geometry with a span of 1.8 m and a height of 1.0 m, while the present fabrication focuses on the first module/segment as a proof-of-concept test. The fabrication process consists of robotic layer-by-layer shaping of a recyclable sand support, followed by the placement of recycled concrete rubble and the application of high-performance mortar to form a load-bearing prototype module representative of the larger arch system. Unlike conventional formwork-dependent construction, the proposed method uses temporary granular support that can be removed and reused after curing, thereby reducing waste and accommodating material irregularity. The study combines material assessment, geometric rationalization, robotic fabrication planning, and full-scale module-level testing. The results indicate that irregular recycled concrete rubbles can be reorganized into a structurally coherent module-level compression-dominant assembly through an appropriate fabrication logic.

Keywords: robotic assembly, recycled concrete rubble, hyperbolic arch, support-free manufacturing, circular economy.

1. Introduction

The construction industry is both a major consumer of raw materials and a major producer of waste [1], [2]. Concrete rubble constitutes a substantial share of construction and demolition waste, yet it is typically crushed into recycled aggregate rather than directly reused in structural applications. Although aggregate recycling diverts waste from landfill, it also reduces the dimensional and material value of larger rubbles and requires additional processing[3], [4].

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Figure 1: Concrete recycling factory located in Shenzhen, China. The image illustrates the prevailing treatment process of construction and demolition concrete waste. Source: Author.

Direct reuse offers a more value-retentive alternative, but its application to recycled concrete rubble remains limited [5]. The principal obstacle is irregularity: rubble vary in size, geometry, density, edge condition, and residual strength, making them difficult to standardize, assemble, and predict structurally [6]. This challenge suggests that the reuse of rubble cannot rely on conventional construction logic based on uniform components. Instead, it requires fabrication systems that can accommodate variation while maintaining geometric and structural control. Robotic fabrication provides a promising basis for such systems. Robots can execute customized placement operations with high repeatability and are therefore well suited to non-standard materials [7]. At the same time, computational design enables geometries that are structurally efficient and fabrication-aware [8]. Among these, arches are particularly relevant because they are compression-dominant and therefore compatible with rubble–mortar assemblies, whose tensile and interfacial behavior may be less reliable than their compressive resistance. Hyperbolic arch geometries further offer geometric stiffness and formal adaptability, making them a useful testbed for robotic construction with irregular materials.

This paper investigates the automated assembly logic for a hyperbolic arch system using recycled concrete rubble and a reusable sand-based support system, with the present study focusing on the first full-scale module of a 1:1 arch as an initial demonstrator. In the proposed workflow, a robot first shapes a granular support bed according to a predefined digital model. Recycled concrete rubble are then placed and bonded with high-performance mortar to form a continuous load-bearing structure. After curing, the sand is removed and reused. The method eliminates the need for rigid bespoke formwork while accommodating irregular geometry during assembly.

The study has four objectives: to assess the material feasibility of rubble-based composite construction; to develop a robotic workflow for the fabrication of a first full-scale module derived from a 1:1 hyperbolic arch geometry; to evaluate the fabrication feasibility and local structural behavior of this prototype module through full-scale testing; and to discuss the implications of this system for circular construction and robotic assembly with reclaimed materials. The contribution of the paper lies in integrating recycled concrete rubble, robotic placement, reusable granular support, and module-scale physical testing within a single design-to-fabrication framework for future hyperbolic arch construction. In doing so, it positions demolition rubble not as a residual waste stream, but as a non-standard construction resource with architectural and structural potential.

2. Literature review

2.1. Recycled concrete rubble and circular construction

Construction and demolition waste is a major challenge in sustainable building, with concrete representing a large share of this waste stream [3]. Most existing research focuses on crushing demolished concrete into recycled concrete aggregate for new concrete production. Although effective for waste diversion, this process requires significant reprocessing and often reduces material quality and

value [3]. From a circular economy perspective, it is therefore closer to downcycling than high-value reuse. Direct reuse offers a more value-retentive alternative by preserving larger rubble with minimal transformation. However, direct reuse of concrete rubble remains limited because rubble are irregular, non-standard, and difficult to assess, represent, and assemble [4]. To make such reuse viable, new frameworks are needed that combine material evaluation, geometric classification, and construction logic. Recent studies suggest that digital tools and robotic fabrication may help address these challenges, but applications at the scale of real structural prototypes remain rare. This study contributes by testing an integrated workflow for reorganizing concrete rubble into a structurally legible system.

2.2. Robotic construction with irregular materials

Robotic construction is particularly relevant to irregular and reclaimed materials because it can manage component-specific variation rather than relying on standardization, existing research has explored strategies such as scanning individual elements, computational matching, and robotic placement of non-standard parts[9], [10], [11]. These studies show that digital and robotic systems can support coherent assembly from irregular materials. However, much of this work remains focused on fabrication process and formal demonstration, while structural performance is less thoroughly examined. A key challenge is therefore not only whether robots can place irregular rubble, but whether the resulting assemblies can function as credible architectural systems. This study addresses that gap by linking robotic construction with structural logic and prototype evaluation.

2.3. Arches as compression-dominant systems

Arches are well suited to reused rubble because they transfer loads primarily through compression rather than tension[12]. This makes them compatible with brittle and irregular materials whose interfaces and tensile behavior are difficult to control. In rubble–mortar systems, local variability can therefore be accommodated more effectively within a compression-based structural form[13]. Recent advances in computational design and robotic fabrication have renewed interest in arches as efficient geometries for non-standard construction. Among these, hyperbolic arches offer both structural efficiency and parametric adaptability. Despite this potential, their application in rubble-based robotic construction remains underexplored. In this study, the hyperbolic arch serves as the main structural and experimental framework.

2.4. Support-free manufacturing and reusable granular formwork

Support-free manufacturing here refers to replacing conventional rigid formwork with alternative temporary support systems. Traditional formwork for curved structures is often labor-intensive and wasteful, especially for customized geometries. Granular materials such as sand provide a promising alternative because they are inexpensive, reconfigurable, and reusable; unlike rigid molds, sand can accommodate local irregularities and provide distributed support [14], making it suitable for assembling non-standard rubble. This study treats shaped sand not simply as formwork, but as an adaptive and reusable support medium. It supports placement and curing, absorbs geometric discrepancies, and can be removed and reused after assembly. This integration of robotic shaping, granular support, and irregular rubble placement forms a core contribution of the research.

3. Materials and methods

3.1 Research framework

The research framework combines four interrelated parts: material assessment, geometric design, robotic assembly, and structural evaluation. First, recycled concrete rubble and mortar-based specimens were tested to understand baseline mechanical behavior. Second, a hyperbolic arch geometry was defined as the target structure. Third, a robotic support-free fabrication workflow using recyclable sand

was developed for assembly. Fourth, the completed prototype module was subjected to a human-applied incremental loading test to evaluate its local stability, integrity, and deformation response.

3.2 Material system

The structural system consists of two primary material categories: recycled concrete rubble and high-performance mortar. The rubble originates from demolished concrete elements and is used in rubble form rather than being crushed into fine aggregate. This preserves larger pieces and reduces material downcycling. The mortar functions as a binding matrix, filling interstitial voids and creating a composite action between adjacent rubbles. Based on the test reports of project, the mechanical performance of the material system can be summarized as follows: Representative compressive strength of cube specimens: 26.0 MPa; Representative splitting tensile strength: 4.52 MPa; Measured elastic modulus range: 26.8–33.8 GPa. These results suggest that the material possesses basic compressive and tensile resistance but suffers from considerable variability. Accordingly, the prototype was conceived as a compression-dominant arch rather than a flexure-dominant beam or slab.

3.3 Prototype geometry

The target geometry of the overall system is a 1:1 hyperbolic arch with approximate dimensions of span: 4 m and height: 3 m. However, the present study does not fabricate the entire arch; instead, it constructs the first module as 1.8m span of this geometry as a full-scale test unit. The term "reconfigurable" refers to the system's ability to adapt geometric parameters while preserving an underlying assembly logic. In practical terms, the arch can be adjusted in span, rise, local thickness, and rubble distribution strategy according to available rubble pieces and structural requirements. The hyperbolic profile was selected for three reasons. First, it offers a structurally favorable compressive path. Second, it provides a distinctive non-standard geometry suited to robotic shaping. Third, it demonstrates that irregular recycled matter can support formally expressive architecture, rather than being limited to utilitarian applications.

3.4 Robotic support-free fabrication workflow

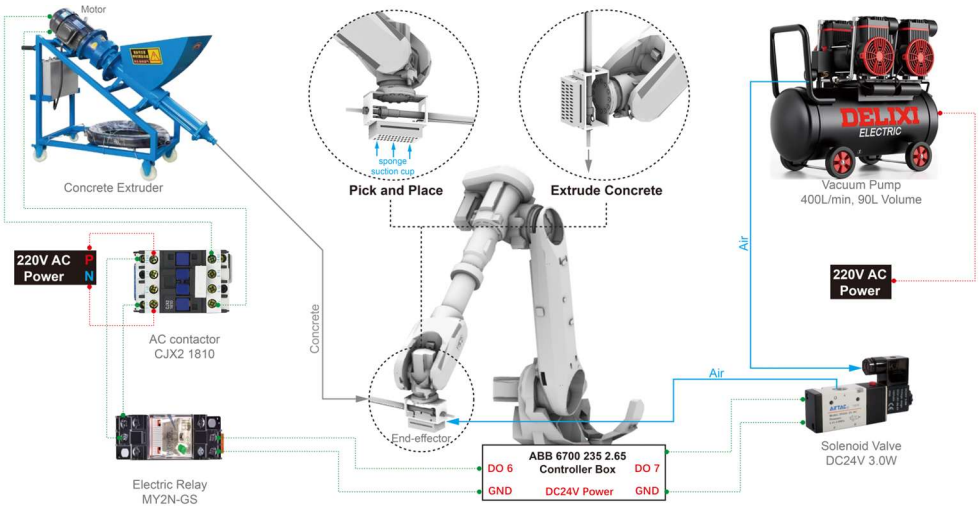


Figure 2: An integrated robotic control system for the assembly of concrete rubble. Source: Author.

The system is centered on the ABB IRB 6700-235/2.65 industrial robot, integrating concrete pumping, spraying, and vacuum suction functionalities, shown in Figure 2. Through precise electro-pneumatic control and standardized construction workflows, it enables the digital fabrication of double-curved concrete arch structures. System employs a hybrid electro-pneumatic control architecture. The controller sends signals through digital output ports (e.g., DO6, DO7) to drive MY2N-GS relays, which in turn

control the switching of DC24V solenoid valves, enabling precise regulation of the pneumatic components on the end-effector. Concurrently, CJX2 1810 AC contactors manage the start/stop operations of high-power equipment such as the concrete pump and vacuum pump. A DC24V power supply provides stable low-voltage current for the controller, relays, and solenoid valves, while a 220V AC power source drives the motor-driven equipment. The fabrication workflow involves the following stages:

The system comprises four main components: robot, the end-effector, the concrete supply module, and the control unit. The robot serves as the core motion execution unit, responsible for carrying the end-effector and moving along predefined trajectories to achieve three-dimensional positioning for the double-curved arch construction. The end-effector integrates two key functions: first, a concrete spraying head, connected to the shotcrete system, which applies concrete uniformly to the designated positions; second, a vacuum suction device, driven by a vacuum pump, used for picking and placing concrete rubble, thereby assisting in the formation of complex curved surfaces. The concrete supply module includes a concrete pump and motor, ensuring continuous delivery of concrete to the spraying head. The control unit comprises a controller, relays, solenoid valves, and AC/DC power supplies, coordinating the synchronized operation of all modules.

a. Digital modeling: a digital model of the target hyperbolic arch system is generated, including overall geometry, approximate thickness, and assembly sequence. Based on this model, the first module is extracted as the fabrication object for the present study.
b. Sand base preparation: recyclable sand is deposited and shaped layer by layer by a robotic arm to create the support geometry corresponding to the underside of the first module of the arch.
c. Rubble placement: recycled concrete rubble are selected and placed onto the sand bed according to the digital model and local fit conditions. Larger pieces are preferentially used in regions expected to carry higher compressive force or require greater geometric continuity.
d. Mortar application: high-performance mortar is introduced between rubble to fill voids, improve contact, and form a cohesive composite body.
e. Curing period: the assembled structure remains supported by sand until the mortar reaches sufficient strength.
f. Sand removal and recovery: after curing, the sand is removed and retained for future reuse. This process is described as support-free manufacturing because it avoids conventional rigid formwork and scaffolding. The support is temporary, loose, and fully recoverable.

4. Results

4.1 Material performance interpretation and digital aggregation configurations

The supplied mechanical test data indicate that the rubble-based material system has moderate compressive capacity and promising splitting tensile behavior, but insufficient consistency for reliable modulus characterization. A representative compressive strength of 26.0 MPa suggests that the material is viable for compression-oriented structures at prototype scale. The splitting tensile representative value of 4.52 MPa indicates that the mortar-rubble composite may retain useful crack resistance, possibly through mechanical interlocking and frictional engagement between rubbles. These material characteristics directly informed the structural strategy. Rather than attempting a beam-like system dependent on tensile continuity, the research adopted an arch form where force paths remain predominantly compressive. This decision reflects a core principle of sustainable structural design: the geometry should be adapted to the material's strengths rather than forcing the material into unsuitable structural roles.

The scanning process captures geometric irregularities of each rubble, which are then processed through algorithmic arrangement strategies to optimize spatial fit, stability, and assembly logic in Figure 3.

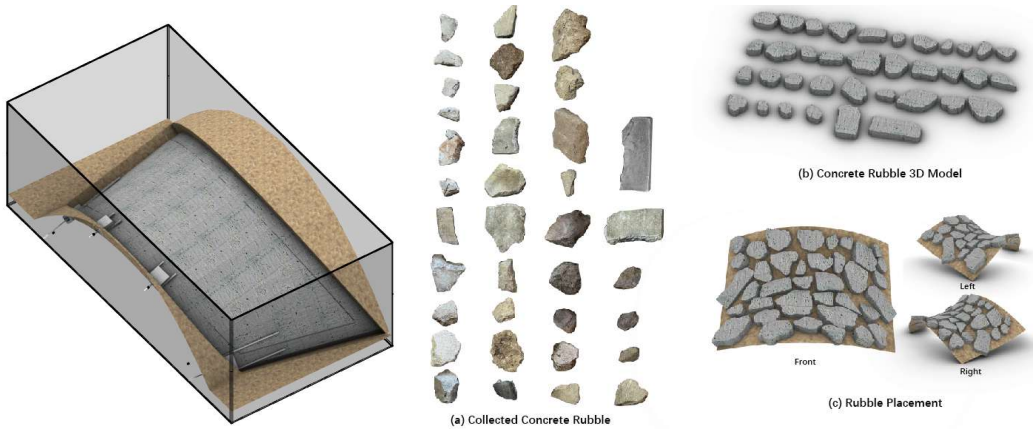


Figure 3:3D scanned concrete blocks and computationally generated aggregation configurations. Source: Author.

4.2 Fabrication observations

The Figure 4 shows the operational interface and hardware configuration enabling synchronized control of suction gripping and grouting mechanisms during robotic assembly of irregular recycled concrete elements.

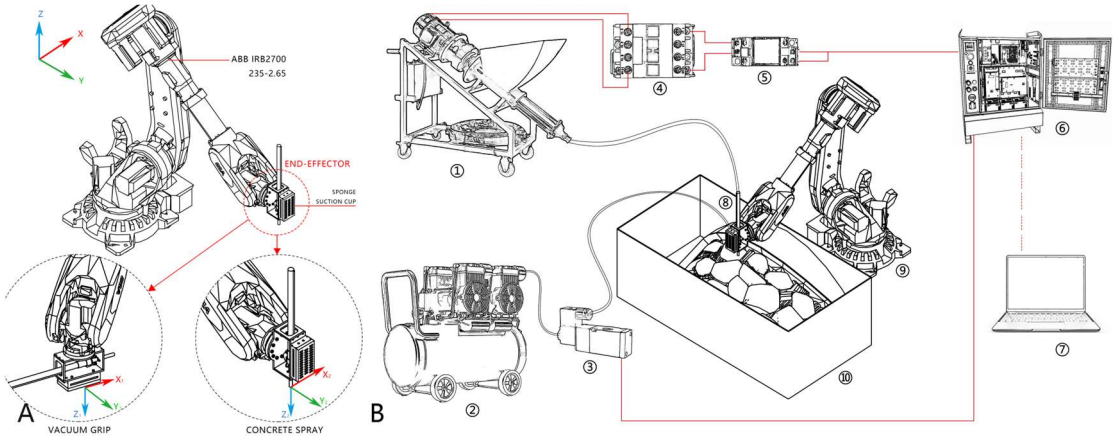


Figure 4: Control system of the robotic end-effector. Source: Author.

The steps are executed cyclically, advancing layer by layer until the target first module of the double-curved arch system is fabricated. During each cycle, the robotic arm precisely controls its motion trajectory and material output volume based on the predefined digital model, guaranteeing the geometric accuracy of the prototype module surface and its correspondence to the target arch geometry. The Figure 5 documents the initial experimental setup and procedural workflow used to evaluate assembly feasibility, structural stability, and material behavior prior to full-scale implementation.

Step 1: Compact Sand: a sand layer is first laid on the foundation bed. A compaction tool or auxiliary device attached to the robotic arm compacts and levels the sand, creating a stable and smooth base for the subsequent upper layers.

Step 2: Spray Concrete and Cover Rubble: the robotic arm, carrying the spraying head, uniformly applies concrete onto the sand bed surface. Simultaneously, crushed stone aggregates are embedded or spread over the fresh concrete layer.

Step 3: Install Joints: joints or nodes are placed at designated positions according to the specific design requirements of the double-curved arch structure.



Figure 5: Preliminary construction testing proces. Source: Author.

Step 4: Pick and Place Concrete Rubble: using the vacuum suction or gripping mechanism of the end-effector, the robotic arm accurately picks up and places concrete rubble or blocks at their designated positions, gradually forming the primary structure of the prototype module.

Step 5: Fill in the Gap: after the placement of the rubble, any remaining gaps between the blocks are filled with concrete. The robotic arm switches to its concrete spraying mode, uniformly injecting fine-aggregate concrete or mortar into the gaps, ensuring the overall structural continuity and compactness.



Figure 6: Preparation of the sand base and placement of concrete rubble. Source: Author.

After assembly positioning, concrete was poured to secure the components, then left to cure for three days before demolding and removal from the base, shown in Figure 7. The robotic shaping of the sand base proved critical to the success of the assembly process.



Figure 7: Concrete casting and curing process. Source: Author.

Because the arch geometry is non-standard and spatially curved, manual preparation of a precise temporary support would have been laborious and inconsistent. The robot-enabled layer-by-layer shaping approach ensured repeatable control over the support profile and reduced geometric error during the placement of rubble. The use of recyclable sand as a temporary support medium provided several practical benefits. It accommodated minor deviations in rubble shape, distributed support evenly during mortar curing, and could be easily removed without damaging the structure. This approach also reduced

dependence on custom timber or foam formwork, thereby reinforcing the circular logic of the system. The Figure 8 shows the completed modular unit, demonstrating the integration of reclaimed concrete blocks and cast connections.



Figure 8: Final appearance of the first constructed module after curing and extraction. Source: Author.

Placement of recycled concrete rubble revealed both the potential and limitations of the material. On the one hand, rubble irregularity increased interlocking opportunities and gave the assembled arch a robust tectonic character. On the other hand, piece selection and orientation remained highly consequential. Regions with better rubble fit required less mortar and appeared more coherent, whereas poorly fitted regions relied more heavily on the binder matrix and exhibited greater vulnerability to local discontinuities.

4.3 Local structural behavior of the prototype module under loading

Under static human loading, the structural response of the prototype module was evaluated in terms of local stiffness and assembly integrity rather than global arch thrust behavior. Four adults applied a combined load of approximately 300 kg (≈3 kN). No visible displacement, cracking, or differential settlement was observed during loading. The module maintained geometric stability and exhibited compression-dominated behavior, indicating effective load transfer across rubble–mortar interfaces. As this experiment was conducted on a single full-scale module without instrumentation, the results should be interpreted as a qualitative validation of segment-level constructability and local structural coherence, rather than a quantitative assessment of ultimate capacity. Nevertheless, the test confirms the feasibility of the assembly logic and the compatibility between robotic placement, reusable sand support, and rubble-based composite construction.

5. Discussion

5.1 Why the system works and the role of robotics in circularity

The viability of the proposed arch system arises from the alignment of three elements: material logic, structural logic, and fabrication logic. The material logic recognizes that recycled concrete rubble is irregular and mechanically variable. The structural logic responds by selecting an arch form that privileges compression over tension. The fabrication logic introduces robotic shaping and temporary granular support to manage geometric complexity and construction uncertainty. The system works not because the material becomes standardized, but because the design framework is tailored to the

material's actual nature. This point is important in the broader discourse on circular construction. Too often, waste materials are judged by their ability to imitate virgin industrial products. In contrast, this study demonstrates a different path: instead of forcing rubble to behave like standardized aggregate or modular block units, it is assembled as a discrete, irregular, yet structurally legible composite. Such an approach preserves more of the material's embodied value and opens new formal and tectonic possibilities.

Robotics does more here than automate labor. It acts as an enabling interface between digital geometry and non-standard materiality. The sand-shaping operation, in particular, shows how robotic precision can support circular construction even when the final structural material itself is irregular. This hybridization is significant. It suggests that high-tech fabrication and low-value waste streams are not opposites, but potentially complementary components of a new construction ecology. Moreover, robotic workflows can eventually be extended to include scanning, rubble classification, grasp planning, and adaptive placement. Such developments would further increase the structural reliability and scalability of rubble-based construction.

5.2 Limitations

Several limitations must be acknowledged. First, the current study is focused on a single prototype geometry. Although the system is described as reconfigurable, broader parametric validation across multiple spans and rises remains to be done. Second, the human-applied loading protocol, while practical and relevant, provides only relatively low load magnitudes compared with machine-based testing and does not fully characterize ultimate capacity. Third, long-term durability issues such as shrinkage, moisture cycling, freeze-thaw behavior, and fatigue were not addressed in the present scope. Most importantly, the present study does not constitute a full structural validation of a complete hyperbolic arch. It tests only the first 1:1 module, and therefore the conclusions are limited to fabrication feasibility, material compatibility, and local structural behavior at the segment scale.

5.3 Future work

Future research should proceed along at least four directions. First, the rubble selection process should be improved through digital scanning and classification to reduce assembly variability. Second, numerical modeling should be developed to simulate thrust paths, contact behavior, and potential failure modes in rubble–mortar arches. Third, more refined displacement measurement techniques such as digital image correlation or marker-based photogrammetry should be introduced during loading. Fourth, the system should be tested at larger scales and under environmental exposure to evaluate its potential for semi-permanent or permanent architectural applications.

6. Conclusion

This paper presented an integrated framework for the automated assembly of reconfigurable hyperbolic arch systems, validated through the fabrication of the first full-scale 1:1 module using recycled concrete rubble, high-performance mortar, robotic sand shaping, and support-free manufacturing principles. The study responds to a key challenge in circular construction: how to transform irregular demolition waste into structurally meaningful architecture without excessive reprocessing. In response to this material condition, a compression-dominant hyperbolic arch was selected as the target structural typology, and its first module was fabricated as a full-scale demonstrator. Robotic layer-by-layer shaping of a recyclable sand base enabled precise support generation for assembly without rigid formwork. Recycled concrete rubble were then integrated with mortar to form a cohesive prototype module representative of the broader arch system. More broadly, the research suggests that circular architecture should not be limited to substituting recycled content into conventional building products. Instead, it can involve the invention of entirely new design and assembly logics in which irregularity becomes a generative condition rather than a defect. Within this perspective, robotic assembly is not merely a tool of efficiency,

but a mediator capable of reconciling material unpredictability with structural and architectural intention. The proposed first-module prototype of the hyperbolic arch thus operates both as an experimental construction unit and as a conceptual argument for the future of automated circular construction.

Acknowledgements

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