Philippe Block, Matthias Rippmann and Tom Van Mele

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Bottom-Up Performance for a New Form of Construction

Block Research Group/ETH Zurich with Ochsendorf DeJong & Block Engineering and the Escobedo Group, Armadillo Vault, 'Beyond Bending', Venice Architecture Biennale, 2016

Comprising 399 individually cut limestone pieces, unreinforced, assembled without mortar, and proportionally half as thin as an eggshell, the Armadillo Vault's funicular geometry allowed it to stand in pure compression.

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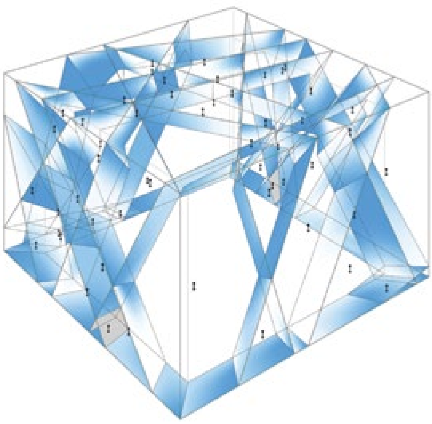
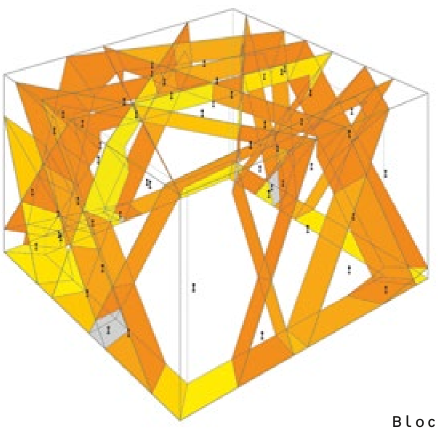
From Inuit igloos to Roman arches to Gothic cathedrals, builders have long used friction and balance to make structures hold together. The Block Research Group at ETH Zurich is involved in ongoing research that investigates historical techniques and fuses them with the latest technologies, including robotics and 3D printing, to establish new methods of architectural assembly. Group founder **Philippe Block**, co-director **Tom Van Mele** and team member **Matthias Rippmann** explain.

In distributed structures such as the Roman arch, components work together collectively to create a stable whole. Remove one component and the entire structure collapses. Each part is essential to the achievement of something greater – truly the sum of its parts. This form of bottom-up performance presents opportunities beyond traditional hierarchical structural systems to develop new forms of construction and to introduce alternatives to steel, concrete or timber.

The ongoing work by the Block Research Group at ETH Zurich revisits historical references and technologies to demonstrate that paradigm-shifting innovations can be achieved with distributed structures such as discrete-element assemblies by favouring compressive flows during and after assembly. It shows that the logic of compression-only geometry provides the opportunity to minimise or even totally eliminate falsework, simplify connection details, use weak materials, and fully embrace novel fabrication technologies such as 3D printing to significantly reduce the energy embodied in constructions.

As an extreme example of these principles, the Armadillo Vault, part of the 'Beyond Bending' exhibition by the Block Research Group with Ochsendorf DeJong & Block Engineering and The Escobedo Group at the Venice Architecture Biennale in 2016, defies the commonly assumed limitations of masonry and stone engineering and, by extension, the geometric limitations associated with discrete-element structures.[1] However, realising the shell required extensive falsework. To fully exploit the potential of discrete structural systems in pure compression and to clarify opportunities beyond their literal application in masonry, construction logics, sequencing and optimisation therefore need to be addressed.





Block Research Group, Discrete-element assemblies, Institute of Technology in Architecture, ETH Zurich, 2015

Surprising discrete-element assemblies can be designed by controlling the location and orientation of the interfaces between the elements; for example, an unreinforced, 'vaulted' box standing only due to compressive and frictional contact forces.

Reducing Falsework

Discrete elements such as bricks or stone blocks can be assembled into stable structures without mechanical connections or 'glue' at the interfaces, not only through the formation of arches, but also by using friction and/or corbelling or balancing. When fully embracing all of these structural actions, even a box can become a 'vaulted', unreinforced discrete assembly.[2] Furthermore, in combination with informed construction logics, falsework for these kinds of assemblies can be reduced or even eliminated. An igloo, for example, can be built without a supporting structure by cutting the ice blocks so that they can be placed in a spiralling sequence. Masonry domes can also be built without falsework by working in stable sections; with every completed ring of bricks, the structure is stable, and during construction of the ring the mortar's adhesion prevents the individual bricks from sliding.

For geometries that cannot be built using a spiralling or circular logic, Gothic builders developed systems using ropes, counterweights and pulleys to assemble and construct vaults with minimal supports, effectively cantilevering out in space, providing temporary reaction forces with the ropes.[3] Similar approaches could theoretically be extended to the construction of discrete, 'freeform' shell structures, using only a finite number of hooks and anchor points.[4] Although this solution is perhaps a bit optimistic and/or academic, the relevance of such research lies in finding strategies and optimisation algorithms to assemble discrete structures with the minimum amount of support or, even better, with only a few 'helping hands'.

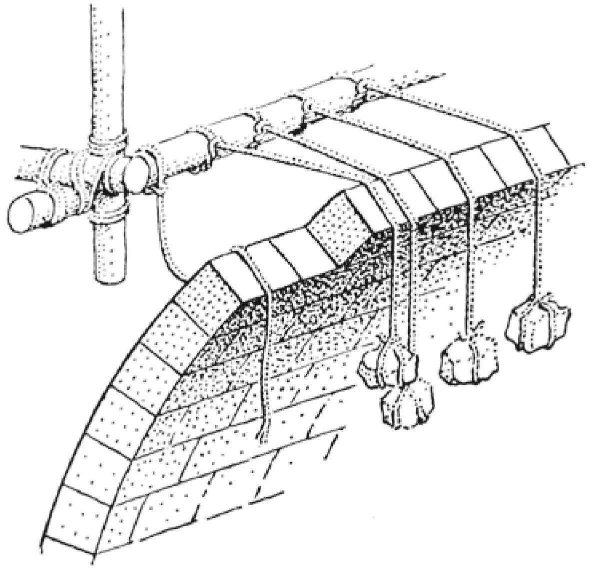
Taking this literally, the Block Research Group, in collaboration with the Autonomous Systems and Robotic Systems Labs at ETH Zurich, is investigating how complex discrete-element structures and aggregations can be assembled using only two robotic arms. These provide intermediate support where needed to maintain stability at each stage of the build until the assembly is completed. The objective of these robotic, 3D-puzzle-building exercises is to discover surprising new masonry forms and to develop efficient ways to build them with only temporary supports. In addition, the obtained knowledge can be used to optimise the construction sequence of, for example, large-scale shell roofs such that they can be safely installed from large pieces without falsework and using only a limited number of cranes on site.

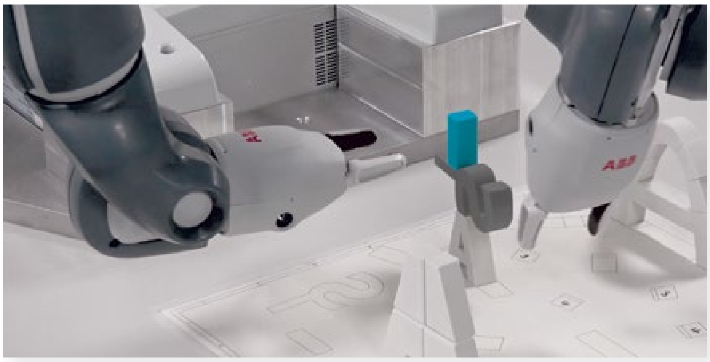
The cupola of the Sports Palace in Tbilisi, Georgia, for example, was erected in 1961 by the alternating placement of precast modules with custom, stepped-element geometries according to a specifically designed assembly sequence. The structure, with a span of over 75 metres (246 feet), could therefore be constructed without scaffolding or falsework using only two cranes placed inside the building.[5] Although the cupola has a simple domical shape, it serves as an inspiration for how smart construction logics could be applied to more complex architectural forms to optimise the erection process.

If discrete-element assemblies are designed to have only compressive and frictional contact forces at the interfaces between the discrete parts, the assembly process can be further simplified by designing the interfaces or even the entire parts so that they facilitate building in stable

John Fitchen,
System of ropes and counterweights,
1981

Gothic builders reduced the need for falsework by using a system of ropes and counterweights. From John Fitchen, *The Construction of Gothic Cathedrals: A Study in Medieval Vault Erection*, University of Chicago Press, 1981.





Autonomous Systems Lab,
Robotic Systems Lab and
the Block Research Group,
Robotic Discrete
Assemblies, National
Centre of Competence in
Research – Digital
Fabrication,
ETH Zurich,
2016

Robotic assembly of a discrete model structure using two collaborative robotic arms to temporarily support and position block elements until a new equilibrated configuration is formed.

sections with little or no temporary support required. They can be designed, for example, to be self-registering to simplify placement and alignment of the discrete elements. Furthermore, their geometry and/or that of their parts can be tailored to prevent local sliding failure and to guarantee stability in intermediate construction states, without the need for mortar or other forms of 'assembly glue'.

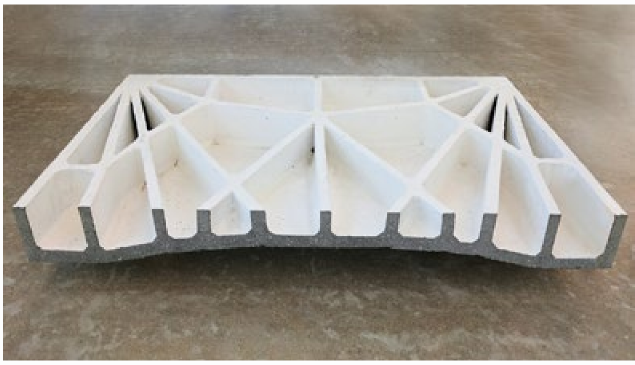
Controlling Force Flow

Following the geometry and logic of compressions, to design and discretise structures results in low stresses and therefore allows for the use of less, and even weak, material: more specifically, materials that take (humble amounts of) compression, but no tension or bending, such as stone, brick, unreinforced concrete, adobe, compressed soil and recycled waste. It also enables the removal of (steel) reinforcements, which are subject to corrosion and/or fire damage, and therefore contribute to the detriment of many structures. This presents opportunities in developing or generally resource-constrained environments where high-performance materials are often unavailable.

By 'pre-cracking' these structures to create hinges that determine the location of thrust lines in all load cases, their behaviour can be dictated further to avoid bending at all times. This principle was used, for example, by Robert Maillart when designing the Salginatobel Bridge (1930) in Schiers, Switzerland, as a three-hinged arch. Otherwise, the state of the structure is indeterminate and per definition unknown to the designer. In a manner of speaking, the structure will decide how it stands and will develop cracks accordingly in zones of tension. This is exemplified by the large radial cracks in the Pantheon in Rome,[6] or in the microcracks that develop in beams subjected to bending to activate the tensile reinforcements.

Embracing New Fabrication Technologies

The significant potential material savings achievable through the logic of compression is demonstrated in an unreinforced concrete funicular floor developed by the Block Research Group. With a 2-centimetre (0.8-inch) thick stiffened shell, the floor required 70 per cent less material than a conventional floor slab and thus resulted in a weight reduction on the beams, columns and foundation.[7] Cavities between the shell and the stiffeners can also be used to embed low-energy heating and cooling, media and other services in places that would typically be filled up by material (in conventional systems).[8] Therefore, by integrating functions into the floor rather than layering them on top, the height of the floor can be reduced significantly. In certain contexts this results in one building level gained for free every three to four floors.[9] However, the prefabrication of this optimised structural geometry is expensive, requiring the making of double-sided moulds and therefore limiting the application to a repeated-unit or modular system.



Block Research Group,
Unreinforced concrete floor,
Institute of Technology in Architecture,
ETH Zurich,
2013

Cross-sectional cut of the unreinforced concrete floor system with a thickness of only 2 centimetres (0.8 inches) for spans up to 6 metres (19.7 feet).

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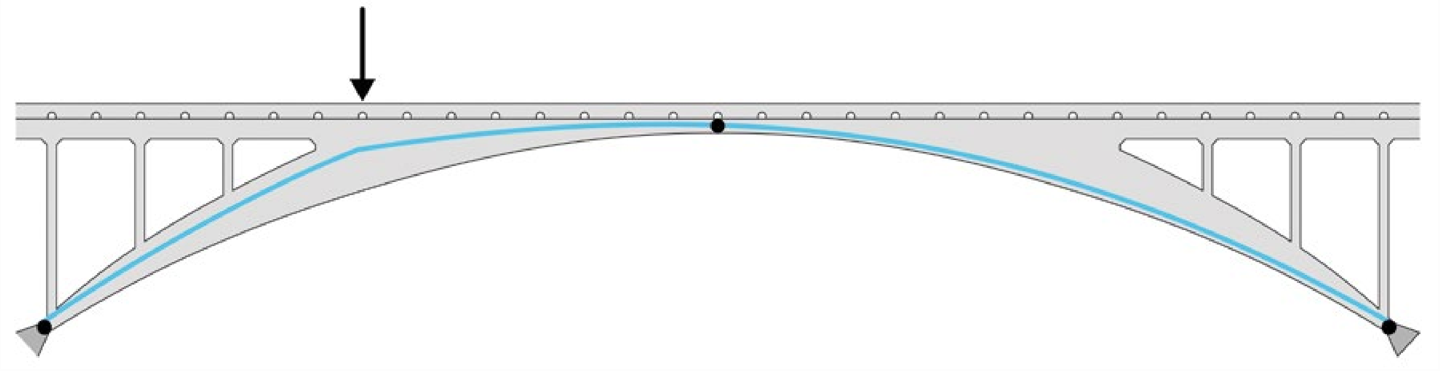
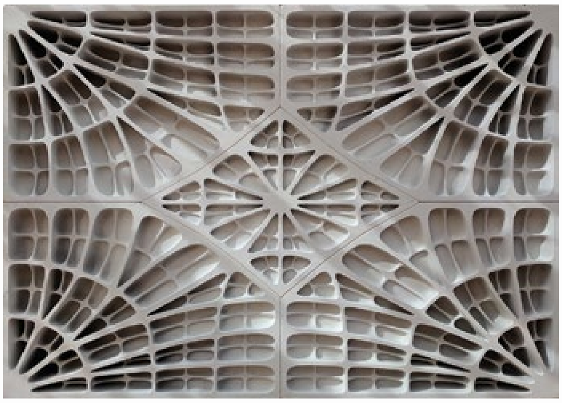


Robert Maillart,
Salginatobel Bridge,
Schiers,
Switzerland,
1930

The bridge was designed as a three-hinged arch to determine the location of thrust lines in all loading cases, and thus control the compressive force flow. Redrawn by the authors/Block Research Group.

In comparison, powder-based 3D printing has several advantages: it is bespoke; it does not require a mould, making it possible to print cantilevers, undercuts and so on; and it is highly precise, with a resolution literally that of a grain of sand. However, this method also brings limitations. It is challenging to integrate reinforcement, and the current maximum print size is 4 x 2 x 1 metres (approximately 13 x 7 x 3 feet). Furthermore, the printing materials are weak, with acceptable compressive strength but negligible bending capacity. As discussed above, these apparent constraints can be avoided through the use of funicular geometry and by designing pre-cracked structural systems with discrete parts.



Block Research Group, Ribbed 3D-printed floor, Institute of Technology in Architecture, ETH Zurich, 2016

The unreinforced, structural floor consists of five discrete elements with externalised tension ties. The rib pattern and discretisation layout are aligned with the 'force flow'. Male–female interlocking features on the interfaces guarantee proper alignment between neighbouring elements.

Further Potential

The concepts presented here are thus a perfect match for new fabrication technologies such as 3D printing, since complex structural components shaped by the local force flow and sophisticated, stereotomic interfaces can be printed to the highest precision. Additionally, and with the same effort, the integration of other functions and media is possible, and material can be carefully placed for room and vibro-acoustical performance and optimisation.[10]

If we are able to make 3D-printing materials safer and more eco-friendly, the results could lead to a significant reduction in the carbon footprint of our buildings and a potential paradigm shift in the construction industry. Floors would become much lighter and more compact, include integrated features, demonstrate higher comfort, and even be more aesthetic and longer lasting.

Research on the design and development of discrete-element assemblies acting predominantly in compression also creates possibilities for the development of self-supporting, stay-in-place formworks, for example for concrete surfaces and spatial structures without the need for scaffolding (and therefore foundations) to support the wet concrete.

Employing a 'masonry model' as the underlying structural principle thus not only provides the opportunity to reduce or even totally eliminate falsework, even for non-funicular final geometry, but also to optimise construction processes in general, and to discover structural applications for new technologies. ⅅ

Notes

1. See Philippe Block *et al*, 'Armadillo Vault: An Extreme Discrete Stone Shell', *DETAIL*, 10, 2016, pp 940–42; Matthias Rippmann *et al*, 'The Armadillo Vault: Computational Design and Digital Fabrication of a Freeform Stone Shell', *Advances in Architectural Geometry*, 2016, pp 344–63; and Philippe Block, Matthias Rippmann and Tom Van Mele, 'Structural Stone Surfaces: New Compression Shells Inspired by the Past', in Achim Menges, *ⅅ Material Synthesis: Fusing the Physical and the Computational*, September/October (no 5), 2015, pp 74–9.
2. Ursula Frick, Tom Van Mele and Philippe Block, 'Decomposing Three-dimensional Shapes into Self-supporting Discrete Element Assemblies', in Mette Ramsgaard Thomsen *et al*, *Modelling Behaviour: Design Modelling Symposium 2015*, Springer International (Cham), 2015, pp 187–201.
3. John Fitchen, *The Construction of Gothic Cathedrals: A Study of Medieval Vault Erection*, University of Chicago Press (Chicago), 1981.
4. Mario Deuss *et al*, 'Assembling Self-Supporting Structures', *ACM Transactions on Graphics: Proceedings of ACM SIGGRAPH Asia 2014*, 33 (6), 2014, pp 214:1–224:10.
5. DI Kadzhaya, 'Precast Spherical Cupola Roof for Sport Palace in Tbilisi and its Erection by Overhang Method', in *Symposium on Problems of Interdependence of Design and Construction of Large-Span Shells for Industrial and Civil Buildings*, IASS (Leningrad), 1966.
6. Jennifer Zessin, Wanda Lau and John Ochsendorf, 'Equilibrium of Cracked Masonry Domes', *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics*, 163 (3), September 2010, pp 135–45.
7. Andrew Liew *et al*, 'Design, Fabrication and Testing of a Prototype, Thin-vaulted, Unreinforced Concrete Floor', *Engineering Structures*, 137, 2017, pp 323–35.
8. Gearóid P Lydon et al, 'Coupling Energy Systems with Lightweight Structures for a Net Plus Energy Building', *Applied Energy*, 189, 2017, pp 310–26.
9. Arno Schlueter *et al*, '3for2: Realizing Spatial, Material, and Energy Savings Through Integrated Design', *CTBUH Journal*, II, 2016, pp 40–5.
10. Tomás Méndez Echenagucia, Bert Roozen and Philippe Block, 'Minimization of Sound Radiation in Doubly Curved Shell Structures by Means of Stiffness', in Ken'ichi Kawaguchi, Makoto Ohsaki and Toru Takeuchi (eds), *Proceedings of the 2016 IASS Symposium* (Tokyo), 2016.