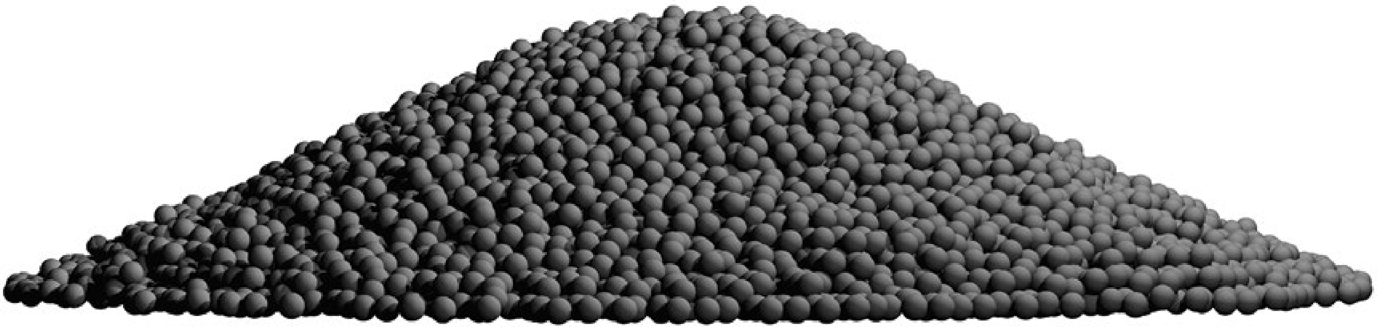
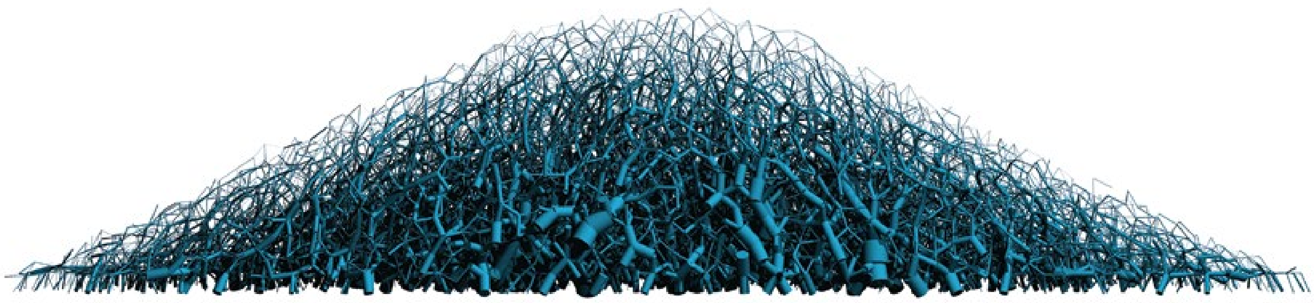


Aleatory Construction Based on Jamming

Stability Through Self-Confinement

Kieran Murphy, Leah Roth and Heinrich Jaeger,
Adaptive granular networks,
JaegerLab,
James Franck Institute,
University of Chicago,
2016

As granular particles are poured into a pile (*above*),
they form and continuously re-form a complex network of contact forces (*opposite*) until a stable configuration is reached.
This simulation of 20,000 spheres grants detailed information about the strength of the local forces,
indicated by the thickness of the lines.



The physical process of jamming could take architectural sustainability/recyclability to a whole new level. It involves achieving structural rigidity through the crowding of particles within a confined space, rather than by permanent bonding. Project Z-Form, a collaboration between a team of physicists from the JaegerLab at the University of Chicago – including PhD students **Kieran Murphy** and **Leah Roth** and professor **Heinrich Jaeger** – and artist **Dan Peterman**, sets out to develop a pourable material that not only self-supports but can also bear loads. Here they explain the project and the concepts behind it.

With traditional building methods, structural stability is attained through detailed preplanning and precise placement of components. Is it possible to engineer a material that can produce its own stability purely through interactions among the constituent parts, without external intervention? Aleatory construction, an emerging approach to this problem, uses randomly assembled elements that autonomously configure to attain loadbearing capability. In physics, the transformation from a loose collection of non-cohesive particles into a disordered solid is referred to as the jamming transition, which describes how micro-scale interactions generate macro-scale rigidity. Generally this occurs through confinement: the available volume is shrunk until there is not enough room for particles to rearrange, and the aggregate locks up spontaneously. The autonomy of this jamming process supplants preplanning, and the democratisation of design at the scale of individual building blocks opens up the potential for adaptability and recyclability beyond traditional methods. At the same time the disorder and configurational ambiguity inherent to jamming serves to introduce structural and textural complexity.

Aleatory construction applies these fundamental principles to designing constituent elements so that the properties of jamming, and thus the stability of the aggregate, emerge via self-confinement. The ongoing work in the JaegerLab at the University of Chicago's James Franck Institute takes these ideas further by removing the need for fastening or bonding agents. The goal has been to identify particle shapes that link to each other solely by friction and geometric entanglement, enabling architectures that can be rapidly deployed by pouring into a mould and easily recycled afterwards to be used anew. In using Z-shaped particles to create basic loadbearing structures such as freestanding columns and arches, the work lays a foundation for further explorations in aleatory architecture.

Jamming as a Route to Rigidity

The idea of jamming is a familiar one in everyday life. Pour coffee beans into a bag and they will flow like a liquid until they settle into a stable yet random arrangement. This configuration is fragile: a squeeze of the bag will easily cause the beans to shift and reconfigure. However, once the particles become just slightly more confined and are given less space for rearrangement, for example upon vacuum sealing, a deeply jammed aggregate is generated that can sustain significant force before deforming.

There are two important points to be highlighted. First, the flowable nature of the unjammed material allows it to be poured, quickly filling arbitrarily shaped volumes. No planning for the placement of the individual elements is needed: after providing an overall form or mould, the specific adjacencies among particles become aleatory – that is, they involve an element of chance. Second, the transition between flowable and rigid states is easily controlled via the degree of confinement. The highly irregular and disordered configuration of the particles causes them to lose their ability to move past one another upon only a slight decrease in aggregate volume, jamming the aggregate and making it rigid to external loads. Once the confinement is removed, the material can flow again and is ready to take the next shape into which it is poured.

Most assembly and construction methods, on molecular as well as architectural scales, create rigidity by carefully bonding together specific subunits. Jamming operates in a fundamentally different way: subunits press against each other due to their randomly generated adjacencies, and rigidity is achieved solely by imposing external constraints on the material as a whole. In granular media, as found in railway beds and harbour breakwaters, the individual subunits

Kieran Murphy,
Leah Roth,
Dan Peterman
and Heinrich Jaeger,
Project Z-Form:
engineered disorder,
Experimental Station/
Peterman Studio,
Chicago,
2016

Z-shaped particles, fabricated from recycled plastic, pour like sand into formwork but jam into a rigid yet highly disordered state. Upon removing the external confinement, a solid structure remains standing, ready to support weight or be recycled and used again.

Herzog & de Meuron,
Gabion wall,
Dominus Winery,
Napa Valley,
California,
1998

View from the interior of the winery. Confinement of granular material by gabions provides a means to create loadbearing walls.

rearrange to balance force and torque autonomously until they jam under their own weight. This allows the jammed granular aggregate to adapt and accommodate significant changes in mechanical load without compromising its integrity.[1]

The vein-like, highly interconnected network of stress paths inside a granular pile demonstrates the origin of this adaptivity: any local rupture in one of the links can easily be taken up by forming new connections that reroute forces through neighbours. Particles throughout the material then rearrange until all movement is arrested. The extreme disorder and heterogeneity that characterises a jammed material at the local scale thus provides an important benefit, namely the ability to rapidly reconfigure and self-heal.

The absence of cohesive bonds between particles also implies that jamming is fully reversible. Jammed granular structures that are quickly and easily deployed, starting by simply pouring the material, come apart equally easily when unjammed. This provides opportunities for creating rigid yet non-permanent structures whose elements can be recycled completely and reused.

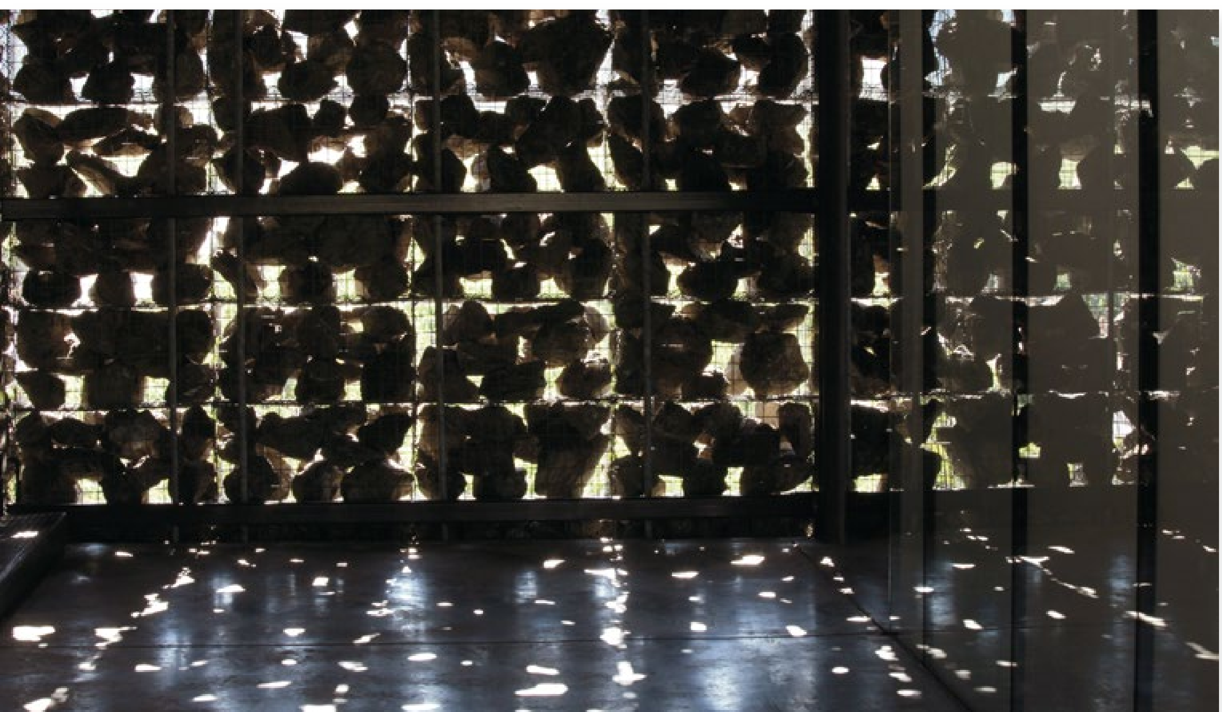
Ulrich Knaack, Tillmann Klein and Marcel Bilow, Vacuum-jammed bridge, Architectural Engineering and Technology, Delft University of Technology, Delft, the Netherlands, 2007

Vacuum-induced confinement of granular packing inside an impermeable membrane can be used to form stable structures such as the footbridge shown here, which was part of the Deflateables project.

Aleatory Architectures

Cohesionless granular materials that are widely available as bulk commodities, such as sand or gravel, offer only a limited range of options for aleatory construction. Without external confinement to contain them or binding agents to provide cohesion, these materials only allow for mild slopes, as in mounds, dams or embankments. This puts severe constraints on the overall form of any structure made from such materials. In particular, it precludes the creation of freestanding structures such as slender vertical columns or arches. To create freestanding structures from cohesionless granular matter, therefore, requires further confinement.

One possibility is the use of a thin, impermeable outer membrane that allows for rigidly jammed forms by vacuum-sealing the interior, as with the coffee beans mentioned earlier. An example is the footbridge constructed as part of the Deflateables project by Ulrich Knaack and his team at the Delft University of Technology. Another option is to confine the loose material by wire cages or gabions, which have been used to construct whole buildings such as Herzog & de Meuron's Dominus Winery in Napa Valley, California (1998). However, the gabions, as well as the footbridge's membrane, play a prominent role both structurally and aesthetically, and they limit reconfigurability and recyclability.



Over the last years several groups of scientists, architects and engineers have developed innovative ideas that can go beyond these limitations, creating initial examples of jamming-based aleatory architecture.[2] Rather than using external confinement, they have explored mechanisms internal to the particle assemblage. Gramazio Kohler Research at ETH Zurich have used string for this purpose. In Rock Print (see pp 82–6 of this issue), a large freestanding structure by Gramazio Kohler Research in collaboration with the MIT Self-Assembly Lab for the Chicago Architecture Biennial (2015), the string is laid in a preprogrammed pattern by a robotic arm and then becomes sandwiched between layers of gravel as it is poured, thereby providing tensile strength.[3] Alternatively, particle shapes that enable neighbours to interlock or entangle can provide autonomous self-confinement, simply through their geometry. Prime examples are the star-shaped particles used by Karola Dierichs and Achim Menges of the Institute for Computational Design at the University of Stuttgart in their extensive work on aggregate architecture (see also their article on pp 88–93 of this issue).[4]

Project Z-Form

A collaboration between physicists in the JaegerLab at the University of Chicago and artist Dan Peterman, who is also on the faculty of the University of Illinois at Chicago, Project Z-Form seeks to engineer a pourable granular medium that both provides its own confinement and is able to bear structural loads. The Z-shape is one of the simplest geometries able to sustain inter-particle tension, torsion, compression and shear. Variations on the prototypical Z-particle were explored in computer simulations designed to measure the resulting aggregate's ability to self-confine and withstand loads, which were then 3D-printed at centimetre scale and tested in the laboratory.[5]

Of all the Z-shapes tested, the non-planar form, with two arms pointing at 90 degrees to each other, exhibited the most dramatic properties. Snapshots from simulations show how these particles interlock, sustaining the tensile forces needed to hold the aggregate together when the column is under axial compression. Movement is frustrated due to these tensile forces and the structure is unable to collapse. From a simple shape thus emerges robust self-confinement.

Though there are multiple particle shapes capable of self-confinement, few are able to withstand additional loads beyond self-weight. Remarkably, instead of weakening under axial load, columns of Z-shaped particles strengthen and jam more deeply. In fact, as long as the column remains under compression – thus staying sufficiently jammed – the particle entanglement is secure enough to allow the entire structure to be picked up and rotated horizontally.

Testing the structural integrity and self-confinement of these shapes on an architectural scale requires larger particles. To this end, Z-forms, each 14 centimetres (5.5 inches) along their length, were cut from planks of recycled post-consumer plastic (PET), then heated and twisted into the non-planar Z-shape. Created by pouring the particles into wooden formwork and consolidating the assemblage by tamping, the jammed structures turned out to be remarkably sturdy and mechanically stiff, as well as capable of bearing significant loads. The special entangling qualities of the non-planar Z-forms lend themselves to assembling arches and spans simply by pouring the particles over inserts embedded within the mould that are later removed. As the inserts are withdrawn, the jammed structure adapts to the changing loading conditions and reconfigures in order to reroute the forces to the legs of the arch.

Kieran Murphy,
Leah Roth,
Dan Peterman
and
Heinrich Jaeger,
Project Z-Form:
strengthening
under load,
Experimental Station/
Peterman Studio,
Chicago,
2016

A column composed of Z-shaped particles, standing without external confinement, is able to support significant axial loads. This structure was assembled by pouring the particles into formwork and tamping to compress the aggregate before removing the confinement.

Kieran Murphy,
Leah Roth
and
Heinrich Jaeger,
Project Z-Form:
geometric entanglement,
JaegerLab,
James Franck Institute,
University of Chicago,
2016

Simulations show how tensile forces can be supported by entangled particles. The column of non-planar Z-forms (*below left*) is unconfined on all sides but the top and bottom, yet it remains rigid and loadbearing due to a minority of particles tugging their neighbours inwards (*below right*).

Kieran Murphy,
Leah Roth
and
Heinrich Jaeger,
Project Z-Form:
3D-printed prototypes,
JaegerLab,
James Franck Institute,
University of Chicago,
2016

below: Experiments with different 3D-printed Z-forms showed that a variant that has its two arms positioned at 90 degrees to each other exhibits surprisingly strong geometric cohesiveness: when assembled into a column, the structure is able to sustain both axial and non-axial loads, as demonstrated here by rotating the column.

Kieran Murphy,
Leah Roth,
Dan Peterman
and
Heinrich Jaeger,
Project Z-Form: arch,
Experimental Station/
Peterman Studio,
Chicago,
2016

above: To create an arch, non-planar Z-forms were poured over a spacer insert in the formwork, which initially supported much of the central weight of the structure. Upon removal, rapid restructuring of the force network occurred, yet the particles remained rigidly jammed and autonomously adapted to the significant change in confinement.

right: Close-up image of the central portion of the arch.

Project Z-Form highlights the subtlety of the structural differences that transform flowing into rigid particle configurations as the jamming transition is crossed. Whereas crystallisation reorganises the disordered internal arrangement of a liquid into the perfectly ordered lattice of a regular solid, jamming transmutes one disordered state into another through changes that are visually imperceptible. In this way, an aleatory construction produced by jamming effectively retains the particle arrangement of its unjammed precursor. The result is the intricate and highly irregular texture of a particle fluid arrested in motion.

The fluid-like particle arrangement in the jammed state suggests precariousness, yet a jammed aggregate exhibits remarkable robustness precisely because of the inherent disorder. By removing a few particles from the structure, material is locally released into its unjammed state. The aggregate flows, rearranges and quickly locks back into place. In this way, the disorder associated with aleatory construction facilitates self-healing.

Reconfigurability and Recyclability

Aleatory architecture subverts the customary hierarchy of design, suggesting a fresh perspective on how one approaches materials and forms. The dialogue between material and function is given a new edge: the architect is able to engineer the mould, but must surrender a certain amount of control and rely on the particles themselves to give shape to the structure. Tension between simplicity and complexity is at the heart of Project Z-Form. The blueprint for this novel building material contains nothing more than the simple, scale-free geometry of a single Z-shaped particle, yet emergent rigidity arises from a complex web of entanglements in the aggregate.

Jamming-based aleatory structures evoke questions not only about the traditional linkage between structural order and mechanical stability, but more generally about the quest for permanence in architecture. Where traditional construction creates resilience and permanence by fastening or bonding together individual building components, jamming uses only geometrical entanglement and friction. This makes jammed structures more transient, and at the same time opens up new opportunities: driving the aggregate back into its unjammed state, by releasing the mechanical load or toppling a column, returns the material to its flowable state, available for immediate reuse. Such recycling makes it possible to reconfigure jammed assemblages, giving them new form or rebuilding them elsewhere.

In Project Z-Form, these ideas assume an additional conceptual role. Fabricating the particles from recycled material mirrors the complete reconfigurability of the structure itself, tying the transition between jamming and unjamming to the changing of forms and states. The dual nature of the particles, composed of a recycled material and also comprising a larger structure that can be fully recycled, points towards a cycle of invention, production and generation with echoes in ecological responsibility and petrochemical dependency. In this way, aleatory architecture is placed prominently into the larger context of a materials life cycle that minimises waste and emphasises reusability.[6] AD

Notes

1. Heinrich M Jaeger, 'Toward Jamming by Design', *Soft Matter*, 11, 2015, pp 12–27.
2. Sean Keller and Heinrich Jaeger, 'Aleatory Architectures', *Granular Matter*, 18, 2016, article 29.
3. Petrus Aejmelaeus-Lindström *et al*, 'Jammed Architectural Structures: Towards Large-scale Reversible Construction', *Granular Matter*, 18, 2016, article 28.
4. Karola Dierichs and Achim Menges, 'Aggregate Structures: Material and Machine Computation of Designed Granular Substances', in Achim Menges, AD *Material Computation: Higher Integration in Morphogenetic Design*, March/April (no 2), 2012, pp 74–81; Karola Dierichs and Achim Menges, 'Towards an Aggregate Architecture: Designed Granular Systems as Programmable Matter in Architecture', *Granular Matter*, 18, 2016, article 25.
5. Kieran Murphy *et al*, 'Freestanding Loadbearing Structures with Z-shaped Particles', *Granular Matter*, 18, 2016, article 26.
6. HMJ acknowledges support from the National Science Foundation through grant CBET-1605075. Project Z-Form was made possible by a grant from the Graham Foundation for Advanced Study in the Fine Arts.