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NEGOTIATING DESIGN & MAKING**

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Fig. 1: Matter Design, *La Voûte de LeFevre*, Banvard Gallery, 2012.



LA VOÛTE DE LEFEVRE: A VARIABLE-VOLUME COMPRESSION-ONLY VAULT

BRANDON CLIFFORD, WES MCGEE

Particle-spring systems are commonly used to develop compression-only form-finding systems. This paper proposes to use a particle-spring system in response to a desired form in order to generate a variable-volume, compression-only structure fabricated of volumetric material. By varying the depth and the volume of the system, loads can be re-directed through the depth of material in order to result in a desired form, as opposed to a structurally optimal form that assumes a uniform thickness approach. This paper proposes to generate, build, and test a compression-only vault composed of variable-volume units. This research will advance knowledge surrounding volumetric physics calculations as well as volumetric fabrication methodologies.

INTRODUCTION

Thin-shell compression-only structural systems are relatively new to the built environment. Compression-only structures, on the other hand, are ancient. Thin-shell structures assume a minimal and consistent cross-section. This assumption is driven by material efficiency. The results are forms developed exclusively by structural concerns (typically gravity), hence the term form-found. Architecture has to respond to structural concerns, but it also has to address a variety of other issues, e.g. acoustical, formal, programmatic, etc. It is not necessary for form to be driven strictly by structural requirements. For example, Gothic cathedrals contain the thrust-vector within the variable depth of the stone's cross-section. These cathedrals are not determined by idealised catenary form, but through a confluence of architectural desires with compression-only principles. With this approach as inspiration, this paper addresses the potential of compression-only systems to be resolved through a variable volume in order to obtain a desired form.

Much research has been done in analysing existing variable-depth structures to determine if a thrust vector falls inside the depth of material.¹ Other methods assume a fixed depth of material in order to generate a design. The method proposed in this paper assumes a desired geometry and allows for a variable-

volume to redirect the thrust vector as a means to produce a viable design that concerns both structure and other formal concerns. If typically one assumes thin, this paper assumes form.

This method is dedicated to addressing architectural concerns with structural results. This paper does not advocate for the reversion to a past architecture. It promotes the insertion of lost knowledge into our current means and methods of making.

PARTICLE-SPRING SYSTEMS

Particle-spring systems are based on lumped masses, called particles, which are connected to linear elastic springs. The solver used for this research is part of a particle-spring system implemented by Simon Greenwold.² 'Each particle in the system has a position, a velocity, and a variable mass, as well as a summarised vector for all of the forces acting on it.'³ This Runge–Kutta solver is not necessary to generate a catenary (even load distribution), but it is necessary when evaluating an irregular load case. The method applied in this research will always be an irregular load case because it is assumed the resulting geometry is not an idealised catenary form.

Particle-spring systems have been explored to create virtual form-finding methods such as Kilian's *CADenary* tool.⁴

COMPRESSION-ONLY STRUCTURES

A compression-only structure will stand as long as the thrust vector of the system falls within the middle third of its cross section. It is not always predictable that a structure will fail, though it is possible to know if it will stand. A paper by Jacques Heyman introduced the safe theorem for masonry structures.⁵ This theorem states that a compression-only structure can stand so long as one network of compression forces can be found in equilibrium within the section of the structure. This solution is a possible lower-bound solution. When evaluating existing structures, it is not always possible to understand exactly where this force network is.⁶ The method applied in this paper can calculate and ensure a thrust vector falls within the thickness of material.⁷

FORM RESPONDING

Form-finding analogue models by such researchers as Otto⁸ and Gaudi, or even the virtual versions like Kilian's *CADenary*,⁹ have proved it is difficult to control and predict the results of the final found-form. Moreover, if that form does not correspond with a force that is external to the form-finding model, it is difficult to resolve the two into a solution. This paper proposes form-responding as approach. Form-responding takes a desired form as input and produces a variable-volume solution to allow for interaction between these external forces and the solver-based model.

METHODOLOGY

The vault is computed with a solver-based model that elicits a compression-only structure from a structurally non-ideal geometry. The model requires a fixed geometry as input and opens apertures in order to vary the weight of each unit. This dynamic system reconfigures the weight of the units based on a volumetric calculation. If unit A contains twice the volume of unit B, then unit A weights twice as much. It requires that the material of the project be consistent, and solid (hollow does not work). The computed result produces a project that will stand 'forever' as there is zero tension in the system precisely because of the weight and volume of the project, and not in spite of it.

BASE GEOMETRY

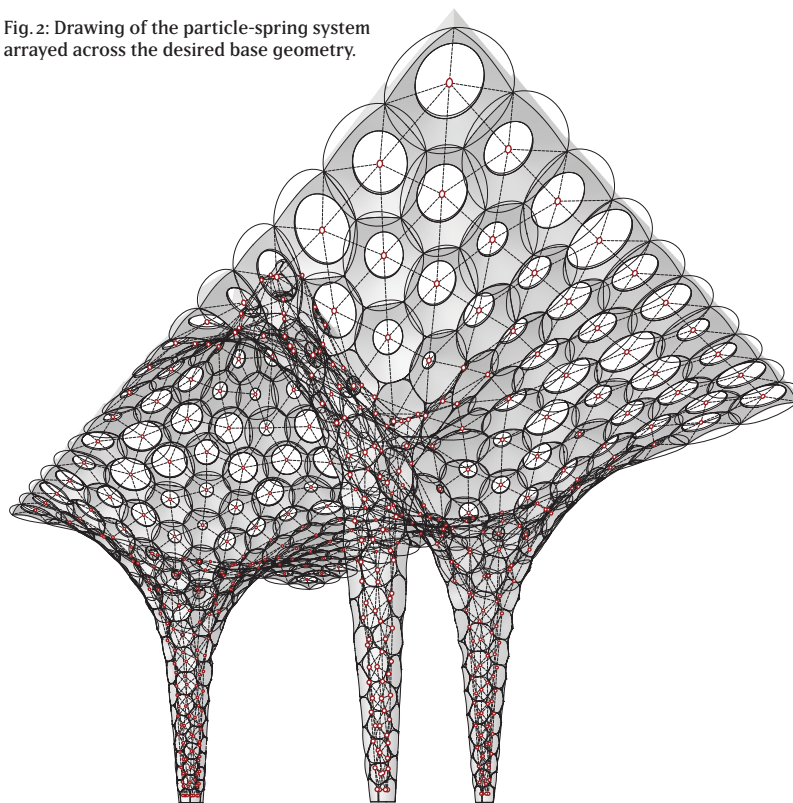
This paper assumes the base geometry as fixed. The assumption is that this geometry has been predetermined by a force external to the model: acoustics, formal, building code, etc. Future research could allow for a more fluid and reciprocal re-

lationship between the structural requirements and these other formal drivers. While this geometry is not strictly aligned with structural concerns, it must be close in order to result in a solution. In previous versions of the calculation,¹⁰ almost any geometry would work as input. The variable-volume calculation is more nuanced.

This calculation requires a number of inputs to the system. It requires both an upper and lower bound surface. These surfaces parameterise the depth of the units as variable during the form generation, but fixed during the variable-volume calculation. The calculation also requires a location for the node of each unit to be located within the system.

These particles are evenly distributed across a base geometry that falls between the upper and lower bound surfaces. This distribution employs another particle-spring system to locate and distribute the points across the surface, increasing in distance from each other as they approach the upper elevations of the geometry. Figure 2 demonstrates the result: an enlarging of the units in the vault, and a tightening of the units in the columns. The particle-spring system computes itself against these three inputs, which serve as the data.

Fig. 2: Drawing of the particle-spring system arrayed across the desired base geometry.



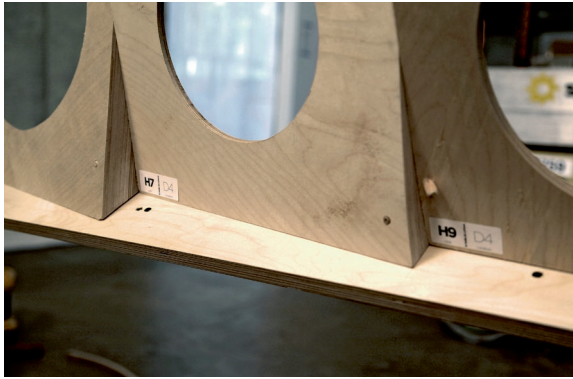


Fig. 3: Detail of the voussoir connection and indexing.

PARTICLE-SPRING SYSTEM

The particle-spring system is composed of a number of particles, the length of the springs that connect the particles, and the continual resulting forces on each particle informing the system. While the organisation is consistent, the system has been reconfigured in a variety of solutions.¹¹ This paper employs an evenly distributed system as described above.

VERTICAL DISTANCE VERSUS VOLUME

When analysing masonry arches, it is common practice to use static block analysis to break down an arch into a few polygons. The area of each polygon determines the vertical thrust vector.¹² Previous iterations of this calculation employed a high resolution of vertical distances to inform each particle with its new relative weight. This paper employs volume as opposed to area or distance. Similar work has been conducted using volume to analyse and determine the viability of a structure.¹³ This paper employs the variability of the volume to ensure a solution.

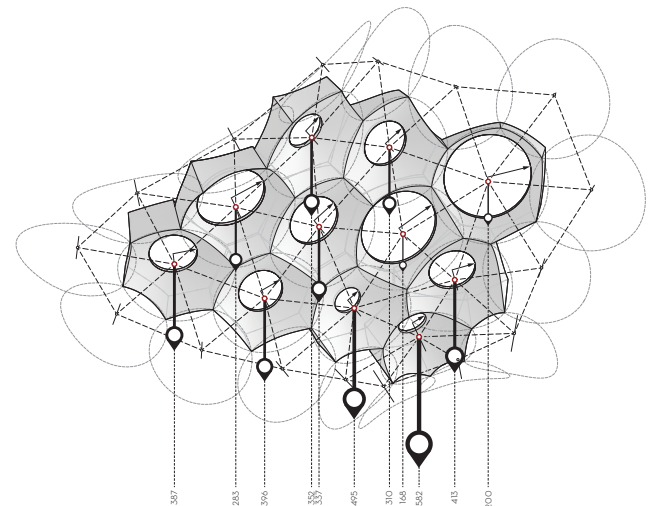
The location of the particles defines the virtual thrust network. In order to ensure a solution, these particles are required to be moving during the calculation until they find equilibrium. At each interval of the calculation, a number of operations occur, complicating the calculation beyond a simple distance measurement. The new location of each particle generates a three-dimensional Voronoi calculation that intersects with the lower bound base geometry surface. This intersection then produces points at the intersection of each curve where an interpolated curve is generated. Simultaneously, the centroid point (also the particle) finds the closest points on the upper bound surface and generates a circle perpendicular to the line connecting these two points. The plane this circle is



Fig. 4: The upper bound geometry skips continuity at the connection of the voussoirs due to the requirement for the milling operation to have a flat surface.

generated on also serves as the flat backside that sits on the table of the computer numerically controlled (CNC) router, a useful fabrication constraint (see figs. 3, 4). The circle and the curve are then lofted with each other, producing a surface that is trimmed with the rest of the surfaces in the system. The intersection of these surfaces extrudes to the closest position on the upper surface, producing the voussoir¹⁴ that discretises each unit in the vault.¹⁵ Each unit now contains an enclosed volume that can inform the system with its weight relative to its neighbours. Figure 5 demonstrates these operations. These operations are calculated continually until the system finds equilibrium and a solution can be detected.

Fig. 5: Diagram of particle-spring system and the variable volume calculation. The volume of the enclosed surfaces equals the vertical thrust on the particle.



DESIGN

A deliberate attempt was made in this project to topologically¹⁶ transition from column to vault. No break is inserted in this transition; however, this is a lie. In reality, there is a difference between column and vault. The column is solid (fig. 6). It is treated as a single unit. The vault on the other hand is discretised into its constituent units.¹⁷ This moment of discrepancy is attempted to be seamless; however, the grain of the wood demonstrates the reality. There is a good reason for this false reality. A column does not perform in the same manner as a vault. The thrust vectors inside the column are vertical, not progressively horizontal. To that end, a column does not resist horizontal thrust. It resists buckling. The solidity of the column is paramount.

The discrepancy in transitioning from solid column to discretised vault is resolved via rhetoric. The rhetoric of individual units continues down the column as if the single and solid column was in fantasy an impossible continuation of the units to the ground. This rhetoric is not a simple continuation of the conical-Boolean geometry that composes the vault. It is a new, yet similar approach. It refers to the conical-Boolean, without repeating it. This shift in geometry allows the system not only to calibrate volume (as applied in the vault), but also to perform another transition from fragmented to smooth. As the units make their way down the column, they do get smaller, but the dimples slowly make their way to the surface, producing the illusion of continuity, only to push through that continuity as the very base. This punctuation to the statement suggests that the weight of the vault above is so great that the column is forced to bulge outward.

Fig. 6: Column detail, Matter Design, *La Voûte de LeFevre*, Banvard Gallery, 2012.



FABRICATION

The vault was produced with Baltic birch plywood. The plywood is sourced in three-quarter-inch thick sheets awaiting the 'thickening'. Perhaps it is evidence of the state of the industry that volumetric material is difficult to procure. Each custom unit is digitally dissected and sliced into these thicknesses, cut from the sheets, and then physically reconstituted into a rough volumetric form of their final geometry. These roughs are indexed onto a full sheet and glued, vacuum-pressed, and replaced onto the CNC router as demonstrated in figure 7. This process is materially more efficient than carving these units from one solid block of material, though it is more laborious.

Fig. 7: Roughed aggregated blanks of the desired geometry await the milling operation on the five-axis machine.



Fig. 8: Swarf milling the voussoir edges.



This project is produced on a five-axis Onsrud router.¹⁸ The swarf¹⁹ toolpaths utilised are dedicated to removing the most material with the least effort (fig.8). Instead of requiring the end of the bit to do the work, this path uses the edge of the bit to remove much more material. Because this method traces the geometry with a line, as opposed to a point via Philibert De L'Orme's technique stereotomy,²⁰ it requires the units are constituted of ruled surfaces.²¹ This constraint informed the conical-Boolean geometry in the vaulted portion of the project, though relaxed in the columns where a more typical surface milling operation produces the rhetorical bulges. This shift in tooling operation also speaks to the understanding of the difference between column and vault.

ANALYSIS

This project was fabricated with an assumed zero-fill approach. As part of the requirement that the vault must be dismantled, there is no mortar. Discrepancies, errors, and gaps were impossible to resolve because of this zero-tolerance approach. In order to ensure completion on site in difficult locations, a manual band saw handled the work of removing collision material on the backside of the problematic units. This on-site carving did not affect the front edge of the units, but it did produce a gap where the voussoir surfaces were not coincidental. This happy accident aligns precisely with the Inca wedge²² process, where masons would fill from the backside of a wall with mortar into a voided wedge between stones, while the front and

Fig. 9: Array of all the unique voussoirs that compose the vault.



Fig. 10: Various unique voussoirs that compose the vault.



Fig. 11: Assembly of the vault.





Figs. 12, 13: Matter Design, *La Voûte de LeFevre*, Banvard Gallery, 2012.

architectural face appeared to be mortarless. There is room for further exploration to capitalise on the potential of the Inca wedge method.

CONCLUSION

La Voûte de LeFevre demonstrates the potential of informing contemporary fabrication methodologies with past knowledge concerning volume. It successfully employs physics simulation to ensure stability through volumetric calculations that serve in reciprocity with volumetric making processes. While aggregate Baltic birch plywood serves as an analogue, potential is seen in other volumetric materials, such as autoclave aerated concrete, plaster, or stone.

ACKNOWLEDGEMENTS

This paper presents results of an ongoing research project that began at the Princeton University School of Architecture under the tutelage of Axel Kilian and continued at Ohio State University, Knowlton School of Architecture (with Howard E. LeFevre Emerging Practitioner Fellowship funding) and the Massachusetts Institute of Technology (with Belluschi Lectureship funding). Two particle-spring systems have been used. The first was implemented by Simon Greenwold in Java as a library for 'Processing' (www.processing.org), an environment developed by Ben Fry and Casey Rease. gHowl (www.grasshopper3d.com/group/gHowl) by Luis Fraguada was used to communicate via UPD between processing and Grasshopper (www.grasshopper3d.com), a plug-in developed by David Rutten for Rhinoceros (www.rhino3d.com), a program developed by Robert McNeil. The second particle-spring system was generated entirely inside Grasshopper with the aid of two plug-ins: Kangaroo (www.grasshopper3d.com/group/kangaroo) by Daniel Piker served as the physics simulation of the particle-spring system and Hoopsnake (www.volatileprototypes.com/projects/hoopsnake) by Volatile Prototypes allowed the vertical distance to loop back into the calculation.

NOTES

- 1 Philippe Block, Thierry Ciblac and John Ochsendorf. 'Real-time limit analysis of vaulted masonry buildings', *Computers and Structures*, 84 (2006), pp. 1841–52.
- 2 The first particle-spring system was implemented by Simon Greenwold in Java as a library for 'Processing' (www.processing.org), an environment developed by Ben Fry and Casey Rease. Greenwold, Simon and Edward Allen. 'Active Statics', 2003, accessed 1 November 2011. <http://acg.media.mit.edu/people/simong/statics/data/>; Ben Fry and Casey Reas, 'Processing web site' (2011), accessed 1 November 2011. <http://www.processing.org/>.
- 3 Axel Kilian and John Ochsendorf, 'Particle-Spring Systems for Structural Form Finding', *Journal of the International Association for Shell and Spatial Structures*, 46/2 (2005), pp. 77–84.
- 4 Ibid.
- 5 Jacques Heyman, 'The Stone Skeleton', *International Journal of Solids and Structures*, 2 (1966), pp. 249–79.
- 6 Philippe Block and John Ochsendorf, 'Lower-Bound Analysis of Unreinforced Masonry Vaults' in Dina d'Ayala and Enrico Fodde, eds., *Proceedings of the VI International Conference on Structural Analysis of Historic Construction* (London: CRC Press, 2008), pp. 593–600.
- 7 For further reading on lower-bound analysis of unreinforced masonry structures: Jacques Heyman, *The Masonry Arch* (Chichester: Ellis Horwood, 1982); Santiago Huerta, 'Mechanics of Masonry Vaults: the Equilibrium Approach', in Paulo B. Lourenço and Pere Roca, eds., *Historical Constructions 2001, Universidade do Minho, Guimarães: Possibilities of Numerical and Experimental Techniques* (Coimbra, Portugal: Institute for Sustainability and Innovation in Structural Engineering, 2001), pp. 47–70. Santiago Huerta, *Arcos, Bóvedas y Cúpulas: Geometría y Equilibrio en el Cálculo Tradicional de Estructuras de Fábrica* (Madrid: Instituto Juan de Herrera, 2004).
- 8 Frei Otto and Bodo Rasch, *Finding Form: Towards an Architecture of the Minimal* (Berlin: Edition Axel Menges, 1995).
- 9 Kilian and Ochsendorf (see note 3).
- 10 Brandon Clifford, 'Thick Funicular: Particle-Spring Systems for Variable-Depth Form-Responding Compression-Only Structures', in Xavier Costa and Martha Thorne, eds. *Change Architecture Education Practices: 2012 ACSA International Conference* (New York: ACSA Press, 2012), pp. 475–81.
- 11 Brandon Clifford, 'Thicker Funicular: Particle-Spring Systems for Variable-Depth Form-Responding Compression-Only Structures', in Paulo Cruz, ed. *Structures and Architecture: Concepts, Applications and Challenges* (London: CRC Press, 2013), pp. 205–6.
- 12 Block and Ochsendorf (see note 6).
- 13 Block and Ochsendorf (see note 6).
- 14 Voussoir: a wedge-shaped element, typically a stone, used in building an arch or vault.
- 15 The surface geometries enclosing this volume are generated with ruled surfaces due to a reciprocal relationship with the method of fabrication. For more information on this process, see note 6.
- 16 Topology: in mathematics, the study of the properties of a geometric object that remains unchanged by deformations such as bending, stretching, or squeezing but not breaking.
- 17 A similar strategy of the solid column transitioning into voussoirs above was employed in Peterborough Cathedral. These voussoirs also misalign on the upper bound geometry, while aligning precisely on the lower bound (visible surface). For more information, see Robin Evans, 'Drawn Stone', in *The Projective Cast: Architecture and Its Three Geometries* (Cambridge, Mass.: MIT Press, 2000), pp. 178–239.
- 18 With fabrication support from the University of Michigan Taubman College FABLab.
- 19 Swarf machining is a technique that allows side cutting with an end mill while proceeding along the surface of a part, such as the sidewalls of a tapered rib.
- 20 Philibert de L'Orme (sixteenth century) was, like Palladio, the son of a mason. He merged into architecture, not through a series of rigorous understandings of form or technique, rather from the builder or mason. In his printed work of 1567, *Le Premier tome de l'architecture*, Philibert de L'Orme introduced the method and definition of *art du trait géométrique*. This method developed as a way to reciprocally draw what can be built and vice versa. Because of this emergence, de L'Orme can also be credited as the first professional architect, because his technique served to instruct and communicate between the designer and the builder, though an important distinction should be drawn between the representations of architecture we now generate and de L'Orme's descriptive geometry that served as method template to construction. In a way, de L'Orme can be considered the predecessor to digital fabrication. For more information on this topic, see Evans, 2000 (see note 17) and Brandon Clifford and Wes McGee, *Range: Matter Design* (Reykjavik: Oddi, 2013); as well as Matthias Rippmann and Philippe Block, 'Digital Stereotomy: Voussoir Geometry for Freeform Masonry-Like Vaults Informed by Structural and Fabrication Constraints', in *Proceedings of the IABSE-IASS Symposium* (London, 2011).
- 21 This project is part of a line of work dedicated to this proposal of employing the line for carving. For more information, see: Brandon Clifford and Wes McGee, 'Periscope Foam Tower' in Ruairi Glynn and Bob Sheil, eds. *Fabricate: Making Digital Architecture* (Cambridge, Ont.: Riverside Architectural Press, 2011), pp. 76–9.
- 22 Brandon Clifford, *Volume: Bringing Surface into Question* (SOM Prize Report, SOM Foundation, 2012), pp. 286–9.

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undertaken by Bijl Architecture and in the Buildability research project, which gathered international attention for her critique and vision of the future of construction education in architecture schools.

MARTIN BECHTHOLD is Professor of Architectural Technology at the Graduate School of Design (Harvard University), Director of the Design Robotics Group, and Co-Director of the GSD's Doctor of Design Program. His research on material system innovation pursues computer-aided design and manufacturing applications in architecture, with a focus on broadening design scope through construction automation and industrial robotics. Current projects investigate adaptive material systems, lifecycle design, and fabrication automation strategies for architectural ceramics and other construction systems. Martin is the co-author of *Structures and Computer-Aided Design and Manufacturing* as well as the author of *Innovative Surface Structures*, a book that addresses the increasing conflation of structural design and digital fabrication techniques through the microcosm of thin shells and membranes.

PHILIP BEESLEY MRAIC OAA RCA (Professor, School of Architecture, University of Waterloo; Director, Integrated Group for Visualization, Design and Manufacturing, Director, Riverside Architectural Press) is a practising architect developing responsive kinetic architectural environments that approach near-living functions. He is cited as a pioneer in the rapidly expanding technology of responsive architecture with wide press including WIRED, TEDx, Discovery Channel features. He has authored and edited eight books, three international proceedings and a number of catalogues, and appears on the cover of Artificial Life (MIT), LEONARDO and AD journals. Current projects are in Salt Lake City, Seoul, Edmonton and Hangzhou. He was selected to represent Canada for the 2010 Venice Biennale for Architecture and the 2012 Biennale of Sydney. He works as part of a multidisciplinary collective that includes Rachel Armstrong, Rob Gorbet and Iris van Herpen. Distinctions include Prix de Rome in Architecture (Canada), VIDA 11.0, FEIDAD, RAIC Allied Arts, ACADIA Emerging Digital Practice and Dora Mavor Moore awards. He was chair for the ACADIA 2013 Adaptive Architecture international conference.

BRAD BELL is an Assistant Professor of Architecture at the University of Texas, Arlington, where he teaches undergraduate and graduate courses on the integration of digital fabrication technologies into the architectural design process. He has lectured, taught and written on the uses of such technologies for the past 12 years and has been an invited critic throughout the United States. Brad received his master's degree in architecture from Columbia University in 1998 and a bachelor's degree in Environmental Design from Texas A&M in 1993. In 2012, Brad started TOPOCAST, a design and consultation firm focused on the implementation of innovative methods in casting through the application of digital fabrication technologies.

JAMES BELLAMY is a sustainable builder and runs a socially responsible construction company based in New Zealand, specialising in earth construction methods with a focus on public facilities. His most notable projects include the Pines Calyx in Dover, England and Mapungubwe National Park Interpretation Centre, South Africa. With a passion for ecological systems and a degree in Parks and Recreation Management, his efforts are to design and build structures that resonate with and utilise the local natural setting.

PHILIPPE BLOCK is Assistant Professor in structural design and head of the BLOCK Research Group at the Institute of Technology in Architecture at ETH Zurich, specialising in equilibrium analysis of unreinforced masonry vaults, computational form finding and optimisation of curved surface structures and innovation in fabrication and construction of such structures.

He is a structural engineer and architect, trained at the VUB in Belgium and MIT in the USA. As partner of Ochsendorf DeJong & Block LLC, he applies his research in practice on the structural assessment of historic monuments and the design and engineering of innovative compression shells.

WILLIAM BONDIN is a Maltese architect and creator of Morphs – a reconfigurable architectural system. He completed his professional studies in Malta (UoM) and then undertook research at the Bartlett School of Architecture (UCL), where he focused on interaction design and architectural behaviour. His work has been featured on wired.com and published at the Fascinate 2013 conference, amongst others. Inspired by the architectural works of Ron Herron and Richard Buckminster Fuller and the robotic theories of Rolf Pfeifer and Rodney Brooks, his designs take a fabrication-oriented approach towards architectural performance and behaviour.

BRENNAN BUCK is principal of the firm FreelandBuck, based in New York City and Los Angeles, and a critic at the Yale School of Architecture. His work and writing, which focuses on technology within the discipline and its associated aesthetic culture, has been published in *Log*, *Frame*, *Architectural Record*, *Detail* and *Surface* as well as several recent books on architecture and technology. Prior to teaching at Yale, he worked for Neil M. Denari Architects and Johnston Marklee & Associates in Los Angeles and taught at the University of Applied Arts in Vienna, the Royal Danish Academy in Copenhagen, the University of Kentucky and Pennsylvania State University.

MARK BURRY has published internationally on two main themes: the life and work of the architect Antoni Gaudí in Barcelona, and putting theory into practice with regard to ‘challenging’ architecture; he has also published widely on broader issues of design, construction and the use of computers in design theory and practice. As Consultant Architect to the Temple Sagrada Família since 1979, Mark Burry has been a key member within the small team, untangling the mysteries of Gaudí’s compositional strategies for the Sagrada Família, especially those coming from his later years, the implications of which are only now becoming fully apparent as they are resolved for building purposes. In February 2004, in recognition of his contribution to this project, he was given the prestigious award ‘*Diploma I la insgnia a l’acadèmic corresponent*’ and the title Senyor Illustre by la Reial Acadèmia Catalana de Belles Arts de Sant Jordi and he was recently awarded an Australian Research Council Federation Fellowship. Mark is director of RMIT’s state-of-the-art Spatial Information Architecture Laboratory, which has been established as a holistic interdisciplinary research environment dedicated to almost all aspects of contemporary design activity. The laboratory focuses on collocated design research and undergraduate and postgraduate teaching with associated advanced computer applications and the rapid prototyping of ideas. The laboratory has a design-practice emphasis and acts as a creative think-tank accessible to both local and international practices, including ARUP in Melbourne and London, dECOi in Paris and Gehry Partners in Los Angeles.

MARIO CARPO is Vincent Scully Visiting Professor of Architectural History at Yale University and at the Ecole d’Architecture de Paris-La Villette (currently on leave). After studying architecture and history in Italy, he was an Assistant Professor at the University of Geneva in Switzerland, and has been a tenured Associate Professor in France since 1993. Mario Carpo’s research and publications focus on the relationship among architectural theory, cultural history, and the history of media and information technology. His award-winning *Architecture in the Age of Printing* (MIT Press, 2001) has been translated into several languages. His most recent books are *Perspective, Projections and Design* (2007, co-edited); a translation and commentary of Leon Battista Alberti’s *Descriptio Urbis Romae* (2007,

co-authored); a monograph on the work of Swiss architect Valerio Olgiati (2008, co-authored); *The Alphabet and the Algorithm* (MIT Press, 2011), and *The Digital Turn in Architecture, 1992–2012* (Wiley, 2012). His recent essays and articles have been published in *Log*, *The Journal of the Society of Architectural Historians*, *Grey Room*, *L’Architecture d’aujourd’hui*, *Arquitectura Viva*, *AD/Architectural Design*, *Perspecta*, *Harvard Design Magazine*, *Cornell Journal of Architecture*, *Abitare*, *Lotus International*, *Domus*, and *Arch+*.

GIOVANNI CESARETTI is Marketing and Sales Manager at Alta SpA. After completing his PhD, he worked for government bodies and Technology Transfer Centres. In 2005, he moved to Alta, where he was in charge of the bids and tenders sector. He is also Project Manager for various activities, and since 2004, he has been a reviewer of research and development projects for Italian and European institutions in the fields of information technology and space engineering.

ZACHARY CHRISTIAN is a research associate in the Department of Timber Engineering, Materials Testing Institute (MPA) at the University of Stuttgart since 2012. He completed his master’s degree in Structural Engineering (MSc) at Chalmers University of Technology in Sweden in 2012 and a bachelor’s degree in Civil Engineering (BSCE) at Purdue University in the USA in 2007. Between his degrees, he worked for 3 years in Madrid as a structural engineer, dealing mostly with prestressed concrete bridge design. His current research focuses on timber as a building material, with projects ranging from fatigue in special timber elements to creep of wood adhesives.

BRANDON CLIFFORD is currently the Belluschi Lecturer at the Massachusetts Institute of Technology as well as Principal at Matter Design. Clifford received his Master of Architecture from Princeton University in 2011 and his Bachelor of Science in Architecture from the Georgia Institute of Technology in 2006. From 2006 to 2009 he worked as project manager at Office dA. Brandon also served as editor of *Pidgin Magazine* from 2009–11, the 2011–12 LeFevre Emerging Practitioner Fellow at the Ohio State University Knowlton School of Architecture, and the founder of the Malleablist Movement in architecture. He has received numerous prizes, including the prestigious SOM Prize in architecture and urban planning in 2011 and the Architectural League Prize for Young Architects + Designers in 2013.

VALENTINA COLLA obtained a master’s degree in Engineering in 1994 from the University of Pisa and a PhD in Robotics in 1998 from Scuola Superiore Sant’Anna of Pisa, where she is currently working as a Technical Research Manager at the Institute for Communication Information and Perception Technologies. Her research interests deal with simulation, modelling and control of industrial processes and industrial data processing through traditional and AI-based techniques. She has been involved in about 40 projects funded by the EU and many projects supported by industries. She is presently coordinator of two projects supported by the Research Fund for Coal and Steel. She is a member of the European Steel Technology Platform (ESTEP).

MARJAN COLLETTI is an architect, educator, researcher, author, and co-founder of marcosandmarjan (with Marcos Cruz). She is currently Senior Lecturer at Bartlett UCL and University Professor at Innsbruck University, as well as elected Head of the Institute of Experimental Architecture. Previously she was guest professor in the US, UK and EU with workshops at École Spéciale d’Architecture Paris, Royal Danish Academy of Fine Arts Copenhagen, School of Architecture Oslo, Tonghai University and Feng Chia University Taichung Taiwan. Marjan was invited expert/peer reviewer/board member of RobArch2012, ICESEP China, Ministry of Education Russia,

Canada Foundation for Innovation, American University of Sharjah UAE, Queen's University Belfast, *Journal of Cultural Economy*, Taylor and Francis, Ashgate Publishing, and Initiative Architektur Salzburg.

DAVID CORREA is a doctoral candidate at the Institute for Computational Design at the University of Stuttgart. He completed a Master of Science in Architecture at the University of Calgary and a Bachelor of Science in Architectural Science from Ryerson University in Toronto. In 2012, he was awarded the Royal Architectural Institute of Canada's Student Medal for Academic Excellence. Prior to joining the ICD in August 2012, he worked professionally as a designer in both architecture and commercial digital media. His research focuses on the physiological relation of information intensive technologies with architectural theory, practice and material production.

KRISTOF CROLLA is a licensed architect who combines his Assistant Professorship in Computational Design at the Chinese University of Hong Kong (CUHK) with his practice at the Laboratory for Explorative Architecture & Design Ltd. (LEAD). After graduating from Ghent University and practicing in Belgium, he trained and taught at the Architectural Association's Design Research Laboratory (AA-DRL) in London. He worked for several years as Lead Architect for Zaha Hadid Architects before moving to Hong Kong in 2010, and has been an invited jury critic, lecturer and tutor in numerous institutions throughout Europe, China, Chile and South Africa.

XAVIER DE KESTELIER is a partner at Foster + Partners, where he jointly heads Foster + Partners' Specialist Modelling Group, a project-driven R&D group that specialises in complex geometrical problems, computation and building physics. Besides this, he was also responsible for the implementation of rapid prototyping technology in the practice and has initiated several research projects on the application of additive manufacturing on an architectural scale. He has been Visiting Professor at the University of Ghent, Adjunct Professor at Syracuse University and a teaching fellow at the Bartlett School of Architecture (UCL). In 2010, he became a Director at Smartgeometry, a non-profit organisation that promotes advances in digital design in architectural research and practice.

BENJAMIN DILLENBURGER is an architect and programmer with a focus on computational design in architecture. He is currently based at the CAAD group at the Swiss Federal Institute of Technology's Architecture Department in Zurich. He holds a Master of Advanced Study degree from ETH Zurich and a Master of Architecture degree from the Technical University of Kaiserslautern. Benjamin is also member of the spin-off company KAISERSROT, an interdisciplinary consulting and design team exploring the potential of information technology for architecture and urban planning.

ENRICO DINI graduated in Civil Engineering from the University of Pisa, and has spent most of his career on the implementation of robotic automation of shoe manufacturing. During these years, Enrico came across rapid prototyping technology, which he made his sole focus from 2004 onwards. Since then, he has developed a large-scale 3D printer using inorganic binders. In 2008, his first large-scale 300-nozzle 6 × 6 meter 3D printer became operational. His technology has been used since then to make 3D print sculptures and architectural mock-ups. Recently, he has been working on a 'maritime' printer suitable for printing artificial reefs for coastal protection.

JORGE DURO-ROYO, born in Barcelona, graduated as an architect from the Polytechnic University of Catalonia School of Architecture and as a mechanical engineer from the Polytechnic University of Catalonia School of Industrial and Aeronautic Engineering, where he graduated with honours.

In 2006, he spent a year in Paris on an Erasmus Scholarship at the École Nationale Supérieure Paris-La Villette. From 2009 to 2010, he co-taught Introduction to Parametric Architecture for 4th and 5th year students with the Coda Group. In 2010, he attended the master's degree programme in Advanced Design and Digital Architecture at the Pompeu Fabra University. In 2010–11, he completed a master's degree in Architecture, Energy and Environment at UPC-ETSAB. He has worked in Europe in international offices such as Dominique Perrault DPA and Duro Architecture and Engineering. Jorge co-founded Dumolab in 2008, a young architecture, engineering and research studio that focuses on experimental design, data management in architecture, innovative material systems and programming of new design tools. He has spent the last two years in Cambridge MA, collaborating with MIT professors on multiple innovative research subjects. In 2013, he joined the Mediated Matter Research Group as a Research Assistant.

DAMIAN ELEY led the design of the superstructure on the Leadenhall Building since its inception. An Associate Director with 20 years' experience in Arup's London office, Damian works closely and creatively with architects and the rest of the design team to create exceptional designs. He has a particular passion for pursuing the clear and elegant expression of structural behaviour in his design work, and his portfolio of projects includes Osaka Maritime Museum in Japan, Incheon Airport in Korea and, in London, the exclusive One Hyde Park development, the 'flying carpets' at Unilever House and the 'beacon' at Plantation Place.

GUSTAV FAGERSTRÖM is a registered architect and Associate with Buro Happold New York, where he leads the structural BIM and advanced modelling team. Specializing in design computation, automation and building information modelling, he has developed his knowledge in all project phases from concept to construction. His work focuses on the areas of intersection of architecture, engineering and computer science and deals with the optimisation and automation of design processes by means of novel techniques in computational modelling, analysis and programming. He has practised architecture with Urban Future Organization and with Kohn Pedersen Fox Associates in the UK and with UNStudio in the Netherlands, gaining experience of projects in over 10 different countries. Work by him has been exhibited and published in Europe, Amerika and Asia as well as presented at the Venice Architecture Biennale, CAADRIA, ACADIA and the Smartgeometry conference. Frequently engaging with academia, he has sat on design juries, given workshops and lectures at UPenn, Yale, the AA London, UCL Bartlett, the Royal Institute of Technology and the Royal Academy of Fine Arts in Stockholm.

JELLE FERINGA is co-founder of EZCT Architecture and Design Research. Some works by the office are in the collection of the FRAC Centre as well as the permanent architectural collection of the Centre Pompidou. EZCT participated at the 2004 and 2013 editions of Archilab. In 2007, the office won the Seroussi competition. While working on his PhD thesis, Jelle established the Hyperbody Robotics Lab in late 2011. In spring 2012, he co-founded Odico Formworks Robotics, based on the offline robotics programming platform PyRAPID that lies at the heart of the business. With Thomas Paviot, he has been driving the development of an open-source CAD framework, PythonOCC, a CAD/CAE/PLM rapid prototyping framework for the Python programming language.

LUIS E. FRAGUADA investigates critical issues in architecture, design, and urbanism through various modes, including associative design, scripting, and fabrication. Luis is currently a member of the Faculty of Architecture at IaaC as the principal computation instructor, focusing on the interface between computational processes and fabrication. Luis joined Built By

Associative Data, an architecture and research studio, as an associate and the Director of the Barcelona office in 2010. He currently leads Built by Associative Data Research – the research component of the office which focuses on creating tools and processes to push the computational capabilities of the team as well as expand the project focus of the office into areas such as gastronomy and fashion design.

NEIL GERSHENFELD is Professor and Director of MIT's Center for Bits and Atoms. His unique laboratory is breaking down boundaries between the digital and physical worlds, from creating molecular quantum computers to virtuosic musical instruments. Technology from his lab has been seen and used in settings including New York's Museum of Modern Art and rural Indian villages, the White House and the World Economic Forum, inner-city community centers and automobile safety systems, Las Vegas shows and Sami herds. He is the author of numerous technical publications, patents, and books including *Fab*, *When Things Start To Think*, *The Nature of Mathematical Modeling*, and *The Physics of Information Technology*, and has been featured in media such as *The New York Times*, *The Economist*, and *The McNeil/Lehrer NewsHour*. He is a Fellow of the American Physical Society, has been named one of Scientific American's 50 leaders in science and technology, as one of 40 Modern-Day Leonardos by the Museum of Science and Industry, has been selected as a CNN/Time/Fortune Principal Voice, and by *Prospect/Foreign Policy* as one of the top 100 public intellectuals. Neil has a BA in Physics with High Honors from Swarthmore College, a PhD in Applied Physics from Cornell University, honorary doctorates from Swarthmore College and Strathclyde University and was a Junior Fellow of the Harvard University Society of Fellows, and a member of the research staff at Bell Labs.

HOLLIE GIBBONS studied architecture at the Royal Danish Academy of Fine Arts, School of Architecture, specialising in design and industrial form. Hollie was awarded an MA in Architecture in 2012. She also holds a BA (Hons) in Architecture from Kingston University, London. After graduating, Hollie joined CITA as Research Assistant. She has worked on a number of CITA research projects with a focus on design and fabrication, including the large-scale installation *The Rise* for the ALIVE exhibition at the EDF Foundation, Paris, France, in 2013. Hollie is also engaged in teaching for the master's programme, CITAstudio: Computation in Architecture.

RUAIRI GLYNN practices as an installation artist and architectural researcher. He has exhibited his work internationally, most recently at the Tate Modern London, the Centre Pompidou Paris, and the National Art Museum Beijing. He is co-founder of the FABRICATE Conference with Prof. Bob Sheil and co-chair of its steering committee. He is Lecturer in Interactive Architecture at the Bartlett School of Architecture (UCL), and teaches on both the master's programmes MArch Graduate Architectural Design (RC3) & MSc Adaptive Architecture and Computation. Study across both his courses is based on a design through 'making' methodology, with an emphasis on using and misusing digital and material technologies. The studio builds and tests at a 1:1 scale, experimental objects and interactive installations that uncover new design opportunities to sense and respond to the natural and built environment, to people and other living things, and to data both local and global. This work is done in collaboration with his Associate Lectureship on the master's programme Textile Futures at Central Saint Martins, University of Arts London.

CARLOS DAVID GONZALEZ URIBE was born in Mexico City. He received his undergraduate degree in architecture from ITESM in Mexico City in 2008 and a master's degree in Architecture and Urban Design from Pratt Institute in 2011, where he was honoured with the Pratt Circle Award and for

Outstanding Academic Achievement. In 2010, he was also awarded a Fellowship by the Mexican Science Foundation (CONACYT). After graduation, he worked as an intern in the research and development department of Bentley's Generative Components Department and served as a media consultant at the University of Pennsylvania with Prof. Ferda Kolatan. In 2011, he collaborated with the firm *suu* in the Corallines Project, which was on exhibit at the Istanbul Design Biennial. Currently, Carlos is a Research Assistant at the Mediated Matter Group at MIT.

FABIO GRAMAZIO and **MATTHIAS KOHLER** are architects with multidisciplinary interests ranging from computational design, robotic control and fabrication to material innovation. In 2000, they founded the architecture practice Gramazio & Kohler, where numerous award-winning designs have been realised, integrating novel architectural designs into a contemporary building culture. Built work ranges from international exhibitions, private and public buildings to large-scale urban interventions. Opening also the world's first architectural robotic laboratory at ETH Zurich, Gramazio & Kohler's research has been formative for the field of digital architecture, setting precedence and de facto creating a new research field merging advanced architectural design and additive fabrication processes through the customized use of industrial robots. This ranges from 1:1 prototypical installations to robotic fabrication on a large scale, which is being explored at the SEC Future Cities Laboratory. Fabio and Matthias were awarded the Swiss Art Awards, the Global Holcim Innovation Prize and the ACADIA Award for Emerging Digital Practice. Their innovative explorations have contributed to numerous exhibitions around the world, such as the 2008 Architectural Biennial in Venice, the Storefront Gallery for Art and Architecture in New York 2009 or *Flight Assembled Architecture* at the FRAC Centre Orléans in 2011. Their work has been published in a large number of journals, books and mass media, and has been first documented in the book *Digital Materiality in Architecture* in 2008. Their recent research is outlined and theoretically framed in the book *The Robotic Touch – How Robots Change Architecture*, released in 2014. Together with leading researchers in architecture, material sciences, computation and robotics, they have just launched the first architectural National Centre of Competence in Research on Digital Fabrication.

GEORG GRASSER studied architecture at the University of Innsbruck, Ecole d'Architecture de Paris-La Villette, Vienna University of Technology and holds a postgraduate degree in architecture, with a specialisation in computer-aided architectural design from ETH Zurich. He has taught seminars and workshops in Kosovo and Taiwan and has worked for various architectural offices in Austria, France and China. Since 2009, he has been teaching and researching parametric modelling, script-based design processes and computational fabrication strategies at the Department for Experimental Architecture, Hochbau at TU Innsbruck. In 2013, he was one of the cluster champions of the Robotic FOAMing workshop at the Smartgeometry conference in London. He is currently co-running the university's robotic laboratory.

NORMAN HACK received his Diploma in Architecture from the Technical University of Vienna. A scholarship from the German Academic Exchange Organization (DAAD) allowed him to pursue a postgraduate degree at the Architectural Association in London, from which he graduated with distinction. Norman gained professional experience in renowned offices across Europe, including Coop Himmelb(l)au, UNStudio and Herzog & de Meuron, where he worked as a specialist in computational design and fabrication. His PhD research at the Chair of Architecture and Digital Fabrication at ETH Zurich focuses on material processes for non-standard constructive assemblies.

MICHAEL HANSMEYER is an architect and programmer who explores the use of algorithms and computation to generate architectural form. He is currently based in the CAAD group at ETH Zurich. Recent projects include Platonic Solids and Subdivided Columns. He holds a Master of Architecture degree from Columbia University and an MBA from INSEAD Fontainebleau. He previously worked in the consulting and financial industries at McKinsey & Company and J. P. Morgan, respectively, as well as at Herzog & de Meuron architects.

ALEX HAW is Director of the award-winning UK art/architecture practice *atmos*. Their projects span the scale from algorithmic master plans to data-generated furniture, merge sculptural ergonomics with innovative fabrication technologies and digital mapping, and seek a synthesis of mind and body – creating kinaesthetic experiences that are both meaningful and pleasurable. Alex graduated with a Fulbright scholarship from Princeton and a First from the Bartlett, and has taught Master's Studios at the Architectural Association, the Royal College of Art and TU Vienna. He runs the Latitudinal Cuisine community, writes widely, and played the lead psycho in Chris Nolan's first feature film *Following*.

CLEMENS HUBER is a structural engineer and a graduate of the University of Applied Sciences for Construction Management and Engineering in Graz. He started his professional career as a project manager at the renowned Austrian Glulam specialist Wiehag. Later, he changed to the design and engineering department as Assistant Director. A recent project of interest was awarded the prize Achievement in Engineered Timber in 2009 by Timber Trade Journal for the timber roof of the University of Reading's new business school, where he was responsible for the structural design. Currently, he is Design Manager for the contractor design of the Canary Wharf Crossrail Station timber roof.

RYAN LUKE JOHNS is a research specialist at the Princeton University School of Architecture and co-founder of GREYSHED, a design-research collaborative focused on robotic fabrication in art, architecture and industrial design. He holds a Bachelor of Arts degree in Architecture with a concentration in mathematics from Columbia University (2009) and a Master of Architecture from Princeton University (2013). He was recently the recipient of Princeton University's Suzanne Kolarik Underwood Prize for Design Excellence (2013) and the KUKA Young Potential Award for Best Scientific Paper at RoblArch 2012.

SAŠA JOKIĆ is a researcher and inventor in the field of robotics in architecture and the construction industry. He studied at the Faculty of Architecture in Belgrade, where he earned a master's degree in architecture in 2010. After graduation, he worked as assistant teacher at the Chair for Architecture at Belgrade University. In 2012, he graduated from the Institute for Advanced Architecture of Catalonia specialising in digital tectonics. During his studies, Saša also gained experience in design at UNStudio in Amsterdam. Currently, he is working as a Senior Researcher at IaaC, where he leads several research projects for the Open Thesis Fabrication course.

AMMAR KALO recently received a Master in Science in Architecture with a concentration in Digital Technologies from the University of Michigan Taubman College of Architecture and Urban Planning (2013). Prior to pursuing his post-professional studies, he has held professional posts in architecture and design in Dubai and worked on international projects of various scales. At Taubman College, his work focused on digital fabrication and computational design methodologies. His current research interests include synthesizing conventional materials and digital technologies into hybrid material systems. Ammar holds a bachelor's degree in Architecture from the American University of Sharjah (2008).

MARKUS KAYSER studied 3D Furniture and Product Design at London Metropolitan University and continued on in 2009 with the study of Product Design at the Royal College of Art. Currently, Markus is a PhD candidate at the MIT Media Lab, where he has joined the Mediated Matter Group. Before joining the group, he started his own studio, engaging in discussions about opportunities in the production of design involving new as well as forgotten processes and technologies. Now, as then, his research draws on science, art and engineering and aims to blur the gaps between seemingly separate fields. Experimentation plays a central part in developing his research. Markus's recent work demonstrates the exploration of hybrid solutions linking technology and natural energy to show opportunities, question current methodologies in manufacturing and test new scenarios of production. His work has been widely publicised around the world in exhibitions, broadcasting and web-based media.

OLIVER DAVID KRIEG is a doctoral candidate at the Institute for Computational Design at the University of Stuttgart. With the completion of his Diploma thesis in 2012, he also received the faculty's Diploma Prize. Prior to that, he worked as a Graduate Assistant at the Institute's robotic prototype laboratory, RoboLab, from the beginning of 2010. With a profound interest in computational design processes and digital fabrication in architecture, he has participated in several award-winning and internationally published projects. In the context of computational design, his research aims to investigate the architectural potential of robotic fabrication in wood constructions.

DIRK KROLIKOWSKI has been the architect and associate in charge of the design, development and delivery of the unique external structure (the Megaframe) of the Leadenhall Building, a 51-storey office development in the city of London. Dirk also heads the Digital Research Cluster of Rogers Stirk Harbour + Partners and led the implementation of advanced modelling strategies for Leadenhall, an award-winning project that has received international recognition for its integrated use of digital technology. In 2011, Dirk was appointed Lecturer for Innovative Technology and Design at the Bartlett School of Architecture (UCL).

JORIS LAARMAN is a Dutch designer, artist and entrepreneur best known for experimental designs inspired by upcoming technology. He attended the Design Academy Eindhoven in 1998 and graduated cum laude in 2003. He founded Joris Laarman Lab together with his partner Anita Star. His critically acclaimed work has been added to the permanent collections of many renowned international museums such as MoMA in New York, V&A in London, Centre Pompidou in Paris and the Rijksmuseum in Amsterdam. He has contributed articles and seminars for *Domus* magazine and was a guest teacher at European universities such as the Architectural Association London, Rietveld Academy Amsterdam and the Design Academy Eindhoven. In 2011 he received one of the eight Innovators of the Year awards by the *Wall Street Journal*.

SILKE LANGENBERG is a senior researcher at the Chair of Architecture and Digital Fabrication, Institute of Technology in Architecture at ETH Zurich. Between 2011 and 2013 she was based in Singapore several times to research at the Singapore ETH Centre for Global Environmental Sustainability. From 2006 to 2011 she was Researcher at the Institute of Historic Building Research and Conservation of ETH Zurich. Silke has studied architecture at the Universities of Dortmund and Venice. She received a Scholarship for extraordinary achievements for her PhD in Engineering Sciences about *Buildings of the Boom Years. Architectural Concepts and Planning Theories of the 60s and 70s* (finished 2006). In 2013, Silke was appointed as Full Professor for Design and Construction in Existing Contexts, Conservation and Building Research at the University of Applied Sciences in Munich.

JARED LAUCKS is a trained maker, architect, designer and fabrication specialist. He is currently a Research Assistant in the Mediated Matter Group at the MIT Media Lab, where he is interested in developing novel methods of digital fabrication for design research. Jared graduated from Philadelphia University with a bachelor's degree in Architecture, focused on digital technologies. As an extension of this research, he launched *j_laucks*; initially a platform for experimental design and fabrication, it has since grown into a multifaceted research agenda exploring avenues from architecture and design to computation, material systems, and fabrication. In parallel to working as an architect, he was appointed Adjunct Professor at Philadelphia University, developing a new advanced modelling curriculum. Jared has exhibited work in cities across the globe, including Philadelphia, Berlin, Frankfurt, NYC, Valparaiso, Lyon, Paris, Miami, Sao Paulo, London and Munich.

WILLI VIKTOR LAUER is a research assistant at the Future Cities Laboratory, Singapore ETH Centre for Global Environmental Sustainability, Module II Architecture and Digital Fabrication, led by Fabio Gramazio and Matthias Kohler, where he has implemented a research facility for investigating robotic fabrication methods for high-rise buildings. Between 2009 and 2011, he worked as a Scientific Assistant at the Chair of Building Realization and Robotics at the Technical University of Munich, where he gained in-depth knowledge of the young history of robotic construction technologies and the forerunners in building industrialization. In the context of his master's thesis in 2009, he reconstructed the first architectural robotic arm: the Location Orientation Manipulator by Konrad Wachsmann.

DIETER LINKE is experienced in development and inventions for membrane structures and their details, merging architectural and pragmatic requirements. Following his carpentry apprenticeship, he was awarded a Civil Engineering Diploma from the Munich Technical University in 1991. Key projects are Mina Tent City (PTFE, Medinah), Masoala Rainforest Hall (ETFE cushions, Zurich), AWD Arena (single layer ETFE, Hanover), Allianz Arena (ETFE cushions, Munich), National Stadium (Birdnest, single layer ETFE, Beijing), Sports and Concert Complex, (plane PVC, Baku). Further, the benefits of using ETFE film in modern greenhouse culture and sustainable energy technologies currently hold his interest.

MARTA MALÉ-ALEMANY is an architect, researcher, and educator from Barcelona. Since 1997, she has combined her professional practice with teaching experimental design studios and research seminars in architecture schools from the US (MIT, UPenn, UCLA, SCI-ARC among others) and Europe (AA, IaaC, UIC), in combination with directing several master's degree programmes in architecture. Following many years of exploration in using digital technologies for the production of architecture, her current research agenda focuses on developing innovative material and construction solutions using customised robotic devices, with a particular interest in additive manufacturing for architecture. Marta graduated from ETSAB-UPC (Barcelona) in architecture, holds a master's degree in Advanced Architectural Design from Columbia University (New York), and is currently a PhD candidate at the ETSAB-UPC (Barcelona), investigating the potential of large-scale additive manufacturing technologies to innovate building construction.

ARETI MARKOPOULOU is a Greek architect and educator whose research and practice design explores new architectural models where applications of ICT, energy and fabrication allow built and public space to dynamically adapt to behavioural and environmental changes over time. She holds an MArch by IaaC in the field of 'Prototypes of Urbanity: from Bits to Geography' and a Fab Academy diploma on Digital Fabrication offered by the MIT Center for Bits and Atoms and the Fab Lab Network. She is permanent faculty at IaaC with several published articles internationally. Co-founder of the

Mycity-me nonprofit organization, her practice includes project collaborations with multidisciplinary offices and institutions and she has participated in R + D projects ranging from intelligent cities (such as 'Smart BCN' with City Hall Barcelona, 2013), self-sufficient buildings (such as 'Fab Lab House' at Solar Decathlon Europe, 2010), digital fabrication (such as 'Fabrication Laboratory' at DHUB, 2010) and Internet of things (such as 'Hyperhabitat' at the XI Venice Biennale, 2008). She is currently the Director of the Masters in Advanced Architecture at IaaC in Barcelona and initiator and partner of Fab lab Athens in Greece.

KEVIN MCCLELLAN is a designer, artist and founder of Architecturebureau, a design research office exploring complex systems and their material effects on form. After receiving his master's degree in Architecture and Urbanism from the DRL at the Architectural Association School of Architecture with a Project Distinction in 2005, he subsequently worked in New York for Kevin Kennon and in London with Zaha Hadid Architects. In 2011, he co-founded the UK-based Dsigndot, an online marketplace for the sale of unique and collectable designs.

WES MCGEE is an Assistant Professor in Architecture and Director of the Fab lab at the University of Michigan, Taubman College of Architecture and Urban Planning. As a founding partner and senior designer in the studio Matter Design, his work spans a broad range of scales and materials, always dedicated to re-imagining the role of the designer in the digital era. In 2013, Matter Design was awarded the Architectural League Prize for Young Architects & Designers. Wes has presented his work at many national and international conferences on design and fabrication. He is Chair of the Conference Robotic Fabrication in Architecture, Art, and Design, hosted at the University of Michigan in 2014.

ACHIM MENGES is a registered architect and professor at the University of Stuttgart, where he is the founding director of the Institute for Computational Design (since 2008). In addition, he has been Visiting Professor in Architecture at Harvard University's Graduate School of Design (2009–10), at the AA School of Architecture in London (2009–current) and at Rice University in Houston (2004). Achim Menges graduated with honours from the AA School of Architecture in London (2002), where he subsequently taught as Studio Master of the Emergent Technologies and Design Graduate Program (2002–09) and as Unit Master of Diploma Unit 4 (2003–06). Achim's practice and research focuses on the development of integral design processes at the intersection of morphogenetic design computation, biomimetic engineering and computer-aided manufacturing that enables a highly articulated, performative built environment. His work is based on an interdisciplinary approach in collaboration with structural engineers, material scientists and biologists. He has published several books on this work and related fields of design research, and is the author/co-author of numerous articles and scientific papers. His projects and design research have received many international awards, has been published and exhibited worldwide, and form parts of several renowned museum collections.

AMMAR MIRJAN is an architect with a background in automation engineering. He studied at the Berne University of Applied Sciences and at the Bartlett School of Architecture in London. He has worked for different architecture studios in New York, Tokyo and London. In 2011, he joined ETH Zurich, where he is currently pursuing his PhD at the Chair for Architecture and Digital Fabrication. His research focuses generally on the relationship between design and construction with intelligent machines and specifically on architectural fabrication processes with flying robots.

MICHAEL JAKE NEWSUM is the Robotics Lab Coordinator at the Southern California Institute of Architecture. His work currently focuses on the development of computational tools for the integration of design and fabrication through new robotic workflows. He received a Master of Science in Architecture with a concentration in Digital Technologies from the University of Michigan, Taubman College of Architecture and Urban Planning. Additionally, he earned a bachelor's degree in Architecture from the University of Arkansas, Fay Jones School of Architecture.

PETR NOVIKOV holds a master's degree in Architecture from Moscow Architectural Institute and a master's degree in Advanced Architecture from IaaC. Petr is co-inventor of the Stone Spray technology, which was created during a digital tectonics course at IaaC. The project received the Golden Prize of Spark Awards 2012. During the Open Thesis Fabrication program of IaaC in 2012, he and Saša Jokić worked on the new 3D printing technology Mataerial. Petr has given numerous lectures on the use of robotics in architecture. In 2013, he was featured in *ICON* magazine as one of 50 people pushing the boundaries of architecture.

NERI OXMAN is the Sony Corporation Career Development Professor and the Director of the Mediated Matter Research Group at the MIT Media Lab. Her group conducts research at the intersection of computational design, digital fabrication, and materials science, applying that knowledge to design across scales from the micro-scale to the building scale. Neri coined the term 'material ecology' to describe her work, applying the science of ecology to the world of the artificial. A leader in the field of biologically inspired digital fabrication, her research and design work have been acquired for permanent collections and exhibited at the Museum of Modern Art (NY), Centre Georges Pompidou (Paris), the Museum of Fine Arts (Boston), and the Smithsonian Institute, among others. Neri was named in *ICON*'s list of the top 20 most influential architects to shape our future (2009), selected as one of the 100 most creative people by FASTCOMPANY (2009) and awarded the Earth Award (2009), a METROPOLIS Next Generation Award (2009) and the 40 Under 40 Building Design + Construction Award (2012) amongst many others. She publishes and lectures worldwide.

LAURENT PAMBAGUIAN obtained his PhD in Material Science in 1994 from Paris XI University for the work he did at ONERA, the French Aerospace Lab. Over the last 20 years, he has developed expertise in several advanced materials and processes topics, including metal matrix composites for structures, thermal management and lubrication, cellular materials and carbon nanotube-based materials. He joined the Materials Technology Section of ESA in 1999 and for the last eight years has been involved in the development of additive manufacturing technologies for space use.

BRIAN PETERS is an architect and designer who specialises in emergent design and fabrication techniques. He received a Master's of Architecture from the University of Illinois at Chicago and worked for several years as an architect in Chicago. In 2009, Brian moved to Barcelona, where he received a Master of Advanced Architecture with an emphasis on digital tectonics from the Institute of Advanced Architecture in Catalonia. More recently, Brian was based in Amsterdam, where he started several projects investigating the role of 3D printing in architecture, including Building Bytes and the KamerMaker with DUS Architects. As of the fall of 2013, Brian is teaching and conducting research at Kent State University in the College of Architecture and Environmental Design.

DAVE PIGRAM is a designer, researcher and educator and holds a Master of Science in Advanced Architecture from Columbia University. As co-director of the international, award-winning architecture and innovation practice supermanoeuvre, his research focuses on the use of computation to increase the number and quality of feedback loops between design and fabrication. Dave is currently the Director of the Master of Advanced Architecture programme at the University of Technology, Sydney (UTS) and co-directs research into robotic fabrication at the University of Michigan and is a Research Affiliate at MIT's Media Lab.

JORDI PORTELL is a practising registered architect who has become increasingly dedicated to research as a result of being a master's level student, and later a faculty assistant at the FABbots Research Studio directed by Marta Malé-Alemany. He holds a professional degree in architecture from the ETSAB UPC-Barcelona and a Master's in Advanced Architecture from the IaaC Barcelona. His research is focused on the application of additive manufacturing techniques in architecture, with a special interest in multi-material systems and complex material networks.

JONATHAN RABAGLIATI is an artist whose field of practice extends across architecture, art, design and curation. He is one of the longest-serving members of the Specialist Modelling Group at Foster + Partners. Recent projects include the design and delivery of Canary Wharf Crossrail Station roof, a hypotrochoidal staircase for Bloomberg and defining geometry for the National Bank of Kuwait tower. He engages primarily through sculpting with code, and wrestling with design systems to seek out simplicity, the other side of complexity. In the interstices, he regularly collaborates with Julie Kim, where graphic design meets in a critical dialogue with conceptual art and computational experimentation.

METTE RAMSGAARD THOMSEN is an architect working with digital technologies. Her research centres on the relationship between crafts and technology framed through 'digital crafting' as a way of questioning how computation, code and fabrication challenge architectural thinking and material practices. Mette is a Professor at the Royal Danish Academy of Fine Arts, School of Architecture in Copenhagen, where she heads the Centre for Information Technology and Architecture (CITA).

STEFFEN REICHERT is a research associate and doctoral candidate at the Institute for Computational Design at the University of Stuttgart, Germany. He received a Master of Science in Architecture Studies in the field of design and computation from the Massachusetts Institute of Technology (MIT) and a diploma degree with distinction in product design from the Academy of Arts and Design in Offenbach. His research focuses on the relationship of form, fabrication and performance in responsive, biologically inspired systems based on anisotropic material behaviour.

KATJA RINDERSPACHER is a doctoral candidate at the Institute for Computational Design at the University of Stuttgart and a registered architect. She holds an engineering degree from the Fachhochschule Mainz and a Master of Science in Architecture with honours from Pratt Institute, New York. Her work was distinguished by scholarships (e.g. Fulbright Scholarship, DAAD/German Academic Exchange Service) and awards (e.g. Excellence in Academic Achievement Award). As an architect and project manager, she worked in New York, Switzerland and Germany, including Studio Daniel Libeskind. Her current research involves the integration of geomorphological processes in computational design and digital fabrication for the construction of complex structures.

JEAN ROULIER was trained as joiner, carpenter and wood building engineer. Having accumulated extensive experience in CAD in practice, he co-founded the company Lignocam SA in 2006 in order to develop CAM software for the wood industry. Since then, the homonymous software Lignocam has become the leading CAM software interpreting BTL files. Its objective is the promotion of wood in construction – even the most daring ideas – as well as the realisation of a smooth digital chain in the construction and fabrication process.

VIRGINIA SAN FRATELLO and **RONALD RAE** are architects, artists and educators. They are partners at Rael San Fratello and in Emerging Objects, which is a pioneering design and research company that specializes in 3D-printed materials and objects for the built environment based in Oakland, California. Ronald is Associate Professor at the University of California Berkeley and Virginia is Assistant Professor in the area of Design at San Jose State University. They both hold Master of Architecture degrees from Columbia University in the City of New York. Their research focuses on the convergence of digital, ecological, and creative material explorations. The research is applied through the design and fabrication of innovative buildings and their components, furniture elements and site-specific installations that often look at inherent material resources and have embedded political consequences. Rael San Fratello was the recipient of Metropolis Magazine's Next Generation Design Award for their Hydro Wall concept, a finalist in the WPA 2.0 design competition and winner of the Van Alen Institute's Life at the Speed of Rail competition. Rael San Fratello was voted one of '10 to watch' by *California Home and Design* magazine. Their work has been published in *Metropolis* magazine, *L'Arca*, *DOMUS*, the *NY Times*, *Interior Design* magazine, the *Praxis Journal of Writing and Building*, *Make* magazine and *MARK* magazine.

JOSE SANCHEZ is an architect/programmer/game developer based in Los Angeles, California. He obtained his licence at Universidad de Chile, in Santiago and his Master in Architecture at the Architectural Association's Design Research Lab, London. He is a partner at Bloom Games, a start-up built upon the BLOOM project, winner of the WONDER SERIES hosted by the City of London for the London 2012 Olympics. He is the director of the Plethora Project, a research-based practice investing in the future of on-line open-source knowledge propagation. The project has over 150 videos and an open-source library of code with over 700,000 completed video sessions since 2011. His background in computational design and digital manufacturing is linked to the practice Biothing, where he has been one of the principal designers in numerous projects and exhibitions since 2009. In 2012 he founded the Plexus talks at the Bartlett School of Architecture, bringing together designers from different disciplines speculating on the role of computational design and new media in the practice of the discipline. Today, he is Assistant Professor at USC School of Architecture in Los Angeles and Co-Chair of ACADIA Conference 2014, to be hosted at USC. His research 'Gamescapes' explores generative interfaces in the form of video games, speculating on modes of intelligence augmentation, combinatorics and open systems as a design medium.

FABIAN SCHEURER is founding partner of designtoproduction and leads the company's office in Zurich. He graduated from the Technical University of Munich with a diploma in computer science and architecture. In 2005, designtoproduction was founded as a research group at ETH to explore the connections between digital design and fabrication. At the end of 2006, designtoproduction teamed up with architect Arnold Walz and became a commercial consulting practice, since then having implemented digital planning and production chains for projects like the Hungerburg-Funicular in Innsbruck (by Zaha Hadid), the Rolex Learning Center in Lausanne

(by SANAA), or the Centre Pompidou in Metz (by Shigeru Ban) among others. Fabian Scheurer has taught as guest lecturer/tutor at the AA in London and the laaC in Barcelona. Since 2012, he has been a lecturer for Digital Modelling and Production at HTW Chur.

TIM SCHORK is co-director of MESNE Design Studio and a lecturer in the Department of Architecture at Monash Art Design & Architecture (MADA). His integrated design-based practice, research and teaching investigate the relationship between architecture and divergent domains of knowledge through the use of computation in order to create innovative design strategies for novel spatial structure. His work is trans-disciplinary and fosters connections between and across disciplinary domains such as architecture, other art and design disciplines, engineering and science in order to innovate in design, often challenging the operative boundaries as well as formal and conceptual aesthetics of what is regarded as standard architectural practice.

TOBIAS SCHWINN is a research associate and doctoral candidate at the Institute for Computational Design at the University of Stuttgart. His research focuses on the integration of robotic fabrication and computational design processes. Prior to joining the ICD, he worked as a Senior Designer for Skidmore, Owings and Merrill in New York and London applying computational design at various planning stages. Tobias studied architecture at the Bauhaus University in Weimar and at the University of Pennsylvania in Philadelphia as part of the US-EU Joint Consortium for Higher Education. He received his engineering degree in 2005.

MATTHEW SHAW is an architect, maker and educator based in London. His work is driven by the speculative use of digital technologies, the impact these technologies will have on our lives and the way they shape our architecture. Matthew is co-founder of ScanLAB Projects, tutor at the Bartlett School of Architecture, University College London, and Director of Graticule Architecture.

BOB SHEIL is an architect, Professor in Architecture and Design through Production, and Director of Technology at the Bartlett School of Architecture, where he also runs MArch Unit 23 with Emmanuel Vercruysse and Kate Davies. He is a founding partner of sixteen*(makers), whose work in collaboration with Stahlbogen GmbH '55/02' won a RIBA award for design in 2010, and also includes a ten-year catalogue of experimental projects both internationally published and exhibited. He is an educator, critic, researcher, collaborator and practitioner, as well as an experimental designer who is fascinated by transgression between making, craft, and technology, in architectural design practice. As Director of Technology, he has been responsible for the School's significant acceleration of investment in digital technologies, which led to the establishment of the Digital Manufacturing Centre (2009) and more recently, the Bartlett Manufacturing and Design Exchange (B-MADE). In 2011, he chaired the highly acclaimed inaugural conference FABRICATE with Ruairi Glynn.

MIKE SILVER is an architect, researcher and educator. He is currently on the faculty of the Department of Architecture at the University of Buffalo. Mike directs a multidisciplinary design laboratory that explores emerging technologies such as humanoid robotics, automated fibre placement and mobile design apps for on-site construction. His work has been exhibited at the New Museum of Contemporary Art in New York, the International Design Center Nagoya, the National Building Museum in Washington, DC, the Architecture League in New York and the Cooper-Hewitt National Design Museum, also in New York. He built his first working robot out of Scotch tape and spirograph parts at the age of 12.

ASBJØRN SØNDERGAARD is an architectural researcher working in the field of digital fabrication in relation to architectural design. He is coordinator of Digital Experimentation at the Aarhus School of Architecture, Chief Development Officer and founding partner of Odico Formwork Robotics, a high-technology enterprise framing architectural design experimentation and fabrication in the field of industrial robotics. As the academic project manager of several interdisciplinary research projects, he heads investigations into structural design and architectural robotics. His doctoral research focuses on morphogenetic processes and the development of novel structural logics in relation to numerical fabrication techniques.

DAVID STASIUK is an architect and PhD Fellow at the Centre for Information Technology and Architecture in Copenhagen. His research investigating development strategies for emergent parameterisation is a component of the Centre's larger, multi-pronged Complex Modelling project. His own work is focused on investigating the development of emergent parameter spaces through the integration of simulation systems with topological transformation. His professional work has focused on bespoke detailing for advanced architectural geometries, computational design implementation, and the use of digital fabrication and documentation techniques, some of which was presented at the ACADIA 2012 conference.

HANNO STEHLING is consultant for digital fabrication and parametric modelling at the digital fabrication consultancy designtoproduction in Zurich. He graduated with a diploma in architecture from University of Kassel, where he studied under Prof. Manfred Grohmann (Bollinger + Grohmann) and Prof. Frank Stepper (Coop Himmelb(l)au) and is Dipl.-Ing. Architekt SIA. He has a strong background in computer programming and gradually focused his studies on the intersection between architecture and computer science. He worked as a freelance programmer and as computational designer for renowned architects such as Bernhard Franken before joining designtoproduction in 2009. Hanno Stehling is co-founder of the online platform RhinoScript.org and gives modelling and scripting classes to both academic and professional audiences.

KASPER STOY is a robotics and embodied artificial intelligence researcher holding an Associate Professor position at the Software and Systems Section of the IT University of Copenhagen. He has published more than sixty papers in international conference proceedings or journals and is the author of *Self-Reconfigurable Robots: an Introduction*, published by MIT Press. He holds an MSc degree in computer science and physics from the University of Aarhus, Denmark (1999) and a PhD in computer system engineering from the University of Southern Denmark (2003), where he also worked as Assistant Professor (2003–6) and Associate Professor (2006–13).

MARTIN TAMKE is an architect pursuing design-led research on the interface and implications of computational design and its materialisation. His special focus is on the methods and consequences of digital fabrication and the integration of simulation and feedback in the process of architectural design and production. Martin is a founding member and Associate Professor at the Centre for Information Technology and Architecture (CITA) at the Royal Danish Academy of Fine Arts, School of Architecture in Copenhagen.

KADRI TAMRE is an architect, currently working as a Teaching and Research Associate at the Institute for Experimental Architecture, Hochschule at the University of Innsbruck. She holds a master's degree in Architecture from the University of Applied Arts Vienna / Studio Wolf D. Prix and has working experience in architectural practices in Austria, Estonia, Spain and China, receiving several awards and scholarships. She has been teaching various international parametric design and robotic fabrication workshops. Her

current research focuses on the development of novel interface and material processes and she is co-running the University of Innsbruck's robotic laboratory.

LAVENDER TESSMER is a designer, fabricator and musician. Currently a lecturer at Washington University of St. Louis, she is teaching courses in architectural representation and digital fabrication. Since 2010, Lavender has worked with Yogiaman Tracy Design (yo_cy) on a variety of installations and residential and commercial projects. Her specialisations include parametric design, steel fabrication, connection design, visualisation and material testing. As a recent graduate of Washington University in St. Louis, she received the 2011 Laskey Award, a Fall 2011 Degree Project Award, and was nominated for the Frederick Widmann Prize in Architecture.

SKYLAR TIBBITS is a trained architect and computer scientist whose research focuses on self-assembly technologies for industrial applications in a built environment. Skylar was recently awarded a 2013 Architectural League Prize, the Next Idea Award at Ars Electronica 2013, the Visionary Innovation Award at the Manufacturing Leadership Summit, a 2012 TED Senior Fellowship and was named a Revolutionary Mind in *SEED* magazine's 2008 Design Issue. He has designed and built large-scale installations around the world and exhibited at the Guggenheim Museum NY, the Beijing Biennale and lectured at MoMA and SEED Media Group's MINDo8 Conference. Skylar is the Director of the Self-Assembly Lab at MIT and the founder of a multidisciplinary research-based practice, SJET LLC. Skylar is also on the faculty of MIT's Department of Architecture, teaching master's and undergraduate-level Design Studios and co-teaching How to Make (Almost) Anything at MIT's Media Lab.

KENNETH TRACY teaches architectural design at the American University of Sharjah, United Arab Emirates, where he is an Assistant Professor of Architecture. Kenneth has taught at the Pratt Institute, Columbia University, the New Jersey Institute of Technology, and Washington University, where he established the Digital Initiative Fabrication Research Lab in 2009. He holds a master's degree in Architecture from Columbia University and a bachelor's degree in Design from the University of Florida. In 2005, he co-founded Associated Fabrication, a digital fabrication shop in Brooklyn, New York. Currently, Kenneth co-directs Yogiaman Tracy Design, whose research includes designs, lectures and writing related to digital techniques and culturally resonant craft practices.

WILLIAM TROSSELL graduated from the Bartlett School of Architecture, University College London, in 2009. Since completing a master's degree in Architecture, he has created structures, sculptures and events that draw on an extensive understanding of digital fabrication. Will is co-founder of ScanLAB Projects and tutor at the Bartlett School of Architecture.

ERIK VERBOON is an Associate with Buro Happold New York, drawing upon more than seven years' experience developing computational solutions to advance the Buro's Complex Building Envelope Design practice. His research areas include parametric modelling, object-oriented methodologies, performance- and algorithmic-driven design, environmental and thermal analysis, and rapid prototyping (3D printing). Erik collaborated on the winning entry to the 2007 PS1 Young Architects Program. He has also presented at numerous academic institutions and professional conferences and published in accompanying journals and books. A graduate of the Stevens Institute of Technology's Product Architecture Lab in Hoboken, NJ, he teaches courses there in environmental analysis and design.

ANDREW VRANA is a Principal Architect at Metalab, based in Houston, which integrates expertise in digital media and fabrication with architecture, product development and civic art, from concept through construction. Recent projects include collaborations with artists for turnkey designs and CMservices, including development, optimisation and installation of large-scale civic art. Metalab's product design work has successfully incubated and launched several businesses and product lines through its partnerships. As Assistant Professor at the University of Houston's College of Architecture, Andrew has co-taught the Digital Fabrication seminar since 2005, which has realised numerous award-winning and published works.

ALLISON WEILER is currently working as a Teaching and Research Associate at the Institute for Experimental Architecture, Hochbau at the University of Innsbruck. She also works with LAAC Architekten/Austria in the realm of sustainable Alpine infrastructure development, as well as collaborating with [uto]. She graduated with honours from the University of Pennsylvania, and holds a master's degree in Architecture. Her current research focuses on the development of novel interface and material processes, and she is currently pursuing this work with the REX|LAB, an experimental architectural robotics lab based in Innsbruck.

CHRISTINE YOGIAMAN is an Assistant Professor at the American University of Sharjah in the United Arab Emirates, where she teaches architectural design. Integrating digital technologies into all levels of architecture design education, Christine has coordinated the Graduate Core Studio sequence in conjunction with her development of a digital curriculum in Washington University in St Louis. She directs Yogiama Tracy Design, whose current projects in Indonesia focus on the utilisation of digital techniques along with contextual influences to create culturally embedded, affective work. She received third place for the 2012 Steedman Fellowship in International Design, and has won the 2012 TEX-FAB APPLIED: Research through Fabrication competition.

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