INTRODUCTION
So, here we are with the third iteration of the built environment’s thinking and making biennial celebration: FABRICATE 2017. What began as a polar comparison between the 2011 and 2014 events has developed into a series through which to take stock of the fast-changing fabrication design landscape. Rather than simply reweighing greater sophistication and quicker processes six years after the inaugural event, we believe that the contents of this volume attest to a seismic shift in both professional outreach and construction application, and to a striking expansion in the field of players. Surveying the landscape, practices, industries and design education institutions have even more to draw upon that will boost their confidence as regards the required time commitment and budget to push research and education in fabrication further. Shifts in perspective concomitant with greater investment will be rewarded by the cultural and practical benefits of adventurous, high-quality, responsive architecture produced with correspondingly reduced costs and minimised environmental impact. Looking beyond the immediate glamour of FABRICATE, instead of expertly applying traditional craft and practice, there is a palpable shift in the exception within a shifting set of design priorities. The editor is reassured to find that this year’s take-up of generic and high impact (as opposed to project-specific) scale. It is rewarding, too, to see more projects that speak for and demolished. 

While pavilions have been crucial prototypical conversation starters, the editors are reassured to find that this year’s take has moved to more built examples, some even at a heroic scale. It is rewarding, too, to see more projects that speak of and high impact (as opposed to project-specific) transformations to the way we design and make. FABRICATE surely wants to pull us towards a post-digital design-making maturity where design intention, computational abstraction and automated fabrication and assembly are positioned more as the norm than as the exception within a shifting set of design priorities. This we look for exception not just through stand-out, game-changing examples but through a palpable shift in context towards enhanced building performance in addition to the usual preoccupations about appearance. Work addressing this expanded field of challenges can be readily discerned through surveying this book’s contents.

Whereas we might have been collectively drawn to more singular iconic formalist adventures in recent years, there seems to be greater emphasis on process in FABRICATE 2017’s published projects, not necessarily pointing solely to a concrete outcome but to fresh approaches to transforming ideas into fabricated, tangible outcomes. We can see this by looking at the acknowledgements in many of the exhibited projects – most notably the growing range of disciplines contributing to this fast-evolving dialogue. These transdisciplinary teams include not just the designers, computation and robotics experts and builders, but also – and increasingly – materials scientists and engineers, industrial designers, process and systems specialists, diverse manufacturers and informed end-user participants, to name just a few.

The projects here have been selected from an almost overwhelmingly large pool of candidates, and together are the conscious vector for the questions we might embrace over the coming years. What is the role of schools of architecture and design in all this? Realistically, how can schools participate fully in the face of burgeoning student numbers (in many countries) that make the necessary access to hands-on experimentation with expensive machinery difficult to achieve? And what radical changes in syllabus will be required to ensure that students and researchers are appropriately acclimatised so that they can participate meaningfully in the increasingly diverse design and build teams, beyond mere speculative engagement? These questions are not necessarily in the purview of FABRICATE 2017 in terms of providing answers, but the event and this published record will help fuel the argument for further change in the design and construction industries priorities. They will especially stimulate greater confidence to make the most of trans-disciplinary opportunities. These are opportunities that learning and research institutions such as universities are uniquely equipped to provide, yet so rarely seem to be able to fulfill by the rhetoric. Tuning from the event present, the thinking and making community have John Ruskin as their friend, for it was he who so eloquently called on thinkers and makers to make themselves consciously aware of each other’s contributions.

And yet more, in each several profession, no master should be too proud to do his hardest work. The painter should grind for the sake of his own colours; the architect work in the mason’s yard with his men; the master-manufacturer be himself a more skilful operative than any in his mill; and the distinction between man and machine be only in experience and skill; and the authority and wealth which these must naturally and justly acquire.

Any sceptic who wonders why design schools invest in robots and 5-axis routers over a century and a half later should be clear that such technology is not about assimilating the expertise of others or about dabbling dilettantism. Rather, these contemporary tools are the vital horizon expanders and justly obtain. 1

As the editors of FABRICATE 2017, we have many people to thank. In the first instance, with over 250 submissions from 45 countries, we wish to thank everyone who responded to the call for works, an achievement requiring perseverance and commitment on all sides. We also thank all authors and collaborators on every selected project, and everyone who has kindly agreed to present. Each submission took time and involved others in addition to those who authored the content, so we wish to thank all the teams behind every submission—the assistants, the copy editors, the photographers and the IT teams who ensured that our networks didn’t go down hours before the deadline. We also wish to thank the administrators who ensured that every submission was received, catalogued and of processing them ran smoothly, no matter where those networks went down.

In Stuttgart, Achim would like to express his gratitude to the entire FABRICATE team at the Institute for Computational Design and Construction. First and foremost, thank you to Nicola Buggia for her extraordinary effort in heading the administrative team and for her tireless engagement in preparing FABRICATE in Stuttgart since January 2016. Britta Kurka and Scottie McDaniell have also contributed extensively to various organisational matters. Without this team, the conference would not have been possible. Thank you! In addition, thank you to all the other ICD researchers and students who helped with the wide range of aspects that needed to be taken care of for such a major event. We are lacking the space here to mention all contributions in detail but, again, FABRICATE would not have been possible without the tremendous effort and passion of this fantastic group of people—very well done! Thanks, too, to the University of Stuttgart for providing an excellent context for our research activities, which included making it possible for us to host such a remarkable event.

Each edition of FABRICATE has adopted different organisational models. In 2011, both the event and the book were handled by a small local team at The Bartlett School of Architecture, UCL, led by the project’s founders, Ruairi Glynn and Bob Sheil. FABRICATE 2014 was managed by a team at ETH Zurich, led by chairs Fabio Gramazio and Matthias Kohler, with Silke Langenberg and consultancy from Marilena Skavara. Arrangements for FABRICATE 2017 have been supervised as a collaboration between the Institute for Computational Design, University of Stuttgart, and The Bartlett School of Architecture, UCL, with ICD taking the lead on the conference.

In London, Ruairi and Bob wish to start by thanking Marilena Skavara, who has been involved in every event and production since 2011 as an utterly pivotal figure in the entire enterprise. Now co-editor, Marilena’s key role is fully recognised, as is the impact of her strategic contribution and judgment. So now, as an editorial team of three, we each wish to thank the following people, who have helped us to assemble this wonderful publication. To all, our project editor, has approached it with unlimited reserves of patience and good humour, and her assistant, Alexema Gray, transcribed the interviews between our keynote speakers with forensic skill and concentration. We offer sincere thanks to Dan Lockwood and Patrick Morrissey, our meticulous proofreader and designer respectively, both of whom have executed their tasks with elegance, patience and beauty. Thank you to Lara Spiecher, Publishing Manager at UCL Press, and her team, including Chris Pentfold, James Biggs and Alison Major—we have hugely enjoyed working on our second project with you within six months. It’s also deeply satisfying and enjoyable to be back in partnership with Riverside Architectural Press, led by the inspiring Philip Beesley and his general manager Salvador Miranda. Thank you to James Curwen, Luis Rego and Thomas Abbas for their generous assistance. Finally, we wish to thank those responsible for the tactile experience that you, as reader, are enjoying now. To Tom Gohara and Hugh Jolly of Albion Coker printers: we salute your passion for craft and detail, and deeply appreciate your kindneds and tolerance—qualities that are vital in the making of well-made things.

Finally, from Stuttgart and London, we extend our sincere thanks to all our sponsors, as it is their support that enables FABRICATE to be disseminated widely. Thank you to our Diamond sponsors Autodesk, our Platinum sponsors FARO, Design-to-Production and Trimble. Achim Menges, Bob Sheil, Ruairi Glynn and Marilena Skavara

ACKNOWLEDGEMENTS

1. FABRICATE 2017 peer reviewers Francis Aish, Ehsan Baharlou, Martin Berchtold, Mike Brooks, Daniel Bruce, Mark Burry, Juan-Carlos Contreras, Kwan-Wei Eu, Katrin Fidder, Motiz Dostcumer, David Genzel, Ruairi Glynn, Julian Helm, Jason Kukar, featuring Belarus architects Matomskis, Oliver Kregel, Julian Leonard, Achim Menges, Philipp Moser, Calvin Mueller, Farzad Moshkeri, Niek Neerens, Patrick Okdie, Marissa Sansone, Yassine G Arachid, Tobias Schwinn, Asbjørn Søndergaard, Robert Stuart-Smith, Oliver Tessmann, Tobias Schwinn, Adrian Landerl, Robert Stavr Smilé, Oleksandr Tishkiv, Luis Abbs for their generous assistance.
In the beginning, the idea of a conference that explored the currents between technology, design and industry emerged from the need to understand the ever-changing shape of the world around us. In the six years since the first event, we have received over 800 submissions from more than 40 institutions across 30 countries. From this pool, we have selected 96 papers for publication and 48 for presentation, alongside 12 highly distinguished keynote lecturers. A team of eight Conference Chairs, 12 editors, 12 Panel Chairs and 90 peer reviewers have been intimately involved throughout.

FABRICATE is now widely regarded as the leading international forum in which centres of excellence in architecture, design, engineering and manufacturing can engage, collaborate and create. It has become a unique public platform for open debate on how these disciplines exchange and evolve their design and making expertise.

At its heart, FABRICATE is about doing, the where, who, what, why and how of doing. While it was not initially envisaged as a series, that it would become one was perhaps inevitable. From 'Making Digital Architecture' (2011) to 'Negotiating Design and Making' (2016), FABRICATE has set the agenda during an extraordinary period for the built environment – one which witnessed inspiring collaborations in which expert representation has met expert realisation, and vice versa. The extraordinary range of projects issuing from both were further categorised into the following themes: 'Physical Processes', 'Material/Systems', 'Making and the Bespoke' and 'Representation and Manufacturing'. By FABRICATE 2014, 'Negotiating Design and Making', at ETH Zurich, the event's themes had evolved into 'Challenging The Thresholds', 'Material Enwanced', 'Forming Machines' and 'Living Assemblies'. Chairied by Fabio Gramazio and Matthias Kohler, pioneers of robotic architecture, the event surveyed the extraordinary range of projects issuing from both were.

INTRODUCTION

BOB SHEIL & ACHIM MENGES

Welcome to FABRICATE 2017: 'Rethinking Design and Construction'. This is the third volume in a triennial series of conference publications that began with 'Making Digital Architecture in 2011 at The Bartlett School of Architecture, University College London. From this origin in one of the world’s leading cities for design excellence, in 2014 FABRICATE moved to ETH in Zurich, a pioneering science and technology university, where its theme was ‘Negotiating Design and Making’. In 2017, we are at the Institute for Computational Design and Construction, University of Stuttgart, a world-renowned research lab in design for construction, located in Europe’s innovative and forward-thinking industrial heartland.

Each FABRICATE conference and book evolves from an open call for ‘works in progress’, with a submission deadline ten months prior to the conference. The call is designed to attract submissions from industry and practice as well as academia, and asks for an abstract on the trajectory of the work, including where it will be by the time the conference takes place. Selected projects may then be invited to submit full papers for a second round. The conference theme emerges during this phase, while papers are also categorised into notional sub-themes.

Thus FABRICATE is itself a work in progress about works in progress: an event and a publication that conveys at a point and place in time what is being made both still evolving and ready for sharing. This approach extends to how authors are encouraged to further translate their work as speakers. They are encouraged to go off-script, question and reinvent their medium, reveal what lies between the lines and add any new ideas that have come into play. Writing, after all, is no different to drawing or making – they are all forms of representation that we rely on to make sense of the world. Not only are the evidence and documentation of design and making critical to FABRICATE, but ‘talking, showing and rethinking are, too.

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FABRICATE 2017 recognises how much has changed since 2011. Once the final selection of papers was made, it was clear that the chosen projects were of a significantly larger scale in terms of both size and reach. The categories ‘Production’, ‘Materialisation’, ‘Additive Strategies’ and ‘Construction’ made immediate sense, as did the conference title, ‘Rethinking Design and Construction’.

One key point that has emerged is that we can no longer talk in general terms about ‘digital architecture’. Such a generalisation no longer seems to do justice to the multifaceted cultures of computational design and digital fabrication, their finely differentiated approaches and their diverse physical manifestations – which are explored both in the book and at the conference. Equally, we are witnessing a rapidly blurring boundary between computational design and digital fabrication. The clear line that once existed between these two domains has become increasingly questioned by cyber-physical productions systems and challenged by new forms of man-machine collaboration (designer and robot collaborations, in most cases), which form the basis of a significant number of submissions.

In Germany, this leap forward in the way we design, engineer and produce is often referred to as ‘Industry 4.0’, a term that originates from the high-tech strategy of the German government and indicates the significance of these developments as catalysts in a fourth industrial revolution. FABRICATE 2017 suggests that Industry 4.0 will have – indeed, is already having – a profound impact on the way future built environment is conceived, designed and materialised.

Stuttgart is situated in the heartland of advanced manufacturing, and the south of Germany is home to a large number of micro-leaders and hidden champions, small-to-medium scale businesses that are leading in their respective technological fields. The University of Stuttgart is renowned for creatively engaging with these advanced industries and bringing to such engagements the rigour and insight of its skilled and specialist faculty and students. The most recent manifestation of this spirit is the ICD’s new Computational Construction Laboratory (Fig. 1). It is no coincidence that the opening of this lab coincides with this year’s conference, as it is this very spirit that we consider the ICD’s modest contribution to the continuing success of FABRICATE.

‘Rethinking Design and Construction’ therefore constitutes both a critical assessment and a provocation. On the one hand, it reflects the work of a range of extraordinary thinkers who are challenging old approaches to design and making through ingenious ways of mastering digital technologies and lateral thinking. On the other, it serves as a rallying cry to use computational technologies as vehicles for creative exploration and for making ground-breaking and bold collaborations that would otherwise not happen in academia or industry by themselves.
Autodesk space might be built from these instructions is a copy the realisation of his imagined edifice. Whatever occupied he is concerned, the building he draws is the real building, accurate realisation by the workmen of his day. As far as design intent in detail sufficient enough to ensure its

In Rome, a man labours over a drawing, recording his

diligent and severe Overseers to look after the

The rapid and sometimes instantaneous feedback of these computational structural design environments prefigured further advances of this type emerging today, conveying the promise of improved decisions about buildings when the professional can easily access

This is tantamount to inventing the modern architectural profession with its notion of design drawings and limited liability. Alberti made one of the first declarations of a representational strategy in construction, while

Brunelleschi, in suggesting that originating ideas about buildings was a separate and privileged predecessor to the act of actual construction. He declared:

...certainly it is enough if you give honest Advice, and correct Draughts such as to apply themselves to you. If afterwards you undertake to supervise and complete the Work, you will find it very difficult to avoid being made answerable for all the Faults and Mistakes committed either by the Ignorance or Negligence of other Men: Upon which Account you must take care to have the Assistance of honest, diligent and severe Overseers to look after the Workmen under you."

Brunelleschi and Alberti stand on either side of a historical shift between the Renaissance master builder and the modern architectural profession. In his treatise of 1452, De Re Aedificatoria, Leon Battista Alberti broke

In one sense, building engineers were quicker to transition to the emerging paradigm of design and drawing production that was finally termed Building Information Modelling (BIM). Acclimated to specifying manufactured components in the form of standard steel shapes, structural engineers were quick to adopt computational capabilities to model forces and select appropriate steel within the analytical environment. The rapid and sometimes instantaneous feedback of computational structural design environments prefigured further advances of this type emerging today, conveying the promise of improved decisions about buildings when the professional can easily access relevant information and encoded experiences in computerized building designs. Taking advantage of manufacturing standardisation and digital artefacts as proxies for fabricated objects, engineers in the early days of BIM were able to more closely unite design decisions to characteristics of materials and manufacturing conventions through the medium of computation.
Corresponding activities in the architectural professions of the time remained divorced from computational environments and largely the responsibility of the specification group, even among architectural firms or as an outsourced service to smaller firms, with most architects concentrating on the new possibilities for design understanding afforded by three-dimensional BIM and increasingly advanced computational rendering. For the first time, architects with less than decades of experience could understand the experiential aspects of space and light of their design choices before they were instantiated by construction. While the relatively rigid adoption of BIM by the architectural profession can once again be attributed to a quest for higher production efficiency, some architects quickly understood the possibilities in increasingly detailed digital representations of buildings as the medium of improved understanding and decisions (Fig. 5).

Like CAD before it, BIM arose from a fundamentally pervasive digital representation of finished objects. CAD software conceives of drawing sets as complex arrangements of lines, arcs and circles. Building information models are digital assemblies of generic and construction metaphors than to the design process. BIM, like CAD before it, has emerged from a fundamentally digital representation of finished objects, even more so than CAD before it. While the former stately progression of conceptual design, schematic design, design development, construction documentation, fabrication, construction, operation and renovation has given way to an increasingly optimised process of enveloping phases dependent on the delivery of complete trade packages that, in effect, become accountable for the building they conceptually and physically represent (Fig. 6). In a building market intolerant of sites fallow of anticipated revenue, design differentiation for the same project has afforded options in architectural design that are previously impractical if not impossible, realising the philosophies implicitly and explicitly shared by Brunelleschi and Alberti. Where the former’s regard for his verbal instructions and vegetable instruments of service as perishable media to convey intent has given way to the indefinite preservation of digital artefacts of design and construction planning, his sense of differentiation in understanding construction means and methods has required reanalysis to the architectural profession. It was Brunelleschi’s accurate assertion that he could complete the Santa Maria del Fiore Dome without the need for supporting scaffolding that won him the commission. However, Alberti’s “correct Draughts” remains the standard of care of architects to their clients even today, but the scope of architectural “Draughts” has become nearly as extensive as virtual construction of the intended building.

The facilitation of building representation by digital environments has served to further blur Alberti’s fundamental division between design intent and construction means and methods, already under attack by the modern economic pressures that compelled a faster speed of project delivery. The former stately progression of conceptual design, schematic design, design development, construction documentation, fabrication, construction, operation and renovation has given way to an increasingly optimised process of enveloping phases dependent on the delivery of complete trade packages that, in effect, become accountable for the building they conceptually and physically represent (Fig. 6). In a building market intolerant of sites fallow of anticipated revenue, design differentiation for the same project has afforded options in architectural design that are previously impractical if not impossible, realising the philosophies implicitly and explicitly shared by Brunelleschi and Alberti. Where the former’s regard for his verbal instructions and vegetable instruments of service as perishable media to convey intent has given way to the indefinite preservation of digital artefacts of design and construction planning, his sense of differentiation in understanding construction means and methods has required reanalysis to the architectural profession. It was Brunelleschi’s accurate assertion that he could complete the Santa Maria del Fiore Dome without the need for supporting scaffolding that won him the commission. However, Alberti’s “correct Draughts” remains the standard of care of architects to their clients even today, but the scope of architectural “Draughts” has become nearly as extensive as virtual construction of the intended building.

As BIM environments and their analytical elaborations and generative design successors gain computational capabilities and information access across resources available through cloud connectivity, the enhanced capabilities of digital environments, with their rapid evaluation of modelled building performance characteristics and delivery of highly relevant information critical to improved building decision-making, offer architects means to confidently assert priority in the process of conceiving and realizing buildings.

With the explosive growth of computational power in the second decade of the twenty-first century, the profession is entering a third era, beyond CAD and BIM, of potentially transformative digital capabilities in design and construction. Highly responsive computer processes of physical representation and simulation coupled with digital processes of fabrication, including material science, additive and subtractive manufacturing and robotic construction, are poised to change the essential landscape in which buildings are designed, built and operated (Fig. 7). Projecting this evolution forward, the third era in design computation takes advantage of the best qualities of both Brunelleschi and Alberti’s positions regarding the instrument of representation. Robust simulation and nearly unlimited computing power will...
combining with machine intelligence and generative design to deliver a further unification of intent and interest. Reality capture, digital fabrication and immersive design environments will provide a functionally identical model of digital and physical space. As design tools evolve, Brunsdon’s turnip and its associated conversation will become forever persistent in structured databases. The connectivity of this data will provide opportunities for machine learning, pattern recognition and design synthesis. Generative design systems will support the explicit modelling of knowledge from a variety of domain experts such that when the design requirements change new instructions in the form of drawings or models that describe the author’s intent will be automatically generated (Fig. 6).

This new class of design systems will allow all stakeholders in a building project to represent their intent at the level of detail that best corresponds with functional properties in models used for design, construction and building management. In the event of a budget change or a change in project constraints, the intent of the design team will be preserved or compromised through various strategies for generating solutions employed by the design system. As the accuracy and speed of simulations increase, a wealth of building performance data will become available and complex trade-offs between alternative approaches will be intuitively revealed. Compensation for design and construction services, as well as the standard of care for professional building services, will become associated with the ability to offer the guaranteed level of building performance ensured by these tools.

To realise a vision, the master builder must synthesise many competing objectives relative to changing external conditions. The archetypal master builder understands how design decisions reinforce intent through a sophisticated understanding of aesthetic, performance, constructability, cost and other objectives. In the next era of design practice, any stakeholder will be able to understand the propagating effects of a change and offer feedback that directly influences design decisions. Ease of design changes will ensure that any compromise of intent is comprehensively evaluated before construction takes place. The ability to quickly and easily adjust the needs of participants in the design and construction process will enable the master builder to deliver on their vision (Fig. 5).

Digital artefacts of design and construction are increasingly employed as operational artefacts for the functioning building, joined to a wide spectrum of physical sensors to convey gross and subtle operational behaviours into digital representations where options for elaboration and modification can be readily explored at minimal cost. In the coming era of widely available statistical performance information as furnished by a highly connected built environment, the knowledge and experience once sequenced in fragmented form across many design and construction experts, owners and facility managers will be consolidated and available to inform all design, fabrication and construction decisions. Reality capture technology will provide a “mirrored” representation between the digital artefact and the developing physical manifestation during the construction process and throughout the lifecycle of the building. Design and construction firms that embrace and extend the possibilities of digital enrichment will lead future building projects. Firms that fail to grasp the gains offered by the coming era of connectivity will find themselves becoming irrelevant in approaching time of exacting standards applied to desired building performance with the ready means to confirm predicted project behaviours (Fig. 10).

A generative design system employed in the design of Autodesk’s office in “Bebeto” produced an alternative solution, each respecting the goals and constraints specified by the design team.

Notes
Machines have the ability to manipulate material cooperatively, enabling them to materialise structures that could not otherwise be realised individually. Operating with more than one (mechanical) arm allows for the exploitation of assembly processes by performing material manipulations on a shared fabrication task. The work presented here is an investigation of such cooperative robotic construction, wherein two industrial robots assemble a spatial metal structure consisting of discrete steel tubes. The developed construction method relies on the alternate positioning of building members into triangulated configurations, where one robot temporarily stabilises the assembly while the other places a tube and vice versa. The intricate geometric dependencies of this structural system, as well as the fact that the machines limit each other’s operational range, led to the exploration of robotic simulation and path planning strategies as an integral part of the design process. The experimental results of realizing a space frame structure at an architectural scale (Fig. 2) validate this approach.
As a result, two tubes connect at one point. While this shifted node offers a high degree of freedom in respect to the final pose of the robotic end effector when focusing on the future robotic fabrication, it also presents structural challenges. In contrast to traditional space frame systems that join multiple neighbours via a shared centre point, the reciprocity of this expanded node induces flexural rigidity in the system, leading to a structure with a greater stiffness.

Each newly added tube connects at each side to two neighbouring elements with the objective of assembling reciprocally closed nodes. These configurations are able to take bending forces, although every constructive joint between two tubes is hinged in a static sense. As a result, each tube, once assembled into a tetrahedral configuration, is comprised of at least four connections, making two reciprocal nodes with their neighbours. During the build, the number of connections to an individual tube varies over time and may depend on the overall configuration. This novel construction system leads to geometric dependencies that require the use of computational design to explore possible spatial arrangements and to identify a fabrication sequence that considers the build-up of the structure into stable configurations accordingly.

The overall spatial organisation of the construction system is based on tetrahedra. A tetrahedron creates the minimum stable space frame structure. Combining a multitude of tetrahedra into larger, interconnected structures allows for the creation of complex load-bearing assemblies while ensuring the structural integrity of the individual tetrahedron and, as such, the controlled assembly of tubular elements into spatial aggregations. When designing such an arrangement, the order of placing tubular elements has to be defined. This is directly related to the later construction of the structure. The fabrication space changes over time. Therefore, it is crucial to define where and when to place the next building element and to which tubes it can connect, so that the computational design tool can find the appropriate geometrical solution for the tubular arrangements.

An important aspect of the design process, aside from the definition of the spatial arrangement, is the creation of the robotic movements that allow the integral verification of the fabrication feasibility. As described above, two cooperating robots are used to assemble the structure in a highly constrained three-dimensional space. A series of tests has shown that defining collision-free robotic movements is a challenging task that needs to be addressed at an early design stage. On one hand, this originates from the need to manoeuvre building elements into openings and gaps of already built parts to create the interlocking reciprocal joints, while avoiding collisions between the robot and the structure. On the other hand, the construction environment changes over time, as a result of the sequential and spatial build-up of the structure and of the continuously altering configurations of the robots, which limit each other’s operational range.

Rather than only calculating the final pose of the tool centre point (TCP), the approach required designing the robotic configurations, translated into axis rotations, determining the entire spatial arrangement of the robot over time. For this reason, path planning strategies and robotic simulation tools that linked to the computational design were investigated. The proposed solution makes use of a robotic simulation platform (Coppelia Robotics, 2016) that uses the power of sampling-based path planning algorithms (Kavraki Lab, 2012) to generate collision-free trajectories. A software tool was created in a CAD environment (McNeel, 2013, McNeel, 2015) in order
to integrate robotic simulation capabilities directly into the computational design process. The robotic trajectories can be generated by defining a start configuration of the robot and a desired end pose of the TCP, by outlining the robot’s joint motion or by setting a series of rapidly exploring random tree (RRT) algorithm-specific values, such as the sampling resolution. Following this method, a spatial configuration can be evaluated when deconstructing it, which can be adapted if needed. For example, if no tube was in a digital blueprint rather than based on what had already been built, the tolerances did not accumulate over time, which enabled a successful welding of the entire structure.

Successful cooperative fabrication

The work presented here successfully demonstrates the ability of cooperating robots to build large-scale structures and to integrate computational design, robotic simulation and digital fabrication. However, several aspects of the project require further development. First, the settings of the simulation parameters still require several manual steps and knowledge from the designer about the functionality of the algorithm. Simplifying and further automating the integration of this process with the computational design environment would allow the user to interact more intuitively with the tool when designing robotic movements. Secondly, as described, the welding was manually performed, and further testing to transfer this joining to a robotic method is required. Finally, sensing the spatial arrangement of the structure while building on it would allow compensation for tolerances (for example, from bent tube or error that occur during the construction).

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The AA’s satellite campus out in Hooke Park, Dorset, is the headquarters of its Design+Make programme and operates as a laboratory for architectural research through 1:1 fabrication. In an environment that combines forest, studio, workshop and building site, the large-scale fabrication facilities act as a testing ground where students devote time to advanced speculative research through a hands-on approach.

Designing and building architecture in the woods within an idyllic forest ecosystem that is both material library and site, the programme explores how natural materials, craft knowledge and new technologies elicit exciting and unpredictable architectures while implying a deep connection between site, construction and tree species. It provokes a critical approach to designing and manufacturing – one which encourages a symbiotic relationship with the variability found in nature.

Digital design and fabrication tools are often used to develop non-standard series of components from standardised materials. Timber is usually considered as a rectilinear material, often reduced to sheets, planks or beams before having a complexity returned to it by milling procedures. And yet trees already present a naturally formed non-standard series – each is wholly unique. The Design+Make programme provides an alternative conception of material form in which inherent irregular geometries are actively exploited by non-standard technologies.

INFINITE VARIATIONS, RADICAL STRATEGIES

MARTIN SELF / EMMANUEL VERCRUYSSE
Architectural Association, London
The Hooke Park woodland was first surveyed for trees with appropriately forked trunks, resurrecting the species found within Hooke Park. The Tree Fork Truss project was developed from a finished component. The connection surface geometries varied in different parts of the structure and consisted of either planar face-to-face surfaces between elements along the chords or mortice-and-tenon joints in which a distorted elliptical geometry was used to best satisfy the structural and assembly constraints.

The robotic milling procedure consisted of first defining 3D volumes for router subtraction of connection shapes from the wood, then determining an appropriate robot toolpath to achieve that geometry. The key requirement was to produce precise relative positions of the machined surfaces such that dimensional accuracy during assembly could be achieved. Two strategies were developed to meet this need. Further a consistent reference system was established which ensured that a tree fork component could always be correctly located in space in the virtual modelling environment, the machining cell and the robotic tool.

Woodchip Barn

In a standing tree, the naturally occurring branching forks exhibit remarkable strength and material efficiency, being able to carry significant loads with minimal material. Disregarding non-standard timber components from wood’s inherent forms, the truss of the Woodchip Barn is presented as a unique timber structure that makes full use of the capabilities of new technologies such as 3D scanning and evolutionary optimisation of the placement of discrete components within a structurally determined arch, along with customised robotic fabrication. The rationale for this approach is that the diverse characteristics of natural wood can be exploited directly without wasteful industrial processing, while simultaneously providing fertile territory for an unconventional design attitude. The Woodchip Barn employs twenty tree forks within an arching Vierendeel-style truss. The building provides 400m³ of storage for biofuels and an inverted-catenary form for a compression structure and anisotropic structural properties of wood. Instead, fabrication processes generate complex components from standardised wood products to ensure consistency. An ambition for the project was to exploit the moment-resisting capacity of tree forks. In a standing tree, the naturally occurring forks exhibit remarkable strength and material efficiency, and before processing already present what digital tools are commonly employed in pursuit of a non-standard series.

The Hooke Park woodland was first surveyed for trees with appropriately forked trunks, resurrecting the types they required to construct various components. An initial photographic survey of 204 standing tree forks provided appropriate two-dimensional fork representations with enough detail to make informed decisions about which trunks to cut down. From an analysis of this database, a shortlist of 40 forks was established which a 6-axis robotic arm could always be correctly located in space in the virtual environment. The key optimisation process was a three-dimensional arrangement of the tree fork geometries in which the key setting-out nodes were coincident with the underlying target tree curves. The combination of this nodal set data with discrete linear volumes and diameter data was used to derive the digital fabrication information for the machining of connecting features into the tree fork truss using a router spindle on Hooke Park’s Kuka KR-150 6-axis robot arm. The connections were configured to achieve transfer for compression forces through timber-to-bearing and to reinforce these with steel bolts when additional tension or shear strength was required. The connection surfaces geometries varied in different parts of the structure and consisted of either planar face-to-face surfaces between elements along the chords or mortice-and-tenon joints in which a distorted elliptical geometry was used to best satisfy the structural and assembly constraints.

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Timber is usually considered a non-isotropic material - its irregular forms needed to be standardised sections. The work undertaken to simulate an idealised arch geometry in which inherently irregular geometries are directly expressed by non-standard technologies.

Image: Valerie Bennett.

2. Designmodel projects all fork arches in the design process. The outer profile of their geometry. Following this, local key settings and centroids were calculated for each profile’s section. The structural form of the arched truss was determined, in discussion with the Arup team, to have the appropriate inverted-rectangular forms for a compression structure and a cross-sectional geometry which could accommodate the dimensions and angles of the sourced tree forks. The choice of an equalised triangular section of typically 40cm side dimensions was found to work both for providing stability to the arch and being a size on which the fork could be fitted. The structure is composed of two planar inclined arches in a distorted Vierendeel configuration that exploits the moment capacity of the forked junction. The structure lands at four points, the front slightly wider than the rear, with four inverted tripod legs supporting the robotically fabricated mid-section.

The positioning of each forked component within the truss was determined iteratively using an optimisation script that sought an optimal arrangement of the components to best satisfy structural and fabrication criteria. This was achieved through evolutionary and simulated annealing procedures carried out in the OptaSpace solver within the Rhino-Grasshopper environment. Within the optimisation, there were two levels of position adjustment: the global swaping of components between possible locations in the structure, and the local shuffling of components in which each element was slid along the target arch curves to best find its location. The key criterion was to minimise deviations of the forks’ medial curves from the target curves of the idealised arch centrelines. Further criteria were applied to place the larger diameter trees where axial forces were greatest and to deal with specific geometric constraints (for example, at the points where the truss bifurcated to form its legs). The optimisation was improved by indexing the component set according to the geometric strategy and by sequencing the placement so that the most critical positions were populated first.

The outcome of the optimisation process was a three-dimensional arrangement of the tree fork geometries in which the key setting-out nodes were coincident with the underlying target tree curves. The combination of this nodal set data with discrete linear volumes and diameter data was used to derive the digital fabrication information for the machining of connecting features into the tree fork truss using a router spindle on Hooke Park’s Kuka KR-150 6-axis robot arm. The connections were configured to achieve transfer for compression forces through timber-to-bearing and to reinforce these with steel bolts when additional tension or shear strength was required. The connection surface geometries varied in different parts of the structure and consisted of either planar face-to-face surfaces between elements along the chords or mortice-and-tenon joints in which a distorted elliptical geometry was used to best satisfy the structural and assembly constraints.

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The building is presented as a demonstrator and validation of an approach proposed in various forms over recent years4,5 in which new computation tools are applied to the configuration of material elements so that the underlying arch geometry was largely predetermined (i.e. anticipating typical geometries of the forks but not directly determined by them) and the optimisation was limited to locating components within that geometry. Thus a development of the method will be to enable the underlying structural form itself to self-organise through the varied components acting as agents towards a set of spatial and structural goals.

Advanced and bespoke system operations

Other strategies are now in place to enhance this approach, enabling more complex structural experiments. For instance, establishing the horizontal rotational seventh axis to operate in synchronisation with the 6-axis robot arm has been instrumental to the manipulation of non-standardised timber. This configuration, capable of swinging the gantry around, allows the gantry to simultaneously swing and rotate between two modified lathe end-stocks, means that the natural forked geometry undergoes localised modification analytically and the sculpted profile could be structurally optimised - analogous to the geometry of bone or open-grown trees - and gives timber a material a new ‘plasticity’ (in the art history sense of the word) of form that is difficult to achieve with other materials.

The application of a variety of end effectors provides yet more possibilities for the manipulation of the material. The chainsaw – a tool not known for its exactitude – gains an augmented level of precision and control when wielded by the large Kuka KR150 robot. LiDAR scanning technologies form an essential component within these advanced system operations, not only providing a fully calibrated workspace but also crucially allowing operations on naturally formed geometries with surgical precision.

3D scanning allows us to treat something incredibly unique and complex in form in the same way that we might treat a standard plank of timber. The ability to scan the space of machining to align the worldview of the machine with the actual position of a non-linear object like a tree trunk allows for more flexible machining strategies, as the calibration becomes more organic. The digital form and the physicality of machining on this scale can converge with previously unimaginable precision.

The innovative and radical nature of the approach employed at Hooke Park lies in the strategic precision with which Design-Make teams can augment the natural geometry present there. The variability and complexity is natural – our machine strategies play to the beauty and strength of this complexity and follow its lead6. In this way, we are employing the tacit knowledge of a material on which craft relies, while exploring the possibilities afforded by the pinpoint precision of the technological eye and hand of scanner and robot.

The aim is to use robotic technology not forcefully, for power, repeatability or wilful formalism, but delicately, for the strategic augmentation of a natural and complex material – analogous to the geometry of bone or open-grown trees. The forked grain is a genetic code that can be read and interpreted by design; the process is one of translation, where the material becomes an artistic medium.

Acknowledgements

The Woodchip Barn was designed and built by Design+Make students Minami and Zachary Mollica, with Edith Summerfield and Maxine Rose. The workshop and site team (Christopher Sadd, Charlie Corry Wright and the Big Shed SummerBuild volunteers) oversaw the overall development and, and engineering support was provided by Arias (Franci Archer, Natalie Minara and Copa van Etten).

Notes


7. 8
AUTOMATED DESIGN-TO-FABRICATION FOR ARCHITECTURAL ENVELOPES: A STADIUM SKIN CASE STUDY

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HKS LINE
RODOVAN KOVACEVIC
Southern Methodist University

Working with stadium architecture

The stadium roof structure surveyed in this paper is comprised of approximately 70,000 unique panels with over 500,000 square feet of surface area. These panels are uniquely articulated and cut to specification using a 3-axis CNC-coined die-punch machine and fabricated from titanium anodised aluminium. The panels are shop-fabricated and pre-assembled into mega-panels according to Zahner’s proprietary ZEPPS process. Two key building components were isolated for development of a complete file-to-factory workflow. The panelised geometry and perforation patterns are fully automated and implemented within the examined project. The second component studied within this paper is a 3D printed fixation detail proposed as an alternative to the ZEPPS solution.

Both the exterior envelope’s aluminium panels and the hypothetical node connections are discussed in terms of the challenges and constraints unique to their respective geometry, fabrication process and performance criteria. The design-to-fabrication workflow is described.
Advancement in computational design tools has led to an observable proliferation of architecture exhibiting greater degrees of geometric complexity, variability and differentiation. Although these tools increasingly accommodate the constraints of additively manufactured building components. The workflow adopted leverages a customised C++ framework and implements open source libraries such as Open3D for visualisation and Array Fire v3.2.2 for GPU-based image processing and data operations. The framework presented is not conceived as an autonomous design tool, but rather as a vehicle for the exploration and interpretation of computationally intensive procedures. This case study demonstrates the effectiveness and potential benefits to the workflow over visual programming approaches such as Grasshopper.

Project scope and mounting challenges

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One of the key obstacles examined within this paper relates to communication and coordination between designers and fabricators. Conventionally, designers require that both parties exchange dimensioned diagrams and even the processing of CAD drawings to facilitate the translation of diagrammatic or representational information into a system. In cases where fabricators rely heavily on visual programming approaches such as Grasshopper. The workflow to a speculative fixation detail based on the concept proposed during the early stages of design conceptualisation. This concept and the corresponding six-point fixation strategy were developed to fabricate an effective node connector that could accommodate the high degree of geometric complexity and scale of this project's cladding system. The case study presented is based on the current stage of design and development for an NFL football stadium and future home to the Los Angeles Rams, designed by HKS Architects (Fig. 1). The project will be located in Inglewood, California, and was recently awarded to Turner Construction Company with construction completions scheduled for November 2019. There are a broad number of applications for the different architectural components (Fig. 2). The perforation sizes correspond to a global grayscale heat map indicating two and three-dimensional performance.

Another area of implementation directly affected by this case study is the workflow between design development and shop fabrication. This case study presents an alternative to the current workflow to a speculative fixation detail based on the concept proposed during the early stages of design conceptualisation. This concept and the corresponding six-point fixation strategy were developed to fabricate an effective node connector that could accommodate the high degree of geometric complexity and scale of this project's cladding system. The case study presented is based on the current stage of design and development for an NFL football stadium and future home to the Los Angeles Rams, designed by HKS Architects (Fig. 1). The project will be located in Inglewood, California, and was recently awarded to Turner Construction Company with construction completions scheduled for November 2019. There are a broad number of applications for the different architectural components (Fig. 2). The perforation sizes correspond to a global grayscale heat map indicating two and three-dimensional performance.

These objectives are examined through the lens of a single architectural project. Firstly, through a tessellated double-curved cladding system, and secondly through a speculative structural node which addresses additively manufactured building components and assemblies. Within this examination, limitations to the status quo are discussed, with emphasis placed on trajectories for future research in additive manufacturing and its potential as a direct design-to-fabrication process. The case study presented is based on the current stage of design and development for an NFL football stadium and future home to the Los Angeles Rams, designed by HKS Architects (Fig. 1). The project will be located in Inglewood, California, and was recently awarded to Turner Construction Company with construction completions scheduled for November 2019. There are a broad number of applications for the different architectural components (Fig. 2). The perforation sizes correspond to a global grayscale heat map indicating two and three-dimensional performance.

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To ensure proper coordination, file formatting conventions were established. Each panel was described in both world/project and local/machine space coordinate systems. Node centerpoint positions, corner positions and panel orientation vectors were provided within local machine coordinates. Local machine coordinates were established based on an origin point and a axis coincident with the first node position and first panel edge respectively.

Since the constraints for individual panels were driven by Zahner’s proprietary assembly process, rationalisation of the design surface was performed by Studio NYL, a facade design and engineering consultant contracted by Zahner. Ultimately, the proposed proprietary system would yield an increase of 12% more panels over the in-house panelisation routine, totaling 1,321 additional panels within the surveyed region alone. The governing criteria for these panels was to minimise deviation from an ideal equilateral triangle cut from a slab-wide sheet and oriented consistently within each sheet to maintain uniform material grain.

The host or parent design surface modelled in Rhinoceros and shared among consultants serves as the primary design input for the studium. Once the surface is tessellated into panels, the node centrepoints are extracted using Grasshopper and formatted into text files corresponding to eight regions or zones delineated by the cladding fabricator. These node positions are then loaded into a custom application developed by the authors in C++. The initial data extracted from the model is limited to eight lines of instruction per panel. For improved computational performance, the C++ framework leverages multi-threaded functions and implements open source libraries, such as Armadillo v5.600.2 (Sanderson et al., 2015) and ArrayFire v3.2.2 (Takemanchi et al., 2015), for GPU based matrix operations and image processing. OpenGL is also implemented for visualisation purposes.

As the panel identification and its node positions are read from a source file for each of the regions, this data is stored and a new panel object is defined. This method calculates the transformation from 3D world coordinates into 2D machine space and stores instances of each becoming part of the panel object’s properties. After being described according to a local coordinate system, the panel corner positions and edges are defined according to a predetermined edge offset parameter. Then the panel is subdivided with a permutation grid unique to each panel’s geometry, and the fastener positions are located so that they coordinate with this grid. The node coordinates and intersections are remapped to correlate with hole sizes corresponding to one of eight die-punch tools available during the fabrication process. Once a panel’s fabrication data are fully defined, a text file is generated containing a comprehensive geometric description of the panel. A graphic interface provides a searchable visual display of all the panels within the currently processed batch, alongside a global view of the studio indicating the active panel’s location. Various display states are also available that describe overall system mappings of area deviation, angle deviation and panel opacity. The average file size is 47KB and file sizes range between 4 and 16KB, dependent upon the quantity of perforations specified for each panel.

A similar design methodology is applied to the additively manufactured node definition and utilizes the same code libraries developed in C++. An additional layer of data management is incorporated to ensure that neighboring panels are properly associated with their common node. Vector trees for each node are calculated based on their respective vertex normal, with branching elements connecting adjacent panel fixation points to the intersecting sub-framing below (Fig. 7). Once the branching topology and configuration is defined, the node object is instantiated and a bounding volume for each vector is constructed. Ultimately, these branching volumes will be sized iteratively using FEA of the linear elements of the vector tree and procedurally defined load cases. The FEA solvers have been developed and validated, yet at present have not been fully integrated. Subsequent operations are performed to provide the required mesh density and smoothing necessary for fabrication. Ultimately, the constructed volume can be utilized as an initial design space for topology optimisation. To test this approach, a generic node was generated and topology optimisation was performed using SolidThinking Inspire.

Since the implementation of this building component is speculative and requires assumptions based on an earlier schematic design scenario, performance concerns...
have focused on internal workflow development and prototyping constraints. Cost and production feasibility assessment is underway with the assistance of Concept Laser. It should be noted here that Concept Laser produces additive manufacturing systems and is not a for-service parts fabricator. Fabrication constraints for the proposed nodes are based on the use of their X line 2000R. Concept Laser claims that this is the largest build volume currently on the market for a powder-bed-supported additive manufacturing system which utilizes a laser heat source for production of metal components.

They are currently promoting this machine as one of the key components within their model operation for lean additive manufacturing, which they refer to as the ‘AM Factory of Tomorrow’. The build volume available for the X line 2000R is 800 x 400 x 500mm, allowing an average of two nodes per build and an approximate production time of 36 hours. Due to the required build time, a more compact arrangement would be ideal, but to achieve this, the nodes must be subdivided into its constituent parts similar to the example shown in Fig. 8. Further subdivision may prove advantageous for production, but this decision would have inevitable impacts on production time and coordination due to the additional assembly required. It is assumed, however, that the assembly could be managed in tandem with subsequent print processes.

### Looking at performance gains

While it is generally accepted that lower level programming languages such as C++ provide superior performance over higher level programming languages, a benchmarking trail was established to test the author’s assumptions. Since Grasshopper offers limited prototyper tools to assist with C++ prototyping, the performance gains are not immediately available. Due to this limitation, a trial was conducted recording overall calculation times rather than conducting a piece-wise process comparison. Only the two most computationally intensive functions – calculation of the subdivision-based perforation grid and image-mapped perforation size – were implemented within Grasshopper. Transformations from world to local coordinates and evaluating facets post the 2D to 3D process were omitted. These outcomes were then compared to implementation written in C++ using both single-threaded and multi-threaded programmes, executing the entire procedure required to define and document the perforated panel system. To further simplify the comparison, the input data describing each panel’s world coordinates was internalised within the .gh definition, rather than read from an external source file. Each trial was conducted five times, with the resulting averages rather than read from an external source file. Each trial was conducted five times, with the resulting averages rather than read from an external source file. Each trial was conducted five times, with the resulting averages rather than read from an external source file.

The future experimental workflow development

Conventional methods of communication between the designer and fabricator present logistical challenges to a complete direct-to-fabrication workflow. Despite the advantages present with increased scope and scale of production, conventional means of exchange impede or diminish the ability to truly realise these advantages. The authors propose an experimental workflow that mitigates some of the concerns regarding design development, documentation, fabricator and construction coordination and production feasibility. The alternative means of communication rely on a workflow where graphical diagrams and representational drawings, whilst still possible, are omitted as the primary way to convey information. Computational performance gains are demonstrated using this proposed workflow, and an example of for-service fabricators with the resources to produce the parts described is very limited and presently not sufficient for production at the scope required for the envelopes presented.

### Notes

1. The authors acknowledge that in a triangle mesh a typical vertex is incident with six edges and is significantly more complex than the valence four vertex of typical quad mesh (see Fig. 9). Generally, triangles require more parts and are heavier than quad meshes.

2. For structural elements like nodes, beams and frames, however, the bistable is often lighter and achieves geometry of these structures is often more complex than that of the outer skin. Therefore optimising bistable structures for repetitive elements is highly challenging and inherently impossible. The complete right side of the bistable荣获s an area for future work, and further study is required to optimise the programme for increased scope.

3. AM node prototype

### 3. AM node prototype

The build volume currently on the market for a powder-bed supported additive manufacturing system which utilizes a laser heat source for production of metal components. This communication has been coordinated directly between the authors and the fabricators expected to complete this project. Preliminary mock-ups have been produced to test the hypothesis and work will begin in 2017 to test viability of implementation at scale. As the project moves into construction, and the building envelope is finalised, a comparison between the as-built structural framing and a system which incorporates the proposed 3D printed node can be evaluated.

### Performance comparison showing improved computation speeds

2. Performance comparison showing improved computation speeds.

### System specifications

- Workstation name: PWDA1378
- CPU specification: Intel(R) Core(TM) i7-5930K CPU @ 3.50GHz
- Memory: 63 GB: 256GB/64 GB


- CPU specification: Intel(R) Core(TM) i7-5930K CPU @ 3.50GHz
- Memory: 63 GB: 256GB/64 GB
As the only naturally reproducible green building material, wood has become the first choice when addressing environmental concerns. With the rapid development of laminated wood technologies and other production techniques, modern wood has become a high performance material with a large scale and low weight-to-strength ratio which demonstrates great potential in the future development of the construction industry (Menges, 2011). Digital design has marvellously expanded the scope of wood structure application. While the growing trend for research in robotic fabrication has accelerated the development of mass customisation concepts in architecture, the mass customisation of geometrically complex wooden elements has become one of the major concerns in terms of robotic wood fabrication research and wood-producing industry (Buri & Weinand, 2011). The capacity of current CNC-milling based non-linear wood component fabrication methods, which not only consume a lot of time but also produce a lot of material waste, is falling out of line with the rapid development of digital design technology (Brell-Cokcan et al., 2009). The ‘Robotic Wood Tectonics’ project of 2016 DigitalFUTURE Shanghai explored the combination of...
robotic fabrication and traditional woodwork to produce geometrically complex wooden elements—without the immense material consumption of a CNC milling production process—in a full-scale wood pavilion. Furthermore, this project explored the extent to which this approach has the capacity to mass customise large architectural wood elements, which would be critical to the robust processes demanded by the manufacturing industry. This project aims to demonstrate innovative robotic wood tectonics—an integrated working process from design to fabrication.

Research context

In the wood manufacturing field, milling currently seems to be the only way to deal with geometrically complex wood components. Built projects such as Centre Pompidou Metz and the Nine Bridges Golf Club by Thom Mayne were constructed using a milling approach with indispensable technical support from Designtoproduction. In addition to defects, waste and processing time, data transformation between the design and manufacture stages in CNC milling remains a major constraint, and in fact these issues constitute a large part of Designtoproduction’s work (Scheurer, 2010). Indeed, these defects are more obvious when they relate to factors like design changes.

With the rising trend of research in robotic fabrication, some research institutions are trying to explore new craft with regard to speed, accuracy and material performance. In robotic fabrication of double-curved non-standardized surfaces within the constraints of irregular wood flitches, some research has been carried out at RMIT University (Williams & Cherrey, 2016) has further studied the feasibility of this new craft with regard to speed, accuracy and material finish in the mass customisation of ruled surface fabrication, shown in the paper ‘Crafting Robustness: Rapidly Fabricating Ruled Surface Acoustic Panels’. This has demonstrated the feasibility of this approach in robotic fabrication of double-curved non-standardized wooden elements in furniture and decoration.

Research questions

As demonstrated above, this research is not conceived in previous studies in the ‘crux of scale’ of digital mass customisation, which has been processed at a small scale of industrial design and fabrication but not performed well at the full-scale architectural level. When it comes to full-scale architectural wood components, the speed, accuracy and effectiveness of this robotic fabrication method remain unclear. This project is trying to figure out whether this robotic craft is capable of reaching the speed, accuracy and material mass customisation of full-scale architectural wood components. The research question is studied in detail through the sub-questions:

1. How to negotiate between technical issues like speed, accuracy and stability to ensure the optimum fabrication results?
2. How traditional mechanical tools and the knowledge of materials can be used in guiding robotic fabrication?
3. How the full application of existing wood manufacturing technology might improve the practical significance of the state-of-the-art robotic technology.

Further, this research tries to figure out how this new robotic wood technology might affect the design process to develop a full scale and detail design process from design to fabrication as a new form of robotic wood tectonics.

Research methods

This research is carried out through the design and fabrication of a full-scale wooden pavilion. The material properties, structure performance and fabrication constraints are integrated into the design process, while both industrial prefabrication and digital robotic fabrication are employed in the fabrication stage. Fabrication-oriented form-finding

Based on a structural performance form-finding method, this project takes the Rhinoceros plug-in Rhinovault (Rippmann et al., 2012) and the Grasshopper plug-in Millipede (Michalakos & Kajima, 2007) as form-finding tools, where the former is used to find a reasonable form of compression-only structure while the latter is applied to optimise the size of the structural elements. The initial geometry of the timber structure is first generated through the form-finding process in Rhinovault (Rippmann & Block, 2013), and is then translated into a grid beam system in which the beams are all full size, with lengths varying from 5.8m to 7.5m. According to the structural simulation, the beam sections are optimised to a constant thickness of 100mm, and varied height ranges from 120 to 200mm. The top and bottom surfaces of each structural element are all designed as ruled surfaces in order to be fabricated with wire-cutting technology. Finally, the geometric system is divided into four layers while beams of different layers are connected with the most suitable mortar joints. Taking glued laminated wood as the structural material, the raw beams are produced in a factory with the existing glued technology under the guidance of a CNC template.

The bandsaw effect is a modified jigsaw bandsaw reinforced with a welded steel frame and installed on a hanging KB120 KUKA robot to cut the ruled surfaces fabrication. In contrast to the wires in wire-cutting, the bandsaw blades have a certain width which gives more complicated constraints to both the desired surface curvature in the design stage and the blades in the forward direction. Small surface curvature and high speed may block the saw, and even breaks saw blades. During the fabrication test, a traditional carpenter was employed to provide guidance on the mechanism of the bandsaw—an undeniably important part of the transmitted knowledge of traditional craft and material performance being added to the robotic fabrication process. After several tests, the 13mm-wide blades were employed to meet the requirement of desired surface curvature and ensure fabrication efficiency.

Follow the fabrication tests, the robotic movements were simulated within Rhino. Then generated toolpaths were converted to STL for the KUKA robot with the Grasshopper plug-in KUKA PRC (Reimann & Broll, 2010) (Fig. 3). During the fabrication process, the raw beams are fixed to two adaptable tables, which...
Due to the employing of a mortise-tenon joint system, Site assembly with great accuracy and efficiency. The process of all 16 beams was completed in three weeks with a 24,000rpm spindle, the slots on the beams were than the milling method. By equipping the same robot 5-8m per hour, the time taken for each beam can be adapted to the requirements of industrial mass production. Although this technique has great advantages in material efficiency, there are still some deficiencies to be improved. It is undeniable that there is still a waste of material due to the volume difference between two-dimensional raw beams and the desired three-dimensional beams. The waste may be minimised through the optimisation of gluing technology or by employing a more precise CNC template to guide the material distribution to minimise the volume difference between the raw and desired beams. In addition, there is also room for optimisation in terms of speed control. Due to the continuous change in beam thickness during the fabrication process, an automatable speed control system (to adjust the speed according to the resistance that the blade is facing in real time) will contribute to both fabrication results and the life of the blade itself.

Conclusions
This project presents robust robotic wood tectonics capable of full-scale wood component fabrication. This technology - with its high efficiency in material and time, as well as the capability for the mass customisation of geometrically complex wood - has thrown the traditional ‘subtractive’ mode of CNC milling into question. Oriented by the fabrication technology, this project demonstrates an entire integrated process for digital wood architecture, from form-finding and form optimisation to digital fabrication. The design therefore is not only determined by the physical mechanism of form-finding, but is also defined by the fabrication constraints. Meanwhile, the fabrication process is not merely state-of-the-art research, but also tries to make full integration with the existing wood production method much more valuable in practice. The final outcome is the result of constant negotiation between design expression and fabrication constraints. In addition, while the project is an attempt to provide innovative technical support for modern wooden architecture, it also aims to make this fabrication method the driving force in the design process. Given the great differences from traditional wood tectonics, this innovative method can be considered as representative of the new robotic wood tectonics.

In future research, this novel technology is going to be improved in terms of efficiency, stability and integration with existing design methods and industrial production approaches. On the other hand, as the tectonics applied in this project are only applicable to specific geometry, new tools will be required for the continuous expansion of the capacity and scope of robotic wood tectonics.
This project seeks to enhance press-fit fabrication techniques through the use of hybrid material construction technology and bending-stabilised forms. It overcomes certain press-fit limitations and undertakes a systematic improvement in connection design, which in combination with material and form enhancements allows for an increase in spanning capacities and robustness of press-fit structures, an increase in the reliability and precision of assembled geometry and retention of the critical press-fit benefits of lightweight, high-speed and uncomplicated construction.

Press-fit connection techniques streamline digital construction methods through elimination of mechanical fixing components and thus enable rapid construction of complex three-dimensional geometries. However, the reliance on dimensional tolerance and oversizing, in lieu of mechanical fixing, causes an inherent instability in press-fit connections in the direction of component insertion. This can be partially abated with increased tightness between parts and/or a 3D interlock, but such measures can also offset the ease of assembly and structural performance.
The project aims to address existing press-fit limitations via three key advancements in fabrication: (a) the introduction of material hybridity with the combination of glass fibre-reinforced plastic (GFRP) skin and plywood sandwich segments; (b) the introduction of bending stabilised geometry to the overall assembled configuration; and (c) the utilisation of rotational press-fit joints between structural components. The project is of particular significance due to the combined benefits of these advancements working to create a solution in which any curved profile can be manufactured without the need for moulding or propping.

While the technology may be applied to a range of geometric configurations, the project investigates two specific applications: a tied arch and a cantilever structure, shown in Figs. 2 and 3. Both applications are used to demonstrate the benefits of the three key fabrication advancements, but additional post-fabrication analysis was undertaken for each specific structural type. The arch was tested to failure to demonstrate the suppression of press-fit pop-off instability and the corresponding strength and robustness of the assembly method, and the cantilever was 3D-scanned to demonstrate the extreme versatility, speed and accuracy of the assembly method.

Press-fit construction
Sophisticated digital design processes can reduce a complex structure to a complete set of individual elements suitable for fabrication with the use of automated workshop machines (Eramanz & Kohler, 2008). A key capability in digitising the complexity of traditional construction is the introduction of integral mechanical attachments in place of conventional mechanical fastening systems such as screws and nails. Such integral attachments are particularly suited to timber construction, as their design can draw on a rich history of traditional wood-working joints (Robeller et al., 2011). A correspondingly wide range of integral attachment types is thus seen across recent timber works (Mensae, Schwenk & Krug, 2015). Beyond the streamlining of digital construction methods, the inclusion of integral mechanical attachments can produce structures that possess extreme fabrication and assembly speeds. For example, the ‘Instant House’ clad frame structure was assembled in four days from 584 plywood components (Gass & Ritha, 2006) and the ‘Plate House’ modular sandwich structure was manufactured in five hours and assembled in seven hours from 150 cardboard components (Gattas & You, 2016).

A fundamental type of integral timber connection is the press-fit (or friction-fit) joint. It consists of a male tab and female slot and enables precise alignment and assembly of components, but contains an inherent instability in the direction of component insertion. This can be partially alleviated through a fine control of part tolerance to achieve a friction-only fit (Robeller, 2012), or through interlocking geometry which prevents the movement of two parts in all but one direction (Robeller & Wernand, 2011), but such measures can also offset the ease of assembly. In terms of structural capacity, press-fit structures can possess compressive capacity approaching that of the glued sections, but can also be subject to a catastrophic “pop-off” failure mechanism where sudden loss of friction cohesion causes an explosive bifurcation and complete disassembly (Al-Qayyuri et al., 2018).

Hybrid construction
Fibre-reinforced polymers (FRP) composites have obtained wide acceptance in civil engineering and digital fabrication communities in recent years, due to their high strength-to-weight ratio (Tang, Yu & Fernando, 2012) and versatile construction options (Panaschko et al., 2012). Timber materials, and more particularly engineering wood products (EWP), have similarly seen increased recent uptake for broadly similar reasons to FRP; their high machinability and lightness make EWP’s well-suited for modern prefabricated structures and robotic construction methods.

The use of hybrid FRP-timber structures has been rather limited compared to hybrid FRP-concrete and FRP-steel structures, due to a range of factors including economics, durability and fire performance. However, recent work has hinted at the potential benefits of such material hybridisation. FRP can reinforce weak sections of EWP beams (Kilty & Hart, 2011) and is thus able to upgrade low-quality timber resources for high-performance structural use, minimising the overall system cost (Fernando et al., 2015).

The project seeks to explore the combined value of press-fit and hybrid FRP-timber construction technologies. It will be seen that, with such a combination, a novel fabrication system can be developed that possesses a number of advantageous geometric, structural and constructability innovations that are not available in existing systems which utilise these construction techniques in isolation.
Consider now its modified press-fit beam. Three key innovations have been introduced which together act to eliminate many of the weaknesses seen above.

- Material hybridiy: a GFRP is introduced as a continuous tensile skin, providing a stress transfer mechanism at joint 3 and negating stress concentrations in joint 3, thus enabling the use of thinner, lighter and more economical plywood grades.
- Bonding stabilised geometric orientation is introduced into the beam, which acts to reduce the effective buckling length of the compressive face and introduced into the beam, which acts to reduce the effective buckling length of the compressive face and introduce an inclined compressive stress component. These act to suppress pop-off and fragmentation failures respectively.
- Rotational press-fit connection: the GFRP skin creates a hinge mechanism which can be used for a novel rotational press-fit connection. This retains a shear stress transfer capability but with a rotational direction of insertion that matches displacements from the applied moment loading, i.e. segments can be rotationally ‘folded’ together, rather than axially loaded together. The beam can therefore self-assemble if subjected to a bending load.

As will be demonstrated, these key innovations serve to resolve many of the structural weaknesses, while retaining the speed and accuracy of typical press-fit construction. There is also one further benefit that arises from the above three innovations acting in concert: any curved profile can be manufactured without the need for moulding or propging, as the structure can fold from a flat state. The fabrication process in each of the structural applications that were investigated demonstrates this final capability.

Fabrication

A key fabrication aim for the project is the ability for the segments to ‘self-assemble’ from a flat state, which will now be described in detail. A target beam profile is specified with a control spline and depth offset. This is discretised into segments by subdivision of the control spline. Segments in regions of positive curvature (\( \alpha > 0 \)) run unfolded without issue onto a flat surface when inverted, but segments in regions of negative curvature (\( \alpha < 0 \)) would be unable to readily unfold, necessitating the introduction of additional ‘wedge’ segments. Each segment profile is then translated onto a complete plywood sandwich structure encoded with all necessary press-fit joints. For example, its dark grey segment is shown in isometric view in Fig. 4. It is composed of core plates and face plates with the same joints 4 to 5, as described previously, and with additional joints 6 and 7 for cross plates and facing plates respectively.

The rotational press-fit connection determines the overall surface curvature by controlling the relative inclination between adjacent segments. The connection is composed of joints 5, 4 and 3, with design considerations required for each. Joint 3 shifts the rotation point from plate centres to the outer skin and is composed of an inclined press-fit joint with slight front and back offsets suitable for a 2.5-axis cutter. The staggered tab locations allow the joint to fold without collision. Similarly, joint 4 is an inclined press-fit and acts to enforce the transverse alignment of inside face skins, and by extension precise centralise alignment of core plates. This alignment is important for thin core plates to avoid eccentric loading. Finally, joint 5 bias press fit tabs formed along arc central about the rotation point, and so can travel through the complete folding motion without collision.

Tied arch and structural performance

A 3m-wide asymmetrical arch structure was constructed using the above fabrication process. It consisted of seven segments, each of which was assembled from seven thin plywood plates cut on a CNC router (Fig. 5). Assembled arch segments were placed end-to-end on a flat surface (as the arch’s inverted orientation) and loaded to a continuous GFRP skin. The need for chemical adhesion in the fabrication process does slow down the overall construction time due to placement and curing, although this is offset by the GFRP providing a simple three-dimensional coordination of the segments, virtually eliminating the need for further consideration of set-out or construction sequencing; the only required alignment is readiness achieved on a flat surface through the transverse alignment of segment edges.

Once cured, the structure can be folded into its final shape with extreme rapidity, as all six segment joints are actuated with a single bending load. This was induced with a single post-tensioned tie, providing a line of force between segments. The arch was then tested to failure, with an actuator again applying a force between end segments. The arch was designed so that maximum moment occurred at the arch peak and GFRP material tensile failure occurred prior to the onset of the suppressed compression face instabilities. Fibre rupture occurred first, as predicted in the theoretical analysis. Cantilever structure and construction performance

A cantilevering branch structure was designed to explore the versatility, speed and accuracy of the assembly method. The design of the curvilinear branches was via a digital model with multi-scale parametric control over the geometry of the individual ‘branches’ as well as the generation of all component parts with integral mechanical attachments. Eight counter-balancing cantilevers were constructed from 710 9mm-thick plywood plates, which were assembled, bonded to GFRP, folded into branches (Fig. 7) and attached to a central suspended spine (Fig. 1). The final and longest branch was 5m long (20m tip-to-tip across the branch pair), tapered from a depth of 370mm to 30mm and weighed 70kg. The fabrication phase was just two weeks, with the structure exhibited at the official opening of the University of Queensland Centre for Future Timber Structures. The structure was measured using a 3D laser scanner, and collected point cloud data were processed using a surface error minimisation routine with the Galapagos.
significantly enhance the spanning capacity of members and stability of the modified global geometry act together to from the hybrid material and the improved compressive capacity of the structure, i.e. the cantilever self-weight of the structure showed that the FRP hinge mechanism, thus preventing catastrophic failure of large-scale press-fit structures. Surface measurement of the cantilever structure showed that the FRP hinge mechanism could be considered ’components’ of larger structures, it is envisaged that, through the successful demonstration of the new fabrication technique, testing of the tie architecture was seen as a precice guide for the assembly of adjacent segments to produce a stable and highly accurate overall method. The project has demonstrated a hybrid material and press-fit fabrication technique that can produce key benefits in both structural capacity and ease of construction. The increase in tensile stress transfer from the hybrid material and the improved compressive stability of the modelled global geometry act together to significantly enhance the spanning capacity of members subjected to bending loads, while maintaining a very lightweight structure. The additional use of FRP as a flexible hinge and planar alignment mechanism, combined with the use of rotational press-fit connections for precise curvature control between adjacent segments, was seen to create a robust and versatile construction method.

Two sample applications of the tie arch and an array of cantilevers were explored. Both were fabricated in a condenced timeframe and served to demonstrate the structural and construction benefits respectively of the new fabrication technique. Testing of the tie arch structure confirmed that the bend-stabilised geometry resisted the press-fit ’pop-off’ failure mechanism, thus preventing catastrophic failure of large-scale press-fit structures. Surface measurement of the cantilever structure showed that the FRP hinges successfully acted as a precise guide for the rotational assembly of adjacent segments to produce a stable and highly accurate overall method.

While the two applications illustrated at this time may be considered ’components’ of larger structures, it is envisaged that, through the successful demonstration of the combined innovations, the technologies developed in this project can enable a significant range of possible formal configurations. As the developed improvements to spanning capacity and robustness of press-fit fabrication systems occur alongside the new method for rapid assembly of long-span bending structures, more ambitious applications for larger press-fit structures used in permanent building applications could become a reality.

References


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This project focuses on the role of computational geometry within computer-aided architectural design and construction workflows, i.e., computational geometry as a mediating device between architectural, engineering and construction logics. While the scale of a dining pavilion is relatively modest, the intention is to utilise this research for wider application in larger construction-scale projects. In this regard, the project operates within a tight time-bound, multiple-stakeholder, collaborative and bespoke production pipeline, as typically necessitated by architectural projects.

Digital workflows

Workflows in architectural design can be characterised by two paradigms – one drawing-based, the other model-based. The drawing paradigm is popularly known as Computer Aided Design (CAD) and the model paradigm as Building Information Modelling (BIM). While both drawings and models encode 2D and 3D geometry, a model also contains meta-information about the encoded geometry – its material specification, role in and processes of assembly, etc. Also, the drawing paradigm, especially Computer Aided Geometric Design (CAGD), can support the creation of a wider range of (arbitrarily) complex geometries and their processing for Computer Aided Manufacturing (CAM). An essential aspect of CAGD, as used in disciplines such as automotive or product design, is the abstraction of the complex physical phenomena and machine parameters associated with manufacturing methods into geometric properties and constraints. Famous examples include the automobile, aircraft and shipbuilding industries motivating the development and use of Bézier curves and surfaces, physical splines and developable surfaces (Bézier, 1971, Sabin, 1971, De Casteljau, 1986, Pérez & Suárez, 2007, Pottmann & Wallner, 1999), etc.

This project aims to apply these operative principles from the automated fabrication industry in architectural design and assembly. Thus the project primarily focuses on developing structural and construction-related meta-information for complex geometries – in other words, augmenting complex CAGD objects with construction-specific information, thus enabling the research to be incorporated within larger, more complex
A review of applicable methods of architectural geometry and/or CAGD to address these contextual aspects of the research is described below. The design brief of the project proposes manufacturing an economically prefabricated pavilion using off-the-shelf parts and/or laser cut components. The structural skeleton is to be realised using standard hollow sections and LED lights. Furthermore, the design is to be adequately covered for weather protection and rainwater management. The design brief of the project proposes manufacturing an economically prefabricated pavilion using off-the-shelf parts and/or laser cut components. The structural skeleton is to be realised using standard hollow sections and LED lights. Furthermore, the design is to be adequately covered for weather protection and rainwater management.

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Lightweight construction

The earliest practical work on the deliberate focus on the economical use of material via a geometric understanding of structure and effective channelling of (axial) structural forces can be attributed to the Gothic period (Germán, 1986). The earliest practical work on the deliberate focus on the economical use of material via a geometric understanding of structure and effective channelling of (axial) structural forces can be attributed to the Gothic period (Germán, 1986). The earliest practical work on the deliberate focus on the economical use of material via a geometric understanding of structure and effective channelling of (axial) structural forces can be attributed to the Gothic period (Germán, 1986).

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To define the depth of the structure, an offset mesh \( M' \) is numerically derived from \( M \) by offsetting each vertex along its normal. This approach is well suited to subsequent design development, as its representation as a coarse polygon mesh, \( M \) (Fig. 3). This representation retains an economy of homogeneous material from the input mesh \( M \) and \( M' \) is planar, as it avoids the increased complexity of topological navigation introduced by these non-manifold edges.

**Fabrication and assembly context**

Perturbation

Offsetting the vertices of \( M \) along their normals provides an initial approximation of \( M' \). For most cases of \( M \), however, this produces non-planar faces in \( M' \), requiring that the PQ criteria be solved for numerically. A projection-based approach (Bouaziz et al.) is used to minimal perturb the vertices of \( M' \) such that the faces of \( M'B \) are planar. The constraint is introduced which tries to maintain a constant vector between them. This formulation is analogous to the planarity-energy gradient defined by Poranne et al. (2013).

The design logic of the structure, comprising uniform cross-sections of segmented length, is indicative of expedient engineering load calculations and member sizing for a ‘worst case’ scenario rather than of individual beam performance. Additionally, use of solid sheet and hollow sections compatible with ubiquitous 2-axis cutting technologies eliminated time-intensive milling techniques from design consideration (Schueuer, 2013). Constraining the domain of geometric possibility to developable surfaces (Lawrence, 2011) Subsequently, material workability, geometric tolerance and fabrication constraints related to development and use of standardised elements.

The half-edge data structure was used to represent \( M' \) and \( M' \) throughout design development. While the advantages of this data structure are well documented within the context of discrete differential geometry (Botsch et al., 2012), this project extends its use as a means of structuring fabrication information. In cases where the majority of vertices in \( M \) exceed valence 4, vertices in \( M' \) often become over-constrained and planarity cannot be achieved for all faces in \( M' \). This motivates an iterative revision of vertex offset \( M' \) to find an acceptable balance between preserving structural logic generated via \( M \) and satisfying fabrication constraints related to developability and the use of standardised elements.

**Fabrication information**

The half-edge data structure was used to represent \( M' \) and \( M' \) throughout design development. The half-edge data structure was used to represent \( M' \) and \( M' \) throughout design development. While the advantages of this data structure are well documented within the context of discrete differential geometry (Botsch et al., 2012), this project extends its use as a means of structuring fabrication information. In cases where the majority of vertices in \( M \) exceed valence 4, vertices in \( M' \) often become over-constrained and planarity cannot be achieved for all faces in \( M' \). This motivates an iterative revision of vertex offset \( M' \) to find an acceptable balance between preserving structural logic generated via \( M \) and satisfying fabrication constraints related to developability and the use of standardised elements.

**Relevant assembly details**

The pavilion consists of linear segments of hollow section beams mechanically fastened to building steel plate nodes to form a raised dining platform oversailed by a 4m cantilevered shading canopy. Loops of kerf-cut sheet are patterned and face-fastened to the structure, obscuring the structural beams (Fig. 1). Similarly, the assembly methods are consistent with an accelerated manufacture via prefabricated, mechanically fastened elements, and are further considered as a sequence, material workability, geometric tolerance and fabrication constraints related to development and use of standardised elements.

**Structuring fabrication information**

The pavilion consists of linear segments of hollow section beams mechanically fastened to building steel plate nodes to form a raised dining platform oversailed by a 4m cantilevered shading canopy. Loops of kerf-cut sheet are patterned and face-fastened to the structure, obscuring the structural beams (Fig. 1).

Details address issues of prefabrication including installation sequence, material workability, geometric tolerance and lifetime performance. For example, exposed face-fastening loops and node covers in lieu of concealed hangar elements enable the localised changeability of parts and minimise the composite area of the cladded structure cross-section, tending toward the perception of a lighter, more slender pavilion. Similarly, mechanical fastener joining, in lieu of friction-fitting via slotting, tabbing or clipping, facilitates ease of workability, increases allowable in situ adjustment and promotes the independence of parts from neighbouring element dependencies, further assisting in situ fitting of parts.
The 52 self-similar, individually unique nodes further categorise and are parametrically modelled in response to neighbouring geometric conditions. The typical node is a pre-assembled, welded composite of plate steel and foundation nodes introduces a planar top and bottom plate respectively. The boundary nodes are clad with a continuous boundary edge band, inheriting the same fastening procedure as typical nodes.

**Auxetic material**

Material flexibility and hand-bending in the pavilion is accomplished primarily through kerfing patterns in 2mm plate (Fig. 5). Exacerbating the disparity of assembly processes, elements were fabricated in order of increasing complexity to allow for extended design and prototyping timelines by constructing the pavilion discontinuously, without hoists, from node to next neighbouring node, rather than part-way through, and highlights a requirement to merge early-stage design with fabrication intelligence.

**Assembly process**

The design of the pavilion assemblies anticipates a number of factors, including a remote installation, and the use of traditional tools, a commencement from a completed list of parts, a confined exhibitor space and an install in conjunction with local labourers unfamiliar with the design logic. The prototype beam configuration presented here supports the geometric principles apparent lightness is therefore not a cumulative result for a prescribed loading condition. Converging upon the TO process, as its benefits are not directly structural, but rather are constrained to a chosen fabrication method such as the uniformity of structural cross sections, resulting in unidirectional expression of load, the inherent typical detail at the boundaries resulting in perceived boundary edge thickness, as well as the bounding box approach to preliminary costing resulting in the perceived flatness of the platform and rear of trunk.

While the benefits of design geometry processed as mesh attributes is apparent in a self-referential setting, it is particularly apparent in design and fabrication as an incoherent workflow with regard to anticipated input geometry at each stage. The structuring of data in this regard was imperative to declare delivery workflows to assume fabrication relevant information at the outset of design rather than part-way through, and highlights a requirement to merge early-stage design with fabrication intelligence.

**Connection with design assumptions**

The relative newness of working with the data structure and the speed of delivery assumed to execute the project result in a fast and agile design process, as well as the inherent typical detail at the boundaries resulting in perceived boundary edge thickness, as well as the bounding box approach to preliminary costing resulting in the perceived flatness of the platform and rear of trunk.

The prototype beam configuration presented here supports the potential incompatibility of a discrete node-beam type structure producing from a conceptual TO analysis. Specifically, beam elements are not aligned to principal curvature directions of the surface using TO analyses in the same way that stress accumulation and fall-off are not gradated in beam element assemblies. Such a geometric constraint is not represented within the TO process, as its benefits are not directly structural, but rather are constrained to a chosen fabrication method for a prescribed loading condition. Converging upon apparent lightness is therefore not a cumulative result of material reduction techniques.

**Workarounds**

While the use of auxetic material in the node covers provided a workaround for delivering doubly-curved surfaces in partially torsioned materials using 2 axis cutting, it neither supports the geometric principles of developability nor is particularly suited to exterior environments.

5. Auxetic studies in node covers. (a) Prototypical node showing loop. (b) Node beam assembly. (b1) coarse grating, (b2) dense grating, (b3) equirectangular element showing edges, (b4) ruling aligned, (b5) ruling aligned, (b6) diagonal. (c) Actual node showing edges, corner, (c1) coarse grating, (c2) dense grating, (c3) diagonal. (d) Actual node showing edges, corner, (d1) diagonal, (d2) ruling aligned, (d3) ruling aligned. (e) “Y” node showing edges, corner, (e1) diagonal, (e2) ruling aligned, (e3) ruling aligned. (f) “Y” node assembly. (g) stash back-up. (h) Actual node showing edges, corner, (h1) diagonal, (h2) ruling aligned, (h3) ruling aligned.

6. Assembly crate.
methods/details with regard to durability which presents a new set of fabrication constraints to be geometrically represented within the design model. The use of variable cross-sections among edge members will be of primary importance, allowing for further expression of structural performance via material economy. While this would suggest additional complexity during both design and production, it is anticipated that the impact will be significantly mitigated through the use of the half-edge representation. By defining dimensional attributes per edge, unique elements of the assembly can be resolved with regard to one another through efficient topological spaces – an operation supported by the chosen data structure.

Overall dimensional constraints imposed by the context of the original prototype are significantly relaxed for the second iteration, allowing various formal aspects to be reimagined as needed.

Specifically, variance in the transitions from the trunk to the floor and ceiling can be more evenly distributed, reducing problems related to numerical convergence during subsequent rationalisation. Further effort will be made to better understand and formalise this relationship so as to enable informing design exploration.

References


Breaking boundaries in CNC steel tube rolling

Healing Pavilion, completed in December 2016, explores the boundaries and possibilities of CNC steel tube rolling. Inspired by the prowess of thin structural shells, this project translates the robust double curvature inherent in such forms into a dynamic cage-like array. By delving into the nuances and challenges of bending and rolling tube steel, the design adopts the surface form of a shell while introducing a level of transparency and controlled irregularity only possible through working with a network of individual components. Each tube has a unique three-dimensional curvature and is located at a fixed distance relative to its neighbour.

The pavilion balances structural load paths and assembly considerations with a rigorous exploration of patterning and layering. In addition to creating a space for shade and respite, the porous, shifting grid of steel tubing allows the reading of the complex form to fluidly adjust in relation to its background. The double curvature of the form demonstrates the physical limits of the CNC steel bending and rolling technology. That double curvature allows for structural shape efficiency, which creates natural rigidity through non-planar arcs. With just five construction details for the entire project, this final incarnation isolates and streamlines the design and construction process to tackle structure and the interstices between structural components simultaneously. The five structural details consist of:

1. Where the curved tubes meet the anchor plate at the base;
2. Where the tubes are mitred;
3. Where the tubes are spliced;
4. Where the tubes are capped; and
5. Where the tubes are spaced.

The successful translation of the digital design into a physical fabrication workflow without substantial variation from a digital ideal stands as the key driver defining the success of the project. Healing Pavilion combines a commitment to meaningful place-making with a deeply experimental fabrication goal.
Several context considerations define the parameters of the design for Healing Pavilion. The site represents the first contextual influence. Commissioned by Cedars-Sinai Hospital in Los Angeles, California, the project forms a key element in a larger garden renovation of the hospital’s plaza level. The structure performs as both a leftover concrete structure, the project distributes its 2,722kg weight over a ‘steel table’. The steel table, designed as a customised platform, receives concentrated seismic and gravity loads and transfers them to specific locations on the existing concrete facility structure. More atmospheric aspects of the context guide several defining formal moments in the project. Several openings, including an orculus framing the open sky, follow the path of the sun and orientation of the semi-enclosed space towards the street.

The Healing Pavilion design process

Several questions guided the research and design process of Healing Pavilion. The first concept question - how to make a shell using the logic of a cage – drove the number of studies that followed. Once this key research idea conceptualised, this line of formal inquiry raised the next issues: what kind of machine could bend and roll steel tubing? How to identify its limitations and keep these issues: what kind of machine could bend and roll steel tubing? How to identify its limitations and keep these issues limited within a smooth flow of seismic and gravity-included stresses? This period of investigation led to more questions than it answered. Ball-Nogues Studio then adapted the digital model accordingly and the structural analysts began again. The feasibility of fabrication played a principal role in the design process. In each design iteration, digital adjustments to the curvature of the tubes factored in the rolling machine’s minimum radius.

After digital analysis, the project’s research methodology shifted into physical mock-ups to test the plausibility and difficulty of mock-up of machine could bend and roll steel tubing? How to identify its limitations and keep these issues limited within a smooth flow of seismic and gravity-included stresses? This period of investigation led to more questions than it answered. Ball-Nogues Studio then adapted the digital model accordingly and the structural analysts began again. The feasibility of fabrication played a principal role in the design process. In each design iteration, digital adjustments to the curvature of the tubes factored in the rolling machine’s minimum radius.

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picked an area (Fig. 3) with complex mitre joints and tight three-dimensional curvature to explore next. The result of this mock-up highlighted the CNC bending machine’s capabilities and shortcomings, especially at tight radiused areas. Traces of the machine’s handling manifested as minor kinks in the tube steel. These visible pinches appeared every 10cm, exposing the incremental bending process and allowing the final reading of each curve, but it was especially evident on tight curves.

Before the process of bending tube steel was modernised into a computerised system, each hollow section was traditionally filled with sand to achieve maximum precision during hand-shaping. The sand acted to twist compressive forces and to keep the tube from collapsing. This same logic had to be introduced into the contemporary version of the bending process. The Studio worked with the fabricator to develop a custom mandrel that could fit inside the tube and behave as a buffer during the bending, thereby softening the kinks. Accounting for this custom rod called for a special type of tube with a reduced interior weld. The typical way of forming the tube implied rolling a sheet of steel into shape and then welding the seams from the outside. This welding technique results in a considerable amount of internal slag, which acts as a barrier for fitting anything inside and makes the process of working with tube steel impractical. By developing a more precise tube with minimal welding imperfections, a custom 3mm-long rod with the mandrel attached could then be inserted into the 3mm steel tube to mimic the analogue process of sand-based bending.

For the welding team to access their work from the ground during fabrication, the pavilion was made as distinct panels (Figs. 4 and 5) that could be positioned within reach of welders in the shop (Fig. 6) and connected seamlessly into one cohesive object. Certain panels were shorter than the length of most of the curves in the pavilion (Fig. 5). To accommodate the panels, the machine was pushed too far and certain instances, the machine was pushed too far and certain areas of tight three-dimensional curvature and where tubing needed to be massaged distorted the tubes and therefore the shape of the shell. The granularity of the coating also masks minor welding imperfections and kinks that result from the bending process, further obscuring the footprints of fabrication. The question of how to control for deviation in the steel also influenced the decision to finish the pavilion with a coating of ceramic alumina applied by thermal flame spraying (Fig. 8). This finishing technique was applied by melting the constituent materials and then atomising the molten bath; furthermore, the heat of galvanising could have minimised the deformations in the tubes that typically occur from the heat of welding. Mild steel has a level of imperfections and kinks that result from the bending process, further obscuring the footprints of fabrication. In addition to finish considerations, the features minimised the deformations in the tubes that typically occur from the heat of welding. Mild steel has a level of springback when rolled, as it tries to revert to its original condition. To compensate for this movement, each tube had to be clamped and adjusted by hand to fit within the rigid fixture. Once the tubes were waterjet-cut into place, 2,644 square spacers were inserted to keep the cage in a state of tension (and sometimes compression) to avoid deformation over time. With more than 3,000 360° joints in total, each spacer standardises the distance from one tube to another and standardises the process of welding. While every spacer is the same, the irregularity of their placement relates to key stress points in the form and introduces a compelling pattern to the final design. The commercial project kept within its budget. This issue of budgeting limited the rounds and iterations possible during the engineering phase. In spite of this back and forth between digital and analog processes, the pavilion reflects the digital model within less than 1cm of deviation.

Hands-on problem solving and optimising digital design

Healing Pavilion reconceptualises the output tolerance of digital machines with the allowable tolerances of the physical world. The project recontextualises the concept of fidelity and hands-on problem solving. To translate ideal geometry from a software environment into the tolerances inherent in the output of a numerically controlled tube bender and then into a highly final-form product meant that the machine’s capabilities could not be taken for granted. Reading the available product literature would not answer the questions the project needed addressed. Instead, a specific machine had to be engaged with directly. By building an intimate relationship with the tool, one could identify its capabilities. These understandings helped to craft and optimise translations between one software system and another, as well as to predict the physical ramifications of such digitally based design decisions. Some insights throughout the research influenced the digital aspects of the project, while others directly impacted its physical construction. In a few instances, the machine was pushed too far and certain moments had to be resolved by hand, such as very small radius. Even so, the final incarnation of Healing Pavilion demonstrates the optimal interface between handcraft and the computer, and offers a contribution to the fields of design and fabrication that use CNC tube rolling.
A home away from home

Located across Britain and abroad, Maggie’s Centres were conceived as a place of refuge where people affected by cancer could find emotional and practical support. Inspired by the blueprint set out by Maggie Keswick Jencks, they place great value upon the power of architecture to lift the spirits and help in the process of therapy. The design of the Manchester centre aims to establish a domestic atmosphere in a garden setting.

The building is arranged over a single storey, the roof rising in the centre to create a mezzanine level, naturally illuminated by triangular roof lights and supported by lightweight timber lattice beams. The beams act as natural partitions between different internal areas, visually dissolving the architecture into the surrounding gardens.

It was vital to create an atmosphere that would make visitors feel at ease, as if they were at home. The use of exposed timber for the structural elements enabled the creation of a homely, domestic ambiance throughout the centre, exploiting the warmth and softness of the material.

Using the practice’s expertise in digital modelling and analysis, the structure is the protagonist – a cantilevered timber wing ‘tiptoeing’ lightly over the site. To that end, much work was undertaken to assess how the design intent could be realised with contemporary materials and digital fabrication methods. Investigations were carried out to explore the structural optimisation potential in minimising the material used. For the construction, an Airfix™ (Airfix, 2016) analogy was deemed desirable – a kit of parts fabricated offsite and assembled onsite, facilitating quick erection.

The result is an innovative use of a traditional material, taking advantage of a complete file-to-factory process to provide the driver of the building aesthetic.

Making design match function

Functionally, the building is laid out to provide accessible open spaces along either side of a central zone: public spaces to the west, with the more private cellular spaces on the east. The centralised horizontal core houses the building’s services and an administrative zone on the...
Timber is the natural choice for this type of structure not of the glass in the roof lights (Fig. 5). span, and remove the need for a deflection head at the top significantly reduce the bending moment in the overhead entire structural system more efficient. These elements Slender steel columns just beyond the façade make the spine, with a propped cantilevered roof on either side. This spatial arrangement naturally led to a structural when they may feel at their most vulnerable. at the centre, giving the patients a sense of purpose at a space to grow flowers and other produce that can be used extends to embrace a greenhouse – a celebration of light would experience, thus providing a clearer load path, the choice between CNC-machined timber beams or handcrafted ones was made early in the design process. The choice between CNC-machined timber beams or handcrafted beam would permit individual web connections between each diagonal proved prohibitive. Although digitally fabricating beams from an engineered wood-based I-beams have many advantages, displaying high stiffness and strength for their low weight (Hermelin, 2005), and sustainably sourced timber has the added benefit of being more environmentally friendly than steel. The design intent and structural analysis inferred that the beam webbing could have a number of openings such that the structural behaviour is reflected in its form and materials. It is relatively easy to cut holes in timber webbing, further reducing the weight of the beam. However, the effect of this is to reduce the shear capacity of the member. A central issue was the study of the webbing shear capacity and how this was factored of this type of construction, resulting in large and heavy of the cockpit unintentionally acted to prevent this deflection, placing more load on the greenhouse timber members than they could handle, inducing buckling and thus shattering the glass. Thicker members would render the cockpit structure visually distinct and heavier in comparison to the rest of the building, and the option of making it an entirely separate structure was also deemed incompatible with aesthetic aims. Resolving this structural conundrum satisfactorily was critical to the success of the project and is outlined later in this paper. Physical prototyping and seeking solutions An integral aspect of the practice’s working methods since its inception, physical prototyping was a key part of the design process. Full-scale elevations of the timber beams were printed on paper and hung in the studio. The in-house 3D printing facilities produced many options of node, truss and beam details at multiple scales. Model makers created versions of the entire structure as well as focusing on details, again operating at many scales. Three 1:1 prototypes of the key triangular node were produced for evaluation purposes: one by the Foster + Partners’ Modelshop team, and two by contractors bidding for the job: Blumer-Lehmann AG and Merk Timber. Upon appointment of Blumer- Lehmann AG, an entire full-size mock-up of the final truss was produced. Testing even extended to 3D printing and placing onsite 1:1 models of the ceramic tiles at the foot of each column. These prototyping methods were invaluable, as the process of fabricating full-scale mock-ups greatly influenced the final design. The main timber structure is formed by a series of portal frames printed at the base, with Y-shaped brackets, forming the apex. The frames carry both gravity and lateral loading in the transverse direction. Connections between members are achieved by means of hidden pre-embedded steel flitch plates (Fig. 3) with bolts and screws as fasteners (Bangash, 2009). Linear elastic static analysis in Oasys GSA (Oasys, 2012) was carried out for the basic load cases and superposition used to assess the load combinations. An analysis of the stresses caused by wind load (sideways) and snow and dead loads (vertically) indicated where the timber could be optimised. The beams thus have a top and bottom flange, and diagonals through the web, which vary in density as the shear force varies along the section (Munch-Andersen, J. & Larsen, H. (eds.), 2011). The trusses taper in elevation as the bending forces reduce towards the cantilever tip, through the column to the pin connection at the ground and at the central node above the spine. This taper provides the slope of the roof. The bottom flange of the beam varies in width, reflecting the structural demands upon it. This can be seen in the contouring of the LVL layers on the bottom flanges.
There was much experimentation with the form of hogging moment above the steel prop.

In the final design, a trellis-like geometric arrangement would be suitable, and a script was created in Rhinoceros and Grasshopper that generated the webbing geometry. In the final design, the webbing is solid as the beam crosses the building envelope. This also provides greater support for the hogging moment above the steel prop.

There was much experimentation with the form of the webbing in the trusses. One option was explored that aligned curved timber members to follow the tension and compression stress lines within the beam. This would allow the members to work more axially. Despite predicting an improving outcome, the fabrication constraints were judged too great, although this work has informed a separate research project currently being undertaken by Foster + Partners’ Specialist Modelling Group.

A simpler solution was settled on whereby the trellis webbing is made from a pattern of straight elements whose frequency varies to match the material required to resist shear forces. As the shear force increases, the area of material required to resist it increases. The angle of the roof means that the available cross-sectional area of the web decreases along its length, which creates a varying percentage of webbing that must be solid. Integrating this curve gives another curve whose slope defines the nodes of the struts. As the spacing varies, the angles change accordingly, ensuring the requisite amount of cross-sectional material is provided.

The node that links the beam and column trusses is a key connection in the entire structural system. It is at this node that the vertical loads from the roof – its self-weight and the snow loads – are transferred to the ground. Simultaneously, the node acts as a fixed portal frame to provide stability to the roof without the need for any additional bracing elements or stiffeners. The roof can cater for the racking of the building. The final solution utilized a cantilevered sprung RHS beam to support the cockpit. When the building racks in strong wind, the cockpit is free to move vertically so as not to absorb any load from the building.

Benefits of 3D modelling and CNC manufacturing

The project required close collaboration between multiple teams at Foster + Partners and the contractors involved. The firm’s Specialist Modelling Group produced geometry with Rhinoceros and Grasshopper, which was analysed by the in-house structural engineering team using Oasys GSA, all the while liaising with Blumer-Lehmann and glass contractors Bennett Architectural Aluminium to ensure that architectural aims were met and manufacturing constraints were incorporated. The interaction and dialogue between designers and contractors was key – learning and understanding the limitations of the cutting equipment so that the design intent responded creatively to the manufacturing process.

The back-and-forth of 3D information helped the design and construction process, with CAD models shared from architects to contractors and vice versa for review. The diagonal arrangement of the trusses in plan across the central spine enables the primary timber structure to provide stability to the roof without the need for any additional bracing elements or stiffeners. The roof can be a varying percentage of webbing that must be solid. Integrating this curve gives another curve whose slope defines the nodes of the struts. As the spacing varies, the angles change accordingly, ensuring the requisite amount of cross-sectional material is provided.

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Benefits of 3D modelling and CNC manufacturing

The project required close collaboration between multiple teams at Foster + Partners and the contractors involved. The firm’s Specialist Modelling Group produced geometry with Rhinoceros and Grasshopper, which was analysed by the in-house structural engineering team using Oasys GSA, all the while liaising with Blumer-Lehmann and glass contractors Bennett Architectural Aluminium to ensure that architectural aims were met and manufacturing constraints were incorporated. The interaction and dialogue between designers and contractors was key – learning and understanding the limitations of the cutting equipment so that the design intent responded creatively to the manufacturing process.

The back-and-forth of 3D information helped the design and construction process, with CAD models shared from architects to contractors and vice versa for review. The diagonal arrangement of the trusses in plan across the central spine enables the primary timber structure to provide stability to the roof without the need for any additional bracing elements or stiffeners. The roof can be a varying percentage of webbing that must be solid. Integrating this curve gives another curve whose slope defines the nodes of the struts. As the spacing varies, the angles change accordingly, ensuring the requisite amount of cross-sectional material is provided.

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The timber structure is sustainable and tactile, and was built quickly to a tight budget. The CNC-crafted LVL lattice beams are constructed from Kerto, a MetsäWood product. It is made from 3mm-thick rotary-peeled softwood veneers that are glued together. The spars is sustainably sourced, using whole logs in the manufacturing process, with consequently minimal waste. The waste material generated by the milling of the trusses is used as fuel to heat Blumer-Lehmann’s factory space (Fig.1).

Removing material from the beam’s webbing resulted in a truss that was a third the weight of a similar solid glulam beam. The behaviour of the web as affected by the removal of material was further investigated by a number of finite element analysis models in Oasys GSA in order to assess the maximum and minimum principal stresses and the shear stresses at various locations in the web. These stresses compared favourably to the material strengths (ETA, 2010).

The use of 3D modelling and CNC manufacturing has unlocked new methods of working a traditional material. Crafting timber with these modern tools has resulted in an innovative lightweight structure and therapeutic space that is a fabrication of light and nature (Fig.6).

A successful exploration of material qualities

The product of the twin desires of design intent and structural requirements, the Maggie’s Centre in Manchester continues the long history of actively integrating the two within Foster + Partners’ work.

With a focus on the process of design evaluation through full-size mock-ups and prototyping, using the full range of capabilities at the firm’s disposal, the nature and fabrication of the final structure was evaluated at every step of the journey. Timber was chosen as the primary building material for its warmth and sculptural qualities, giving the building unique scale, depth and texture. There is no attempt at cladding or concealing the distinctive structure; the building is an open, honest exhibition of the material and its biophilic qualities.

The use of advanced manufacturing technologies allowed new ways of exploring the expressiveness of the material to be investigated. The exchange of 3D CAD models between teams within the office and external contractors for architectural, structural and fabrication review was also vital to the project’s success and contributes to a timber structure that is entirely digitally fabricated using a file-to-factor process.

The project combines fundamental design philosophies from the earliest days of the practice – prefabrication, dry construction and the benefits of speed and quality that this process offers – with modern digital simulation and manufacturing technologies. The result is an innovative lightweight structure and therapeutic space that is a fabrication of light and nature (Fig.6).

Project Credits


Client: Maggie’s

Structural engineering: Foster + Partners, Roger Ball, Andrew Sidgdon, Karin Moble, Matteo Bligh.

Environmental engineering: Peter Heath, Eva Giouyannaki, Nathan Miller

Exterior design: Michael Woodrow

Landscape: Dale Rees Studio

Timber fabrication: Blumer-Lehmann AG

Site area: 1,227m2

Built area: 500m2

References


Hermelin, R., 2006, Strength Analyses of Wooden I-beams with a Hole in the Web, Masters, Lund University.


Maggie’s Centre at dusk. Image: Nigel Young/Foster + Partners.
RETHINKING MATERIALISATION
The work of the Infundibuliforms project aims to advance research in lightweight kinetic surfaces as systems that have the ability to create spatial enclosures with minimal amounts of material and that are capable of dynamic reconfiguration. This paper describes the iterative research and full-scale prototype evaluation of a cable-robot-actuated, geometrically deformable elastic net that has been developed through close coupling between geometric explorations in computational spring-based physics solvers and experimental additive manufacturing techniques for net- or mesh-based structures. The title of the project refers to the catenoid forms that define the geometry of a surface; the term ‘infundibula’ is most commonly used to refer to funnel-shaped structures in biotic systems and plant morphology.

The work advances three parallel trajectories in computational, fabrication and geometric research:

- The development of dynamic models to both simulate and control the operation of a physical tensile system in real time.
Additive manufacturing

Additive manufacturing, commonly referred to as 3D printing, has been rapidly advancing the capability of designers across numerous fields to synthesize and manufacture materials and surfaces using materials such as thermoplastic elastomers. How would these surfaces perform under load and what are their formal potentials? Another research question was whether the physics engine-based simulation model? One of the goals of this research has been to develop a digital design environment: what new hardware and software interfaces could the creation and rapid assessment of novel structural forms. In this area, particle spring-based systems, which simulate live physical forces, have been explored by a number of designers (Kilian & Oechslerdorf, 2015, Ahsplung & Menges, 2010).

The primary research question of this project was how to advance the integrated design and control of kinetic lightweight architectures actuated through 3D cable robotics. Within this larger framework, several sub-questions have been advanced.

- Digital design environment: what new hardware and software interfaces can be developed that will enable both the design and the physical motion control of a kinetic tensile structure directly from the physics engine-based simulation models?
- Robotic 3D printed cable nets: is it possible to reliably 3D print lightweight and deformable cable net surfaces using materials such as thermoplastic elastomers? How would these surfaces perform under load and what are their formal potentials?
- Flat-to-form geometric method: given the 3D printing manufacturing technique chosen, the geometric and is quickly opening up novel formal, structural and visual configuration (Bletzinger et al., 2012, Wagner, 2005, Veenendaal & Block, 2012).

While there are several analysis tools for refining form-active structures, there are few tools available to designers for the creation and rapid assessment of novel structural forms. In this area, particle spring-based systems, which simulate live physical forces, have been explored by a number of designers (Kilian & Oechslerdorf, 2015, Ahsplung & Menges, 2010).

Research questions

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true state of the system, creating a 1:1 relationship between the physical system and the simulation. For the purposes of this research, project had to be undertaken into materials that had high elongation and that could be processed using thermal extrusion. TPEs are a physical mix of thermoplastic and rubber. Like most thermoplastics, they have the potential to be recycled and reused. They are available in a broad range of dimensions and melt flows. The melt flow index is a measure of the viscosity of a polymer at specific temperatures in the melting region. TPEs were tested across a range of melt flows in an attempt to balance the characteristics of the extruded bead with the ability to produce a void-free crossing joint in the mesh. A material with low melt flow coupled with a low die diameter was chosen for its consistency in processing while maximizing the deformation potential of the surface. The use of extruded TPE as the surface material allowed for unique discoveries and a novel geometric approach.

### Robotic 3D printed cable nets

In order to produce the tensile surface, the team pursued the fabrication of a monolithic elastic net fabricated through robotic extrusion of thermoplastic elastomer (TPE). To enable the manufacture of the net, an existing polyethylene extruder was modified to be serve-driven and mounted to a 3.5 axes robot (Fig. 3). The design included a specialised hopper for optimised thermoplastics to feed the pellets into a screw-driven extruder. The SuperMatterTools robotic control software, co-developed by author Wes McGee (Mcgee & Pigram, 2011), was used to direct the toolpath of the robot. The liquid TPE is deposited onto a heated 1,200 x 2,400mm aluminium bed to facilitate joint fusion and then allow for controlling cooling into a monolithic textile surface (Fig. 4).

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### Flat-to-form geometric method

This project sought to create an elastic cable net geometry that could be extruded onto flat surfaces and that could then be stretched into tailored anticlastic forms. Working with the elastic stiffness parameters for the mesh, and based on the actual behaviour of the extruded TPE strands, iterative dynamic relaxation in Kangaroo was used to investigate how the final mesh would deform when loaded. As has been noted previously, mesh topology has a profound influence on the behaviour of the loaded form (Hernandez et al., 2013). Physics-based simulations between a base quadrilateral mesh versus a diagonal mesh showed that the diagonal mesh would achieve the more acute funnel-shaped forms that were desired for the project. The difference in performance between the quad and diagonal meshes is due to the fact that, in the case of the diagonal, the mesh edge carries loads from both directions, whereas for the quad, the load paths spiral around the ring, producing more dramatically curved catenoid forms upon stretching, as compared to the conical forms created with the quad mesh's simple point-to-point load transfer.

The question of how to achieve further tailoring of the streching process hinges on the basic principle of introducing a curve instead of a line between two nodal points, so that a greater working length under loading could be achieved. By setting a target length derived from the loaded mesh form, it would therefore be possible to control the resultant length of every individual mesh edge, making it possible to programme a range of naturally stressed three-dimensional forms into the flat pattern. Using Kangaroo’s spring-based physics, the desired edge length of each vertex of the mesh is known. To achieve this difference was slowly stepped up from the 2D length to the 3D length by incrementally increasing a multiplier value from 0 to 1 by 0.01 at a time while dynamically solving the physics simulations) into the geometry of the line. The scripted equation used was: edge length = (L + 2D, where ‘L’ is the extruded to form 1.01. Limitations were programmed into the model to more reliably approximate the physical behaviour of the welded connections produced by the robotic extrusion process, and a collision avoidance component was integrated to maintain the mesh topology and account for the physical properties and dimensions of the extruded TPE load (Fig. 5).

As test prototypes showed, the process works in concert with the natural flexibility, so that when loaded the programmed curves straighten into lines and then relax back into curves when the load is removed, helping the mesh to maintain tension across a number of different states.

### Research evaluation

The work of this project identifies the prototypes as the primary mode of evaluation within the knowledge-based design (Coyne, 1990) methodology of this project. The prototype installation of the Infundibuliforms project not only allowed the team to test the complex interactions between mesh geometry, its fabrication, the cable robot operation and the design and control environment, but also introduced additional design and implementation frameworks that became productive feedback for the iterative development of the research.

The prototype installation consists of a 2*3 m 3D printed TPE cable net surface spanning between an outer conical ring and three weighted inner rings. Due to the scale of the installation and the manufacturing constraints of the extrusion bed, the surface was subdivided into panels that could be individually fabricated and would then be mounted at the seams. To increase the tension at the perimeter, as well as between the individual catenoids, the mesh was subdivided into smaller cells with less curvature between nodes, decreasing the amount of deformation in these areas and increasing the curvature angle of the catenoid. Conversely, cell size and internal length were increased closer to the inner rings, enabling a greater elongation of that portion of the catenoid. This method allows for formal reformation of the surface through the manipulation of the surface geometry.
entire mesh was pre-tensioned by being scaled to 92% tension when under gravity loads. These servo motors position the weighted rings located at the end of each infundibulum. These can dynamically reconfigure the surface between vaulted and chimney forms within a broad range of positions (Fig. 6). The kinetic material systems for architecture. With this framework, this research has attempted to empirically verifying the fidelity of the physical model. The full-scale installation also included a pair of custom-designed and built control cabinets, with 12 interpolated control ring zones. This zone is extruded with a harder, stiffer TPE material (Shore A hardness of 68, compared to 35 for the rest of the piece) and is intended to maintain tension through the middle of the piece to limit self-load deflections (Fig. 7).

Future directions
The increasing capacity for designers to use robotic manufacturing techniques in order to programme performative capabilities into materials has the potential to expand new possibilities for architectural geometries and physical forms. This paper has presented a novel fabrication and geometric development coupled with a form-control method for elastic net surfaces that is informed by material feedback and the advancement of additive manufacturing techniques for surfaces. In addition, this work has begun to add the capabilities of real-time simulation models that can communicate with industrial control systems for dynamic architectures.

Within this specific project, it is also possible to identify a number of areas, both immediate and more distant, that may be pursued with further work. These include:

• Empirically verifying the fidelity of the physical prototype to the computational model by 3D scanning the prototype (such as through LEDAR technology). Since the dynamic computational model is also used to directly control the positions of the individual motors, there is confidence that the spatial location of the inner and outer boundary rings is true. What is less apparent is the geometric accuracy of the surface, relative to the simulation.

• The inclusion of sensors to enable closed loop interactivity with the system. The industrial PLC platform provides an ideal low-level framework for discrete sensors, but higher-level systems (such as depth map cameras like the Kinect) which interact with the computational model though an API are also a possibility for future exploration.

With this framework, this research has attempted to move toward the integrated development of large-scale kinetic material systems for architecture.

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Funding:

Andrew Wald, Iram Moreno Pinon, Isabelle Leysens, Asa Peller, Dustin Brugman, Andrew Kremers, Dominik Kallweit, Johannes Kohler, M., 2015, 'Iridescence Print: Robotically Printed Lightweight Mesh Structures and Modelling Behavior' in 833x453 to 1304x681

Technical partners:

Andrew Wald, Iram Moreno Pinon, Isabelle Leysens, Asa Peller, Dustin Brugman, Andrew Kremers, Dominik Kallweit, Johannes Kohler, M., 2015, 'Iridescence Print: Robotically Printed Lightweight Mesh Structures and Modelling Behavior' in 833x453 to 1304x681

Acknowledgements


Images: © RVTR / The first Infundibuliform prototype was installed at the University of Michigan Teal and McLean, 2013, ‘ShapeOp – A Robust and Extensible Geometric Modelling Platform’ inInternational Journal of Robotic Research, 32(9), p.1173-1186.


Integral joints provide a rapid, simple and mechanically strong connection between parts. Our investigation focuses on the assembly of cross-laminated wood veneer plates, where previous studies have shown that the strength of through-tenons is equivalent or superior to state-of-the-art fasteners such as screws or nails. This mechanical behaviour is highly dependent on a precise fit of the joints, where no gaps are left between the parts. However, the manual assembly of such tight-fitting joints can be complicated. Thanks to its rectangular cross-section profile, a single through-tenon joint is a sufficient assembly guide for an entire plate, but multiple through-tenons are required to establish a mechanically strong connection. This results in a kinematically over-constrained assembly motion (Mantripragada et al., 1996). Additionally, due to fabrication- or material-related tolerances, the joints can be too tight-fitting and manual assembly motions deviate from the precise insertion path. So-called ‘wedging’ occurs during the assembly of tight-fitting joints, especially with larger parts at a building scale (Fig. 1). This requires high forces to be overcome.

Rather than leaving gaps between the parts, which presents one solution for the manual assembly of such systems, we investigate the idea of assembly using an industrial robot. The robot allows for a more precise assembly motion and the application of higher forces in the direction of assembly. The aim of this research is to use these benefits along with the compressibility of wood for the assembly of oversized tenons. While in regular through-tenon joints the width of the tenon is equal to the width of the slot, the oversized tenons in this paper are slightly wider than their slot parts. This assembly will require a certain insertion force, squeezing the tenons into the holes, but the resulting connection will be tight-fitting without any gaps.

Robotic assembly

Robotic integral attachment demonstrates the advantages of combining robotic assembly (Helm et al., 2017) and integral mechanical attachment, such as through-tenon joints. Both methods are used to facilitate the assembly of complex architectural designs, such as freeform shells and space frames. While integral
attachment embeds the instructions for manual assembly into the form of prefabricated components (Fig. 2) (Robeller, 2015). Robotic assembly integrates the assembly logic into the robotic positioning procedure (Gramazio et al., 2014). The aim of this research is to investigate the combination of these seemingly contrary methods.

The two main benefits of integral joints for the design of timber plate shell and spatial structures are their so-called locator and connector features. Locator features, in the form of the joints, reduce their mechanical degrees of freedom and thereby also the relative motions between the connected parts. This allows for the indication of the correct alignment and position of parts to one another. While some joint shapes, such as finger joints, will reduce the mobility of parts to three degrees of freedom and perform as partial assembly guides, other joints, such as through-tennis, will reduce the mobility of parts to only one insertion direction and perform as fully integrated assembly guides.

Integral mechanical attachment allows for a simple, fast and precise onsite joining process. It transfers the complex and laborious aspect of assemblies into the prefabrication of the plates. This is made possible through computational design and automatic prefabrication technology. As a consequence of such improved joining strategies, more complex shapes can be efficiently produced. Geometrically, multi-scale joints were carefully designed and tested. Roche et al. (2015) showed that the shear strength of finger- and dovetail-jointed plywood plates is similar to the shear strength of screwed connections. Li et al. showed that the connectors can be combined with metal fasteners, and further research by Roche et al. (2015) suggests that fasteners can be added to ridges, demonstrating the particular strength of through-tenon joints.

Aiming at the automated assembly of timber plates and the elimination of any gaps that would reduce the stiffness of the joints, the main question was to ascertain what forces would occur during the insertion of through-tenon joints, both with and without oversized tenons.

Further questions arise due to the fact that, during the assembly of timber plate shell or folded plate structures, multiple joints must often be inserted simultaneously. These were: how the insertion forces on individual joints could be reduced through modifications in their form; how the forces would add up during the assembly of multiple joint assemblies; and how insertion forces and possible wedging could be reduced through finite-element built vibration inducing robotic end-effectors.

- What force is required for the insertion of a through-tenon joint?
- What force is required for the insertion of a through-tenon joint with oversized tenon?
- Can the effect of wedging be reduced through optimizations in the form of the joint?
- Can the effect of wedging be reduced through automated robotic assembly?

Experimental set-up

The robotic assembly of elastic and plastic through-tenon joints for cross laminated wood veneer plates was investigated through physical assembly experiments. Using 40mm-thick beech laminated veneer lumber (LVL) plates and a tenon width of 120mm for all specimens, different joint oversizes and parameters were tested. Elastic joining techniques like cast-in-place snap joints are commonly used in other industry sectors, such as consumer electronics or the automotive industry. (Mehta, 2011). They can be generally applied to elastic materials. The application to cross-laminated wood panels has been previously investigated (Robeller et al., 2014).

Plastic joining techniques are also commonly used in various industrial applications, especially in the form of press-fit or friction-fit joints. A well-known example using metal materials is staking, where an undersized boss in a regular-sized hole is expanded through a staking punch. The resulting radial expansion will cause a physical interference fit between the two pieces. Metal screws work in a similar way; the tip of the screw creates a large friction surface, while pressure is applied through its inclination and rotation. In addition to the friction interference, the elasticity of the material plays an important role in plastic interlocks, too. The press-fit, the parts of the joint are squeezed. The elastic recovery force will apply pressure on the contact surfaces, which further increases the friction interference. The primary purpose of the plastic and elastic timber plate joints in this investigation is to eliminate gaps, which may be required for the assembly of joints.

The regular rigid joints were added as a reference for comparison. This elimination of gaps should be achieved through a press-fit assembly of tenons that are slightly wider than their slots. Multiple series of experiments were tested, where the tenon oversize was increased in small steps: 0.0mm, 0.1mm, 0.2mm, 0.3mm, 0.4mm and 0.5mm. During the insertion of the joints, the oversize tenons should be able to fit into the slots primarily due to the material compressibility on the rigid-type through-tenons, and predominantly due to the material elasticity on the elastic-type through-tenons. Here, cuts along the centre line of the slotted part allow for lateral deflections during the joint assembly.

Due to the centre line cut on the elastic through-tenons, their sliver strength will be greatly reduced in comparison to rigid versions. However, the elasticity was also expected to greatly reduce the required insertion force. Such elastic joints may be particularly interesting in combination with rigid or plastic interlocks (see Fig. 3). The plate held by the robot, providing ideal locator features while requiring reduced insertion forces.

The primary challenge in the assembly of the oversized joint is the so-called effect of wedging, where a friction interlock is established between the two parts during the insertion before the final position is reached. This occurs due to tolerances in the size of the parts, resulting from fabrication imprecision or dimensional changes due to changing environmental conditions, as well as imprecisions in the assembly motion, which must follow one precise path in the case of single-degree of freedom joints, such as the through-tenons.

It was expected that the wedging could be reduced through a small inclination of \( \theta \) on the small contact faces across the edge on the through-tenons and on the slots. We can achieve an inclination on these faces using a 5-axis CNC router, with the tool inclined at \( \theta \) for the cutting of the slot part. However, the other two contact faces along the edge of the joint cannot be inclined, as those lie on the top and bottom of the cross-laminated wood plate and cannot be easily cut without turning and re-clamping the work pieces.
For all assembly tests, a 6-axis industrial robot with a maximum payload of 125kg and an additional seventh linear axis was used to insert the through-tenons (Fig. 5). In the first series of single-joint assembly tests, the slot plates were fixed to a concrete block. The insertion motion was then carried out parallel to the robot’s additional linear axis for the single-joint assembly tests. A custom end effector was built with an integrated six-axis force measurement device, from which the pressure values were recorded during the assembly motion.

Following the first series of single-joint assembly tests, the assembly of multiple joints was tested on six full-scale plates out of a folded roof structure, which was generated with the computational tools presented by Robeller and Weinand (2015).

The multi-plate robotic assembly experiment investigates the robotic assembly of prefabricated plate structures, which would fit on standard-size trucks for transport to the construction site. With such a prefabricated assembly, 85 percent of the total edge joints in the case study roof would be assembled automatically with robots, while the remaining 15 percent of the edges must be joined onsite. This paper demonstrates how the material properties of compressibility and elasticity can be exploited for an assembly technique that fully eliminates any gaps, folds, and compressible interlayer. Furthermore, the test showed that an additional ‘pulse’ force in the joints’ assembly direction is beneficial in combination with the vibration device. During the tests, this force was applied manually in order to avoid a premature friction-based interlock. Furthermore, the test showed that an additional ‘pulse’ force in the joints’ assembly direction is beneficial in combination with the vibration device, from which the pressure values were recorded during the assembly motion. The multi-plate assembly test showed that the simultaneous assembly of six through-tenons per plate. A custom end effector was built to hold the plates with an integrated device for the measurement of forces (Fig. 5). This effector was also equipped with an integrated vibration-assisted assembly device for the introduction of vibrations into the plates, in order to reduce the effect of wedging.

The first series of single-joint assembly tests showed the expected increase of insertion forces, along with an increasing oversize of the through-tenon joints. The smallest oversizes of 0.05mm would result in a required insertion force of 0.4kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. At an oversize of 0.15mm, we recorded 0.8kN, while the two largest oversizes of 0.20mm and 0.25mm required much larger insertion force of 0.7kN. Since the assembly of structures such as timber plate shells requires the simultaneous assembly of multiple edges and therefore also multiple joints, it is crucial to estimate the total required insertion force per plate. The multi-plate assembly tests have shown that the assembly of building-scale plates from our case study project is possible with an additional vibration-industry device. Further research is required into the addition of a pulse force, similar to a jackhammer, which can be induced in the plate's direction of assembly.

Boosting the benefits
With their locator and connector features, integral timber plate joints offer considerable benefits for the design of timber plate structures, such as segmented plate shell or folded plates. While the mechanical strength of the joints requires them to be tightly fitted, this can be problematic for the assembly of such kinematically overconstrained joints. The elastic and plastic interlocks presented in this paper demonstrate how the material properties of compressibility and elasticity can be exploited for an assembly technique that fully eliminates any gaps, folds, and compressible interlayer. Furthermore, the test showed that an additional ‘pulse’ force in the joints’ assembly direction is beneficial in combination with the vibration device. This is made possible through the precise assembly motion of an industrial robot, as well as the possibility of it applying an insertion force. Here, the single-joint assembly test series first provides values on the required forces. Since the assembly of structures such as timber plate shells requires the simultaneous assembly of multiple edges and therefore also multiple joints, it is crucial to estimate the total required insertion force per plate. The multi-plate assembly tests have shown that the assembly of building-scale plates from our case study project is possible with an additional vibration-industry device. Further research is required into the addition of a pulse force, similar to a jackhammer, which can be induced in the plate's direction of assembly.
LACE WALL
EXTENDING DESIGN INTUITION THROUGH MACHINE LEARNING

MARTIN TAMKE / MATHEUS ZWIERZYCKI / ANDERS HOLDEN DELEURAN / YULIYA SINKE BARANOVSKAYA / IDA FRIS TINNING / METTE RAMSGAARD THOMSEN

CITA | Centre for Information Technology and Architecture, The Royal Danish Academy of Fine Arts, Copenhagen

Lace Wall explores how design-integrated simulations of real-world behaviour of building elements and machine learning allow the design and manufacture of large-scale resilient material systems from a minimal inventory of elements: 8mm glass fibre-reinforced plastic rods, textile cables and custom-designed HDPE elements to join cables and rods together. The rods are bent and joined into discrete units stabilised by an internal three-dimensional cable network. 80 units are connected into a 12m-long, 7m-high wall (Fig. 2). While the geometry of the rods is identical, it is the differentiation of cable networks which allows the single units to stand the divergent local strains in the structure and to constrain each individual unit into individual geometries that fit into a desired overall macro shape. The high interdependence of elements and scales in the structure permits the use of established design optimisation strategies to find the specification for the cable networks. In order to explore this, we developed methods that combined lightweight simulation, physical models and machine learning in order to evaluate multiple interdependent design parameters and finally establish a machine-enhanced intuition which is good enough to specify structures that behave as expected.

Building complex geometries

Lace Wall belongs to the family of form-active hybrid structures (FAHS), which allow for the building of complex geometries with hardly any machining effort or waste material (Tamke, 2013, Lienhard, 2014, Holden, 2016). The integration of restraining tensile elements, such as membranes or cables, increases their structural performance (Alpermann 2012). In the case of the units of Lace Wall, this increases (in comparison to bending-active-only structures) the possible design space in a dramatic way, as it introduces an added dimension to stabilise, constrain and join elements.

Approaches towards supporting form-active hybrid structure design

The recent efforts of the research community towards approaches that support design, form-finding and structural analysis of form-active structures had a predominant focus on systems of either tensile or compressive members (Menges, 2012, Tamke, 2013). Hybrid systems of interdependent tensioning (rods)
Machine learning as a means for design search

Machine learning has been introduced in engineering to accelerate complex simulations, as in the case of CFD, and to predict plausible complex wind interference patterns by utilizing methods of supervised learning (Wilkinson, 2014). This prediction provides a quick, reliable and precise approximation of the real interference to inform the designer and optimisation loops 3 to 50 times more quickly about the CFD characteristics of the building than traditional CFD methods.

Queries for structures in large and patchy design spaces have recently used methods of unsupervised machine learning. In Thomassen and Stradi (2014), the authors use k-means clustering to analyze the outcomes of the design space exploration – 60,000 bending-active structures have been clustered at high similarity based on 28 parameters. Solution space exploration is also the focus of Haching (2015), who demonstrates how Kohonen’s self-organizing maps (SOMs) can be used for dimensionality reduction. A use of k-means for geometry rationalization is presented by Peña (2012), where the algorithm was used to limit the variation of 15,000 facade panels to conform in 49 families.

While the use of k-means clustering in the case of Lace Wall might seem a viable option, it can lead to the wrong classification of unit load cases. This is caused by the distance metric used to decide on similarity between two data points, which doesn’t take into account the relationships and characteristics of their values. This makes artificial neural networks (ANNs) more suitable for the task, as these are able to account for both the variance and, more importantly in this case, the relationships between the values. The simple plots that resulted from calculating this relationship demonstrate how a wrong classification will ultimately result in the wrong association of optimised solutions with a load case. Intuitively, the k-means clustering would categorize them as the same two units within neural networks (ANNs) are more suitable for the task, as these are able to account for both the variance and, more importantly in this case, the relationships between the values.

The collected experiences of Tøwer (Thomsen, 2015) showed that such stable and balanced bending-active structures are best achieved when they close on themselves, as the ‘9’-shaped ones which were finally showed that such stable and balanced bending-active solutions allows a systematic exploration of solutions through the designer. Similar to the work with physical models, the designers can build up an intuition about promising design options and explore them quickly. These explorations can also take place through the automated generation of design options and a subsequent evaluation and refinement of the form-found solutions according to given aims, such as maximum amount of cables, lengths and relations between elements.

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orthogonal connections that require the transfer of great moment forces.

The exploration used, in parallel, both physical models and the above-described randomised design integrated simulation environment. The limitations of each of these needed to be reflected in the other; for example, the digital representation of joints informed the way elements were connected in the physical assembly.

The development process included several instances of verification, where an alignment of the digital and physical models was pursued with the aim of creating a coherence between both. These processes showed that the simulation environment was able to predict the emerging shape of our hybrid units to a degree sufficient for design decision-making and fabrication. A lack of final precision in quantitative terms can be removed through the material tolerances in the system.

The development resulted in a single unit made from a set of mirrored rods fixed into a ‘double 9’ configuration. This is constrained into shape by a three-dimensional network of mirrored rods fixed into a ‘double 9’ configuration. Each unit has eight orthogonal connections that require the transfer of great moment forces.

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The development of the single unit and the array of many of them into a larger assembly was guided by the overall aim to create a wall-like structure. Performance goals on a local level were, however, far more fluid, emerging through the design process. The interaction with the digital and physical prototypes gave an intuition, rather than a certainty, about the design direction that it might be worthwhile to explore. Crucial parameters and underlying rules for the set-up of the units and the steering of their behaviour were found over many design iterations. However, the analogy gathered therein is patchy and cannot be considered to apply across the board, as it is based on observed relationships between an introduced means and a unit’s overall behaviour – in this case, the idea that a direct connection of the bend rods on each side with tension cables is beneficial for its overall behaviour (Fig. 5).

A reflection on the structural setup of the units links these observations to overarching rules, but the complexity of the structural elements impedes a direct linking of the single unit’s behaviour to structural first principles.

The development process, supported by constant feedback from computational and physical models, built up an intuition on the part of the designers and helped to direct the design search. However, this intuition was never perfect, as it is inclined to move fine-tuned directions. One of these was the distribution of different cable networks across the array of identical units in order to obtain the desired macro shape. A computational global optimisation, where the parameters of every element in every unit are tested and subsequently optimised, was not possible due to the aforementioned combinatorial explosion. Other means of specifying the cable networks in the units accordingly to local force conditions had to be found instead.

Our approach to fabrication using machine learning

The project followed an approach of using machine learning to identify units in the macro shape which present the emergence of the desired overall macro shape that we consider structurally sound. The overall stability is hence dependent on the preservation of the macro shape through preventing single units deforming too strongly from the initial shape or even collapsing under the incoming loads. A generation and analysis of new cable nets is hence possible on the level of the single unit. It was expected that the repeated picking and improvement of the structural behaviour of singular cells would, over relatively few iterations, generate an overall increase in structural performance. For this approach, a set of techniques had to be linked:

1) A method to analyse the overall structural behaviour of the single unit, as well as its assembly (crumetised Kangaroo 2 and the development of Kangaroo 2E).
2) A technique to generate the cable networks: an algorithm was developed, based on the findings from physical prototyping, that showed that a maximum of three cables meeting in a junction and a spatial distribution of cables was preferable.
3) A model to represent the wide range of topologies and performances that the cable networks and linked rods can take on. The encoding capitalises on the fact that the above algorithm creates a cable network unique to any set of distribution points on the rods. An effective and easy way to compare data models emerged where only the order and position of points (genome) and the related performance of the unit (fit): the deviation from the ideal tiling geometry) needed to be stored in order to represent and, where necessary, reproduce units.
4) Modes to evaluate whether and how well a generated unit fulfills the requirements of design, structural behaviour and fabrication. These emerged during the design and prototyping phases and were verified through observations. Two sets of qualifiers were applied that describe the performances of the units:
   (a) Binary ones, which any unit has to meet (durability: red/cable angle above 50°; fabricability: no overlap of cables, structural performance: cables not named, stability: units which need more than 30,000 iterations to solve tend to be unstable).
   (b) Numerical ones, which allow the evaluation of the fitness of a unit (bending forces, fabrication error ratio).
5) A system that can perform the task of picking the units which need to be optimised (the encoding process was trained on an artificial neural network trained with back-propagation).

The assembly of units is generated, form-found (Kangaroo 2) and structurally analysed (Kangaroo 2E).

Form finding and analysis reveal the force distribution and behaviour of the units under load. This data is used to initialise the solutions database, with the two naively picked cases (naive pick initialisation: picked by the lowest and highest sum of load values) then being optimised and saved (optimisation of a single unit with Galapagos and K2).

A second stage evaluates the geometry of the units in order to ensure a healthy breadth of solutions: only those with a genome either better than or different to existing ones are saved for further consideration (Fig. 6).

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The neural network indicates the cells which it cannot classify accurately. This opens the possibility of reusing the optimised solutions database and the trained network in unseen situations.

Artificial neural networks, in particular, with their origins in pattern recognition, seem to be well-suited to the investigation of load distribution recognition problems. The machine learning-based approach presented here demonstrates how neural networks can categorise the shape of complex geometries based on high-dimensional discretisations with up to a hundred input parameters. The neural network is able to learn from a relatively small number of parameters compared with other classification methods, which, in our case, ensured that it was able to precisely describe the load distribution. This approach offers flexibility and precision when it comes to the classification of previously unseen data. This opens up the possibility of reusing the optimised solutions database and the trained network in multiple iterations of the design.

Acknowledgments

Lace Wall would not have been possible without the work of Annelie Linger.

References


This research follows an important body of work from the past decade, which focuses on the design of global surface geometries for compression-only structural behaviour. For example, studies in thrust network analysis have made possible the design and computation of complex unreinforced freeform shell structures that work purely under compressive forces once they are completely assembled (Block, 2009). Recent built projects have shown that while it is possible to construct these structures with standard CNC fabrication tools and for them to demonstrate efficient structural behaviour with minimal bending as expected, a major challenge of building these structures is the development of effective assembly strategies during construction to handle tolerance (Rippmann et al., 2016). A second key challenge is the management of falsework, which is structurally necessary to hold individual voussoirs, or compression blocks, in place until the structure is stable, which is sometimes not until the final stone is placed.

These challenges are important to address in order for efficient, geometrically expressive masonry shell structures to play a larger role in the contemporary architectural fabrication landscape alongside conventional steel, concrete and timber structures. In response, the research presented here offers a new approach for the fabrication and assembly of freeform masonry shell structures that can be built with less error and less falsework. Made possible through a computational workflow that simulates structural behaviour during assembly instead of only after a structure is completed, the approach employs cast-metal joining details that bring ancient stonework techniques into the digital age with customised, mechanically responsive geometries.

New agendas for stone carving

Correlating forces (physics) and form (geometry) in 3D, thrust network analysis and accessible physics simulation environments based on dynamic relaxation have extended historical structural form-finding methods into new versatile digital design workflows (Block, 2009, Rippmann et al., 2011, Piker, 2013). One of the results of the availability of these new geometrical exploration approaches has been a renewed interest from designers...
in historical techniques such as stone carving (Lachauer et al., 2013, Rippmann et al., 2015, Clifford et al., 2015, Kaczynski et al., 2013).

Construction of discrete element structures

Most of the current research efforts in discrete element structures have focused on the production of geometrically challenging thin structures that perform efficiently even once they are finally assembled. These efforts have not emphasised the forces arising during assembly, or have solved this problem through external means such as scaffolding, chains or ropes (as in Deuss et al., 2014). In contrast, this research approaches the problem of stability during assembly through integrated details.

Stone detail precedents and methods

Two types of detail precedent inform this research. The first is the historic process of carving a detail geometry into stone and direct casting metal into that geometry. This detail is often embedded inside the thickness of the mass of stone, but rather by the properties of metal shaping or casting and the carving tools used (Leroy et al., 2013). The second detail precedent is a procedural one. For instance, Inca stonework carries vestigial details that hint at the sequence in which a wall was constructed. Each detail refers to a particular moment of assembly and its relation to previously placed stones. This concept can be seen not only in the way the stones notch into and its relation to previously placed stones. This concept can be seen not only in the way the stones notch into and its relation to previously placed stones. This concept can be seen not only in the way the stones notch into each other, but also in the nubs used to place the stones (Prosser, 1993). This research seeks to condense these two detail concepts in order to incorporate procedural and sequential structural analysis to inform detail locations. These locations are responsive not only to the global conditions, but also to the discrete conditions of the in-progress assembly (Fig. 3).

This project examines the problem of assembling masonry structures through the integration of computation, analysis and simulation during the design phases. The motivation of the research is to develop a streamlined workflow which encompasses design, fabrication and assembly of discrete element structures by leveraging the possibilities of digital fabrication methods. Through a focus on historically inspired details, this paper seeks a new approach that can expand the possibilities for designing and building expressive, efficient structural forms.

The assembly method in this research comprises six steps from design to assembly: base geometry, discretisation, physics analysis, detail design, fabrication and assembly. The method is exemplified by an eight-piece masonry structure case study shown in Fig. 5, manufactured at Quarri Stone in Madison, Wisconsin.

Base geometry

This research employs a method which serves to liberate geometry from the exclusive dedication to structural requirements. Though essential, structural forms rarely align with programmatic, ergonomic, thermal or formal concerns. In order to accommodate a confluence of differing concerns, the potentials of depth and volume are employed, resulting in an in-isomorphous condition, as described previously (Clifford et al., 2015). This deep condition produces a zone of operation that Wolfgang Meisenheimer describes as the ‘work body’ (Meisenheimer, 1965) - a space between the visible architectural surfaces which is dedicated to the means and methods of making. This method begins with a base geometry informed by the above extra-structural concerns. This singular surface approaches a structural logic, but does not satisfy it. Through variable depth and detailing strategies, this non-idealised form transforms into a proposal which satisfies a thrust network within the middle third of the material depth (Fig. 3).

Discretisation

Next is the discretisation of the base geometry into voussoirs. Many different discretisation methods are possible - in this case, a Voronoi-based discretisation is created using a particle-spring system, which creates a random gradient distribution of 3D voussoirs that are larger toward the base of the structure (Fig. 4).

Physics analysis

This method proposes an alternative assembly strategy for freestone stone shells that relies on a local understanding of forces at each step of the assembly sequence (Arcas, 2015). The structural analysis includes two steps: a global analysis that evaluates the dimension of the structure in its final state and a local analysis that evaluates all intermediate equilibrium states. The during assembly. The analyses are conducted with Karamba v.2.2, a finite element analysis plugin for Grasshopper (Frischупur, 2013), and directly contribute to the design and distribution of cast tension details. Specifically, the analyses consider reactions generated at boundary conditions between elements and at the interface with the ground to determine the types and locations of necessary details.

Global equilibrium analysis

Because the base geometry is not generated to fulfil one single constraint (i.e. structural performance), global stability is not guaranteed. The results of the overall calculation of reaction forces at the base of the eight-piece section of the structure are shown in Fig. 5.

Assembly sequence

The sequence of assembling voussoirs does not affect the global stability of the final assembled structure. However, there is a big impact on stability during the assembly process. While this research does not rigorously address this question, the topic has been studied in Deuss (2014). This research establishes a reasonable assembly sequence using 3D voussoirs, and the most stable unit of each ring is assembled first. As each new voussoir is added, it is necessary to prove that the previous state of equilibrium is still valid. Ultimately, every previous interface between voussoirs needs to be checked, since each is affected by every new addition. As a proxy, in this case study the stability of the global intermediate, or the sum of all previously assembled voussoirs, is checked at the base (Fig. 5).
Details design

Details can be inspired by different motivations. In this project, the role of the details is to coordinate different types of components (structural, type, direction and magnitude of reaction forces), fabrication (properties of the carving and casting tools and machines) and assembly (organisation and fixing steps of units). This approach takes advantage of the ability of robots to perform custom non-repetitive stone carving and match it with cast metal’s ability to be formed with geometric flexibility.

Structural constraints

The reaction forces of the discrete analysis are interpreted one by one, matching type, direction and magnitude to find structural detail strategies. Compression forces require surface area, so the planar edges of the voussoirs are left unmodified. Tension forces in the plane require a locking geometry in plane and in the direction of the tension vector to avoid units pulling apart. Out-of-plane tension forces and bending moments are counteracted with couples on opposing faces. In plane shear forces require a locking geometry perpendicular to the plane of action of the force.

Fabrication constraints

The type of stone, the geometric properties and the performance of tools define the carving constraints. This paper’s case study uses Vermont Marble and a blunt electroplated tool. The tool diameter defines the minimum radius of possible carved curvatures, and the tool diameter before the final fixing of the unit. This last parameter is key to specifying possible locations of tension details.

Casting constraints are dictated by the way in which the metal flows through and freezes in the mould when poured. Sharp external corners result in more rapid cooling, leading to increased grain size and brittleness. Sharp internal corners often result in cracking during freezing. Drastic changes in cross-sectional area and volume result in uneven cooling and grain structure. Since traditional clips and butterfly joints in wood or wrought metal do not suffer from such constraints, two-step assembly strategy determines the drafted geometry and the material selection of the drift-pin.

Robot control and constraints

Industrial robots are designed to be highly flexible manipulators, but this flexibility results in compromises with respect to overall volumetric accuracy. One technique for minimising positioning error is to utilise an external synchronous positioning axis (rotary table). By allowing the robot base to be restricted to a smaller range of motion and a reduced range of joint configurations, accuracy can be improved; in addition, the overall work volume of the robot increases significantly. Both of these techniques are employed in the fabrication of the case study. In the final eight-piece case study, individual voussoirs are processed from a solid blank to the finished part using a single fixtureing setup on a flat back face.

Cutting operations

The production of individual voussoirs benefits from an automatic tool change setup and comprises four robotic carving operations (Fig 6). The majority of the stock is removed with a thick diamond composite blade. The first operation, a side-cutting strategy, is used for cutting the flat bearing surfaces of the voussoir. Then a second operation, a side-cutting finishing strategy, is used in a motion perpendicular to the previous direction of the blade. Finally, an electroplated diamond tool is used for a polishing operation that produces the joint void.

Automation of geometry for toolpathing

While the implemented algorithm design approach generates highly unique geometries with relative ease, it was important to identify production bottlenecks early in the project. While fully automated design-to-machine code strategies have been implemented in certain projects, it was determined that a hybrid approach would integrate better with the fabrication workflow at Quarra Stone. This involved the automated generation and organisation of 3D part files with the needed ‘helper’ geometry to work smoothly with the production CAM package used by the fabrication team.

Assembly

Several challenges arise in the placement of the individual voussoirs. First, the stones are not set upon a level surface and the centre of mass of the piece is often not directly over the bearing surfaces, resulting in temporary instability during assembly. Second, while the mating faces of the voussoirs are drafted in all directions, which facilitates positioning, there are multiple degrees of freedom in the movement of the stones as they are individually placed. To counter this temporary instability, a two-step assembly method is implemented.

Fitting and registration

Using minimal, adjustable tension and compression fasteners, each voussoir is fitted in place by hand and registered to its corresponding precast drift-pin applying tension normal to the adjacent faces of the two stones. This registering operation facilitates the minute adjustment of the voussoirs after placement and temporarily holds them in place during the completion of the ring. The malleable drift-pins also have the capacity to be adjusted to fit in case of fabrication inaccuracies.

Casting and fixing

After the placement of an entire ring of voussoirs, the pre-machined drafted voids of the sheer details located between the most vertical faces of the stones is filled with metal in-situ, permanently fixing the ring together. Temporarily holding the course in place are cast over in-situ, permanently locking the drift-pin in place. Additionally, any gaps between voussoirs resulting from the tolerances in fabrication are filled during the pouring of the in-situ joints. This series of operations is then repeated for each consecutive ring.

Research evaluation

The validity of the structural analysis and assembly method was assessed through a series of structural tests of specific cast details and prototypes. The former evaluated the material strength and efficiency of the joint geometry throughout a series of controlled specimens. Different mock-ups explored the possibilities and performance of the various available machining methods; the casting and assembly processes and the materials to be used in the precast and in-situ details. The final eight-piece case study served as a final evaluation of the overall detailing and assembly method.
Material tests

Structural tests were performed on details with two different casting alloys: pewter (AC or Britannia), an alloy of tin, copper and antimony; and zamak 3, an industrial die-casting alloy of mostly zinc, copper and magnesium. Despite having a much lower ultimate tensile strength (51.7 MPa) than zamak (348 MPa), pewter was selected due to its lower melting point, high toughness and brittleness, its resistance to work hardening and its higher flow rate (Fig. 7).

Ten geometric variations of tension joint were tested. Controlling variables included the length, depth and thickness of the joint. These specimens of each geometry were tested to failure under tension. The most successful joints (from upper left, A to J) and tension testing of specimens transferred between 9 and 12.5kN under work hardening and its higher flow rate (Fig. 7).

This last test proved the importance of the geometry of the drift-pin as a tolerance-handling method.

Conclusion

This research successfully demonstrates a new method to design, analyse and construct complex geometry shell structures which satisfy a confluence of architectural concerns, without the need for extensive falsework, formwork or templating. Through computation, digital fabrication and the adoption of ancient detailing strategies, this method points to a possible application in synchronous feedback with the constraints of assembly. While the potentials of such a method accommodate an endless number of possible geometries, the analysis points to a series of constraints. These constraints exist primarily in the structural and material properties of stone and metal, the geometric constraints of fabrication and the problems of compounding errors during assembly.

Future research seeks to further evaluate the capabilities of assembly simulation and sequential fixing in the construction of a full-scale marble caldarium.

Acknowledgments

This research was conducted as part of the 2016 QuarraMatter Fellowship, an industry-academia partnership between Quarra Stone (www.quarrastone.com) and Marcal Stone Design (www.marcalstonedesign.com). Each summer two fellows are embedded at Quarra Stone to produce a research project in advanced fabrication techniques. The fellowship is supported by Quarra Stone as a means to foster the development of advanced computational techniques. A thanks to the Quarring family (www.quarringfam.com) for their open access, financial support and belief in this research. Special thanks to Ed Piker for his technical assistance, to Thomas Flaherty for the design of the Lounge Vault and to the students of MIT’s Architecture Association for their assistance with building the Lounge Vault. This research was supported, in part, by an Industry/University Graduate Fellowship from the National Science Foundation’s Division of Undergraduate Education.

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References


This paper describes research that addresses the variable behaviour of industrial quality metals and the extension of computational techniques into the fabrication process. It describes the context of robotic incremental sheet metal forming, a freeform method for imparting 3D form onto a 2D thin metal sheet. The paper focuses on the issue of geometric inaccuracies associated with material springback that are experienced in the making of a research demonstrator. It asks how to fabricate in conditions of material inconsistency, and how might adaptive models negotiate between the design model and the fabrication process? Here, two adaptive methods are presented that aim to increase forming accuracy with only a minimum increase in fabrication time, and that maintain ongoing input from the results of the fabrication process. The first method is an online sensor-based strategy and the second method is an offline predictive strategy based on machine learning.

Rigidisation of thin metal skins

Thin panelised metallic skins play an important role in contemporary architecture, often as a non-structural cladding system. Strategically increasing the structural capacity – particularly the rigidity – of thin cladding layers offers a way to integrate enclosure, articulation and structure, but requires a consideration of scale and fabrication that lies outside a typical architectural workflow. Thin sheets can be stiffened via isotropic or anisotropic rigidisation techniques that selectively move local areas of the sheet out of plane, with the effect of increasing structural depth. The use of these techniques marked the early development of metallic aircraft, were pioneered by Junkers and LeRicolais within architecture and are currently applied within the automotive industry. This research takes inspiration from Junker’s proposition, made through the transfer of these techniques into building, of thin-skinned metallic architectures. A Bridge Too Far (Fig. 2) presents as an asymmetric bridge. The structure consists of 51 unique planar, hexagonal panels, arranged into an inner and outer skin. The thickness of each panel varies locally, though it is at maximum 1mm thick. Excluding buttresses, the bridge spans 3m and weighs 40kg. Geometric features for resisting local footfall, buckling within each panel and structural...
incremental sheet forming (ISF) method imparts 3D form onto a 2D sheet, directly informed by a 3D CAD model. A simple tool, applied from either one or two sides, facilitates mouldless forming by moving over the surface of a sheet to cause localised plastic deformation (Bramley et al., 2005). A double sided robotic approach provides further flexibility for forming out of plane in opposing directions (Fig. 3). Moving from SPIF (single point incremental forming) to DPIF (double point incremental forming) removes the need for any supporting jig. This allows for more freedom and complexity in the formed geometry, making features that it would be difficult or impossible to create supports for. A second advantage is the creation of a hydrostatic pressure between the two tools, which has been found to delay the initiation of necking for any strain path. The incremental sheet forming (ISF) method imparts 3D form onto a 2D sheet, directly informed by a 3D CAD model. A simple tool, applied from either one or two sides, facilitates mouldless forming by moving over the surface of a sheet to cause localised plastic deformation (Bramley et al., 2005). A double sided robotic approach provides further flexibility for forming out of plane in opposing directions (Fig. 3). Moving from SPIF (single point incremental forming) to DPIF (double point incremental forming) removes the need for any supporting jig. This allows for more freedom and complexity in the formed geometry, making features that it would be difficult or impossible to create supports for. A second advantage is the creation of a hydrostatic pressure between the two tools, which has been found to delay the initiation of necking for any strain path.

Robotic incremental sheet forming

The isostatic forming of individual panels.

Incremental forming is a formative fabrication process, in which mechanical forces are applied to a material so as to transform it into a desired shape. A characteristic of formative fabrication processes, particularly mouldless, freeform approaches, is that their positional accuracy is highly dependent upon a combination of material

connections – for managing shear forces across inner and outer skins - are produced through the custom robotic forming of individual panels.

Robotic incremental sheet forming

The incremental sheet forming (ISF) method imparts 3D form onto a 2D sheet, directly informed by a 3D CAD model. A simple tool, applied from either one or two sides, facilitates mouldless forming by moving over the surface of a sheet to cause localised plastic deformation (Bramley et al., 2005). A double sided robotic approach provides further flexibility for forming out of plane in opposing directions (Fig. 3). Moving from SPIF (single point incremental forming) to DPIF (double point incremental forming) removes the need for any supporting jig. This allows for more freedom and complexity in the formed geometry, making features that it would be difficult or impossible to create supports for. A second advantage is the creation of a hydrostatic pressure between the two tools, which has been found to delay the initiation of necking for any strain path.
there are several approaches to improving geometric accuracy, the most direct of which is reworking. This approach simply re-runs the whole, or significant parts, of the original toolpath. It has been shown to achieve considerable improvement, but can potentially double the amount of fabrication time. A second approach is to use a sensor-based measurement strategy, where the deviations are detected and accounted for on the formed shape. After forming, new adjustment lengths for the next forming cycle can be calculated from accurate measurement of the formed shape. This workflow can again lead to considerably longer fabrication times and also requires sophisticated measurement path planning. A third approach is to use machine code generation that allows the robot to register changing forces on the tool tip during the fabrication process. A live stream of read-outs (approximately one per 50ms, or every 2cm along the toolpath) was established and the data was stored directly in a binary file. This data was used to identify the right amount and type of data for the training of a neural network to improve the overall form. Visualising this information revealed relationships between the fabricated shape and forces acting on the sheet, and showed the following parameters to be significant:

- **Local feature**
- **Distance to fixed panel edge**
- **Current depth of the shape**

A ‘local feature’ is understood to be a small fragment of the shape being currently formed. It informs the model about edges, ridges and other small scale geometry of the panel.

Distance to the edge of the panel is the parameter describing the distance to the closest point on the edge of the formed geometry. It is a result of the physical setup and how the panel was placed in the forming frame (pinned to the underlying MDF board with a panel-specific cut-out). Current depth of the shape is the distance from the initial sheet plane to the current position of the tool tip. It is directly dependent on the material properties and their change over deformation depth. Other parameters – such as the slope angle – are not provided directly to the model. Instead, the local feature is understood as an indirect provider of such information.

**Network architecture and learning process**

The information gained from the force gauge read-outs was overlaid with a 3D scan of the fabricated panel. This coupling of input and output parameters (local feature, distance to the edge, depth vs. formed shape) constitutes the input and output set for the supervised learning process. Given that the output of the network is the depth of the analysed point after forming, the problem is substantially a regression analysis.

The local feature and current depth are encoded as a heightmap, with a real-world size of 5 x 5cm, resolution of 1 pixel per millimetre, without pre-processing the input vector would have to have 2,500 dimensions, making the training process unnecessarily detailed and slow. To reduce its dimensionality, a max pooling technique was applied, resulting in a 5 x 5 x 3 pixel – 81-dimensional heightmap.

The network consists of an input layer with 81 neurons (81 + 1 additional for edge-proximity parameter), a hidden layer with 30 neurons and an output layer with 1 neuron indicating the depth of the resulting point. Back-propagation-based learning was performed on a set of 16,000 samples and took approximately an hour on a regular desktop computer.

**Results**

The network is able to predict, to some extent and resolution, the resulting geometry based on an input heightmap of the target piece. The authors find the network unexpectedly accurate, given that the training was based only on data gathered from a small number of panels. Additionally, the exploration of the network predictions gave more information on the trained model itself, showing that material behaviour isn’t strictly linear – therefore it would be reasonably more challenging to find appropriate functions and ways to encode shape information with a curve-fitting approach (although the neural network is function-fitting as well).

With this neural network-based model, it is possible to predict both form quality and accuracy. Using only multiple queries the resulting panel surface can resemble the target much more precisely.
The training set is a set of randomly distributed fragments on the surface of the panel. The training set output is a heightmap based on a 3D scan of the formed panel (the ground truth), and is used as the training set output.

As the training process might end up with function overfitting, a comparison is made on another panel to assure the network’s versatility.

The values obtained from prediction were used to adjust the fabrication geometry. The method for adjusting the geometry is straightforward: the input mesh heightmap values are increased by the difference between the target and prediction heightmaps. While this method yields a substantial increase in precision, more advanced methods will be a subject of future research.

Conclusion

This paper has addressed the issue of material springback and geometric inaccuracy in the incremental forming process. It has demonstrated the use of sensing and feedback to manage springback and to reduce geometric inaccuracies within the forming process. Two different methods have been presented, the first based on online adaptation and the second based on offline prediction. Both models negotiate between the design model and the fabrication process. The first method changes the design parametrically during the fabrication process, diverging from the desired design, while the second method changes the fabrication geometry prior to fabrication to achieve the desired design. These models are necessary because, for the incremental forming process, the information contained within the design model is not itself enough to achieve accurate forming. On this basis, the authors believe that machine learning processes can be adjusted to achieve the desired part accuracy and prediction heightmaps. While this method yields a substantial increase in precision, more advanced methods will be a subject of future research.

Acknowledgements

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Classical music and performances have long been considered an exclusive pastime. In the past decade, classical performances have faced a declining number of concert-goers, whose median age is simultaneously on the rise. Despite this negative trend, new concert halls and opera houses are being built around the world by some of the most prestigious architectural offices, resulting in some of the most exciting contemporary architectural projects. This is evidenced by the fact that, for example, three of the last four Mies van der Rohe Award winners were concert or opera hall projects: the Norwegian National Opera & Ballet by Snøhetta in 2009, the Reykjavik Concert Hall by Henning Larsen Architects with Batteriid and Elasson in 2013 and most recently the Philharmonic Hall in Szczecin by Barozzi/Veiga in 2015. One may argue that this current interest in new concert hall projects does not contradict the aforementioned attendance crisis, but may instead be interpreted as an effort to rectify it.

In this effort to revive interest in classical concerts, contemporary architects play a vital role. They can help to renew interest by making concert hall buildings more open and accessible to wider, younger audiences as well as augmenting the concert experience as a whole. At the centre of the experience, however, is the performance itself, which may be enhanced on an aural, visual or even tactile level. It is therefore not surprising that in current concert hall projects there is a concerted effort to achieve excellent acoustics, which are in harmony with the architectural language of the building as a whole. New design and fabrication methodologies open up new possibilities, which are a result in part of design software developments over the past decade, an improved understanding of concert hall acoustics towards the end of the last century and a surge in and access to digital fabrication technologies. In order to make these enhancements, it is critical that a close collaboration between the architect, the acoustician and the fabricator exists.

This paper aims to document one such close collaboration: the development and execution of non-standard sound-diffusing acoustic panels in the large concert hall of the Elbphilharmonie in Hamburg.
Sound diffusion

Designed by Herzog and de Meuron, the Elbphilharmonie is located in the HafenCity area of Hamburg, Germany. It comprises approximately 120,000m² of space, including three concert halls, a hotel, apartments, restaurants, a parking garage and a public observation platform. The large concert hall lies at the heart of the project, seating 2,150 people. Yasuhisa Toyota, of Nagata Acoustics, was responsible for acoustical engineering. He collaborated with the architects from the early stages of design through to completion. They approached the project from two perspectives: first, in terms of the overall shape of the design - by optimising the orientation of the sound-reflective surfaces - and second, by developing the sound-diffusing surface geometry applied to the individual acoustic panels.

In broad terms, sound diffusion is the even scattering of sound energy in a room. Non-diffusive, reflective surfaces in concert halls can lead to a number of unwanted acoustic properties, which can be rectified, in part, by adding diffusers. A perfectly diffusive space is one where acoustic properties, such as reverberation, are the same, regardless of the location of the listener. Diffusion in some of the best concert halls in the world, such as the Great Hall of the Musikverein, built in 1870 in Vienna, is now understood to be a byproduct of the uneven surfaces of the rich neoclassical ornamentation of its interior. The antipathy to elaborate ornamentation by twentieth-century architects may have come at the expense of good concert hall acoustics. In the past, bad acoustics could be treated at a later stage, by selectively retrofitting absorbers or diffusers, which resulted in a disjunction between the original architectural intent and its modifications.

Commercial diffusers began to appear towards the end of the twentieth century, as engineers studied the science and physics of sound diffusion. This process was started with the seminal work of Manfred R. Schroeder in the 1970s, which led to the development of his ‘Schroeder diffusers’. It has been noted that Schroeder’s utilitarian approach to diffuser design corresponded well with the architectural styles of his time and were successfully applied to concert hall designs. However, contemporary engineers recognize that the shape of such diffusers is not necessarily in line with contemporary architectural designs. Cox [304], for example, laments: "When Schroeder invented his diffusers, they fitted in with some of the artistic trends of the day. With abstraction at the fore, the fins and wells formed elements in keeping with the style..."
of the day. But in the intervening decades, tastes have moved on. Architecture has been greatly influenced by advances in engineering to allow previously unimaginable shapes to be constructed. Landmark buildings are becoming sculpted with complex geometries and curved forms. To many, Schroeder seemed work with any shaped building. Diffusers no longer match the style required. Fortunately it is possible to design arbitrarily defined, uniquely shaped NURBS cells. A paper by one of the authors of this paper presented at the Design Modelling Symposium in Berlin in 2009 outlined this development in detail. The pattern itself was initially based on the distortion of a two-dimensional, orthogonal grid of Voronoi seeds. The program allowed for random seed displacements, deletion and insertion in order to control both the degree of randomness and the scale, i.e. the cell width of the pattern. In a subsequent step, each closed 2D polygon of the Voronoi pattern was used as input in the 3D formation of a parametrically defined NURBS cell (Fig. 2), which exhibited a peak and trough shape, a motif characteristic to the project as a whole and found in areas such as the roof of the building or the overall shape of the concert hall. The placement of the control points was driven by a total of six parameters, which allowed for the precise definition of depth of each cell and also its overall shape, which included a range of harder and softer edges. All the parameters were driven using grayscale bitmap images, which mapped XY coordinates from the bitmap space to each of the concert hall’s wall and ceiling surfaces’ UV coordinates. In a last step, every control point of every NURBS cell was mapped topologically onto a 2D plane, generating diffusing pattern was assigned to each panel. As each panel was unique, further software programmes had to be developed to automate the 3D planning and digital production of approximately 10,000 CNC-milled gypsum fibreboard panels, as well as to optimise the acoustic surface’s substructure. For acoustical reasons, the weight per unit area of the panels, up to 150kg/m², was fairly large, and had to be achieved by giving the panel thickness a range of between 30 and 120mm. Therefore the highest available density fibreboard panel, with a volumetric density of 1,002kg/m³, was chosen. Since the material is only produced up to 40mm thickness, most of the panels had to be built up in several layers, glued and mechanically fixed together, in order to achieve the desired weight. The architects defined a precise and intricate network of gap lines, which, unlike the sound-diffusing pattern itself, was meant to be seamless across the hall’s surfaces. Therefore the edges of the panels were made to always align with the edges of the neighbouring panels, resulting in planar, curved and twisted edges, including ridges in some cases. Because of the varying degrees of complexity in edge conditions, a 5-axis milling machine was used to manufacture the panels (Fig. 3). The curvature of the front surface was achieved by keeping the back of each panel planar, while the front was milled to shape. For each panel, the edges had to be digitally generated, the fixings had to be placed and a groove along the entire perimeter, for the placement of a sealing band, had to be milled out of the front panel, below the lowest point of the sound-diffusing pattern. In addition, mechanical fixings were placed to secure the glued layers and, most importantly, the previously generated diffusing pattern was assigned to each panel. After this, the panels were ready for manufacturing. Each raw panel was prepared to size. The panels were CNC-milled in two stages. First, each panel was milled from the back, which included the 5-axis forming of...
started in the mid-2000s, when 5-axis milling machines, point out that development of the panels for this project acoustical specifications both necessitated highly precise acoustical standpoint. The seamless design and the project can be evaluated from both a fabrication and Apart from the architectural achievement, the final Trialling new technology at the required precision. them to be fitted with a 5mm gap between panels, and adjustments with three degrees of freedom, allowing them to be fitted with a 5mm gap between panels, and the required precision. Tailoring new technology Apart from the architectural achievement, the final project can be evaluated from both a fabrication and acoustical standpoint. The seamless design and the acoustical specifications both necessitated highly precise acoustical design and digital fabrication methods. While 3-axis and 5-axis CNC-milling techniques have become the norm in architecture today, one needs to point out that development of the panels for this project started in the mid-2000s, when 5-axis milling machines, for example, were not readily available. The workshops involved in this project had to invest in new machinery and train their staff in order to deal with this new technology, which necessitated a close collaboration between all the parties involved. In addition, no one had previously attempted to mill very dense gypsum fibreboard panels in such a way and in such large quantities. In order to exactly and precisely produce large quantities of panels without warping out the machines and tools, several rounds of meticulous tests and trials were conducted, with several mocks ups built. Once parameters had been determined, panels were produced efficiently and to an incredibly high degree of precision, which was necessary in order to assemble the final panels at the desired tolerances. In the end, all the panels fitted together perfectly, keeping the number of faulty panels at a minimum despite each one being non-standard and assembled in a complex manner. Only 20 out of a total of about 10,000 panels had to be replaced due to dulled tools – an error rate of only 0.2%. This extremely small error rate is an achievement in itself given the scale and complexity of this project.

As for the acoustic evaluation, at the time of publication this paper final measurements have not yet been published. Tests are generally conducted on concert halls before the opening concert, which took place on 11 January 2017.

Pioneering collaboration

The development and execution of the non-standard sound-diffusing panels in the large concert hall of the Elbphilharmonie is a noteworthy collaborative effort between architectural design, acoustic engineering and digital fabrication, which resulted in the intentional application of a sound-diffusing surface treatment in harmony with a contemporary, complex architectural design. Software and manufacturing methodologies, as well as related technologies, have advanced greatly since this project began 10 years ago. Implementations in software and computing power for precise acoustic simulations, as well as readily available access to new fabrication technologies, such as 3D printers and robots, alongside the computational methods outlined in this paper, offer great potential for similar projects in the future. Fromm (2014), for example, investigated the potential use of 3D printed cement-bound elements as an alternative, comparing and contrasting them specifically with the CNC-milled gypsum fibreboard panels of the Elbphilharmonie. That points to one of many exciting new possibilities for the design and application of sound diffusers in future concert hall projects.

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QUALIFYING FRP COMPOSITES FOR HIGH-RISE BUILDING FACADES

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Using fibre-reinforced polymer on the SFMoMA addition

Fibre-reinforced polymer (FRP), in this case glass fibre-reinforced polyester resin composite with a polymer concrete face coat, was used in the US for the first time as exterior cladding on a Type I multi-storey building on the San Francisco Museum of Modern Art (SFMoMA) addition. This 11-storey addition, completed in May 2016, makes SFMoMA the largest museum of modern art in the US, with the largest architectural FRP facade application in the US to date.

FRP was chosen to mimic the rippling water of the nearby San Francisco Bay on the east and west elevations. Although recognised by the IBC (International Building Code) in 2009 as an accepted building material (International Code Council, 2009), any FRP material used must pass the same code requirements as other combustible materials. The most difficult of these requirements is the NFPA 285 test. Until this and other requirements are met, no combustible material, including FRP, is allowed.

The design for the SFMoMA project called for over 700 unique, individual, constantly curving panels (Fig. 1).

Although it is possible to construct such panels with metal, the only practical option was to mould the 720 unique panels, thus suggesting precast concrete or the lighter UHPC or GFRC. The less familiar FRP was listed as an alternative by the facade consultant in part because of its more widespread use in European construction.

Although used sparingly on US buildings for decades, FRP has dominated other industries such as corrosion-resistant ducting and chemical storage tanks, wind energy, marine and heavy truck components. However, it has seen no extensive use on Type I buildings. This has been partly because of codes and partly because its primary advantages over other materials are its high strength-to-weight ratio and its ability to be formed into complex shapes. Neither of these characteristics has been very important in construction until recently.
After successfully passing a rigorous evaluation process, FRP was chosen because it offered solutions to several problems presented by the use of other systems. Its primary advantages were its light weight and formability, the very features exploited by other industries in the past and now increasingly relevant in contemporary design and construction.

New materials, models and methods

Aside from curiosity about something new, several factors are pushing building designers towards sometimes radical departures from traditional means and methods. This shaking up of the status quo, in an otherwise rigid industry, is leading to the startlingly rapid deployment of fundamentally new building systems, including to a large degree the building envelope itself. Environmental concern for building materials as well as building operations, health and safety issues relating to building construction and occupancy, rapidly changing regulations and code modifications are driving these new approaches.

Additionally, service life requirements, time to deliver and an evolving design ethic brought about by new means, models and materials are pushing building designers towards sometimes radical departures from traditional means and methods.

Prototype fabrication

The architectural façade design was modelled originally by the architect in Rhino 3D (McNeel Associates) using a Grasshopper script to alter the wavelength, amplitude and frequency of the façade ‘ripples’ over the curved and tilting east and west elevations of the building. Rhino models can be reliably imported into software used to guide CNC cutting tools (in this case PowerMILL by Delcam) which can be used to cut the shape of the part or its mirror image out of a block of material, thus creating a female mould directly from the architect’s model (Fig. 2).

Once made, this rapidly and inexpensively created mould can serve to fabricate a full-scale model of any portion of the façade.

Recent changes in building codes and design are opening the door to more widespread use of composites in architectural and even structural applications. The American Concrete Institute has adapted a design standard for the use of FRP in concrete structures (American Concrete Institute, 2008, p.40.2R-05), including a design standard for FRP composite slab in structural concrete (ACI Committee 430, 2015). ASHTO has published a standard for pedestrian bridge designs using composite structures (American Association of State Highway and Transportation Officials, 2008). DOT initiatives throughout the US and other countries have had experimental bridges and other structures in place for decades and are beginning to publish results indicating successes (American Association of State Highway and Transportation Officials, 2009).

Research questions

- What are the engineering and building code obstacles to overcome to use FRP as an exterior cladding on Type 1 multi-storey buildings in the US?
- How can these obstacles be overcome within the schedule and budget constraints of a project?
- What advantages would an FRP rain screen provide compared to more traditional material alternatives?

The use of FRP cladding on the SFMoMA provides a case study for the use of FRP as cladding on any multi-storey commercial building. Initial prototypes, cost estimation, design assist procedures, code compliance strategies and engineering and installation methods were developed to meet the design intent, budget, project schedule, code requirements and environmental constraints.

Cost estimation

Although no two of the 710 façade panels were the same shape, the use of 3D composite modelling and CNC mould fabrication made cost estimating reliable. Rhino provided an accurate surface area and such key characteristics as panel centre of gravity. Knowing the materials required on a per square foot basis allowed for accurate material cost predictions. PowerMILL includes algorithms that predict milling time for each mould.

Thus, despite the highly complex and variable shapes, accurate cost estimation and scheduling was possible for the testing phase. Through the use of digital fabrication tools and conventional material, labour and manufacturing overhead allocation methods, a reliable cost could be predicted.
design team and specialty contractors. Although the traditional design, but build method is still dominant, it frequently leads to wasted time on the part of design professionals who attempt to produce a plausible ‘construction document’ based on insufficient knowledge of materials or fabrication methods.

Expensive hours are spent attempting to develop a solution that does not optimise current technology, which is frequently lead to inaccurate and faulty conclusions. At best, he or she might propose a ‘construction document’ based on insufficient knowledge of materials or fabrication methods.

Code compliance

Since 2005, the International Building Code (IBC) has recognised FRP as fibre-reinforced plastics and fibre-glass-reinforced polymers in Section 2612. This section of Chapter 26 recognises FRP as a combustible material, allowing its use when the product can demonstrate the ability to meet the code requirements applied to similar architectural products.

Fabrication phase

As we have mentioned, one of the unique characteristics of FRP is it’s very high strength-to-weight ratio. This feature led to panels whose weight was approximately three pounds per square foot (13.5kg/m²), making them light enough to be affixed to the front of the aluminium unised panels used to form the waterproof barrier of the building (Fig. 5). This was convenient for several reasons. It eliminated the need for any penetrations of the waterproofing. It allowed the FRP to be fastened to the panels itself, which avoided the use of a custom FRP rain screen was installed simultaneously with the unised wall. This simultaneous installation eliminated the need for a backup support system and reduced the construction time by replacing an original design requirement that required sealing and also pass, among other tests, the NFPA 285 test.

For the SFMoMA addition, this was a major hurdle which had to be cleared before FRP could be seriously considered for the façade material. The specific formulation for the test panel is confidential and is in fact now patented by the panel fabricator. The STanford University graduate students in a non-peer-reviewed LCA comparison (Stanford University, 2005) also found that FRP had significantly less impact on the environment compared to the alternative system using GFRP or HDPE.

Another unique characteristic of FRP is that the shape and configuration can be economically customised. Conventional unised panel systems are most economical and reliable when creating flat walls. The SFMoMA façade was anything but flat. Resolving the problem created by these two seemingly incompatible features presented a unique challenge. How do you make a flat back on an ever-varying front surface? Not only was the front wavy but it also tilted forward and back as it rose higher and curved in plan through a wide variety of irregular radii. The solution lay in the use of digital tools to create asymmetrical return edges which were different limits, a custom unitised panel was fabricated to ‘twist’ the flat wall into a new facet.

The SFMoMA façade was anything but flat. Resolving the problem created by these two seemingly incompatible features presented a unique challenge. How do you make a flat back on an ever-varying front surface? Not only was the front wavy but it also tilted forward and back as it rose higher and curved in plan through a wide variety of irregular radii. The solution lay in the use of digital tools to create asymmetrical return edges which were different limits, a custom unitised panel was fabricated to ‘twist’ the flat wall into a new facet.

As the façade diverged from a conventional flat wall, the edges of the panels were moulded with edges that varied between 4 and 34in. This allowed for considerable design flexibility before running up to one of these edge dimension limits. The curve diverged beyond these limits, a custom unised panel was fabricated to ‘twist’ the flat wall into a new facet.

Again assisted by digital tools and relying on skilful craftsmanship and valuable collaboration between the FRP façade fabricator and the aluminium unised wall manufacturer, calculation of the balance between the additional cost of these special fabricated unised panels and the cost of fabricating asymmetrical FRP panels determined the use of 4 to 34in edge tolerance. The contractor was able to minimise cost while retaining the original architect’s design within a tolerance of less than 1/2in throughout the entire 11-storey elevation.
Provided the fabricator can meet the requirements of the Section 2612 of the International Building Code in 2009. The future of FRP such as LCA (lifecycle assessment) studies. to conventional materials in environmental assessments of their high material efficiency, often compare favourably products. In addition, FRP products, in large part because engineers in designing structures as well as architectural composite materials; these tests have been in existence criteria for architectural products. Standard test methods The data show that FRP can meet the IBC acceptance 78 to use industry standard design principles. As with any building. Additional benefits were one pass around the improvement of the watertight integrity of the weighing over 1,000,000lbs (450,000kg), as well as would have no negative impact on the project’s schedule. engineering would more than offset testing costs and demonstrate that successful completion of testing and more subjective, but the SFMoMA project was able to these test are valid for three years and can be used for first to verify code compliance. Passing all requisite tests schedule and budget constraints depends on many the process of qualifying FRP while maintaining the schedule and budget constraints depends on many variables. The project discussed here, fire testing came first to verify code compliance. Passing all requisite tests took approximately five months; however, once passed, these tests are valid for three years and can be used for other sufficiently similar projects. Budget constraints are more subjective, but the SFMoMA project was able to demonstrate that successful completion of testing and engineering would more than offset testing costs and would have no negative impact on the project’s schedule.

Advantages to using FRP included eliminating two subcontractors and an extensive steel support frame weighing over 1,000,000lbs (450,000kg), as well as the improvement of the watertight integrity of the building. Additional benefits were one pass around the building instead of three, which would have been required with the other system, and ten fewer moves of lifting equipment such as the tower crane. While offering many advantages, care must be taken to use industry standard design principles. As with any new material, the specifier of composite materials will be greeted with a wide variety of options and prices. Since quality is a function of fabrication, not unlike concrete, it is incumbent on the designer to exercise caution in selecting a fabricator. Conflicting information needs to be reconciled and verified. Engineers must recognize that this is a highly specialised discipline. Being an anisotropic material, there are virtually limitless options in terms of fibre orientation, fibre volume, number of layers, type of resin, resin fillers options, sandwich and single skin construction techniques and cure options. Engineers have control over a dizzying array of material properties, including even thermal expansion and contraction (CTE), which will vary from carbon fibre and its negative CTE to some resins with higher CTE than aluminium.

Use of FRP on the SFMoMA and other façade projects in Europe and Asia demonstrates that properly executed works can result in successful outcomes. However, there are ample examples of less successful outcomes. Although FRP has been proven for decades in applications at least as demanding as building façades and often in those that are much more demanding, making decisions based solely on colour and aesthetic is certainly not a sound way to judge product performance. To avoid this, appropriate formulation and proper quality control, although important, cannot replace the structural properties to compete favourably with alternatives, but can also meet fire and other code requirements. Similar to concrete, the mechanical and other critical properties are largely determined during the fabrication process. Stringent quality assurance is essential and close collaboration with a reliable and properly certified fabricator is critical. The IBC code requires that any FRP part delivered to a jobsite must have affixed to it a correctly registered independent test agency label certifying that it is manufactured in compliance with the code and subject to third-party inspection. Such a label is the first line of defence in the proper selection of FRP products for buildings. Future study will need to explore structural opportunities for composites in construction. Engineering examples and ideally an LRFD model for FRP tailored to the construction industry should be developed. Durability case studies need to be assembled from the wide variety of existing examples to improve documentation. Such studies should rely on properly documented empirical evidence and statistics, of which there are numerous examples (Pauer, 2018).

Therefore, service life estimation needs to be performed using a multi-factorial approach, which includes both the material properties and the environmental conditions. This can be achieved through the use of detailed computer simulations and experimental testing. Further research is needed to develop accurate models for predicting the performance of FRP in long-term applications. In conclusion, FRP offers numerous advantages over traditional materials, including higher strength, lower weight, and better resistance to corrosion. However, proper design and testing are essential to ensure safe and effective use of this innovative material. The future of FRP in construction is promising, and continued research and development will further expand its applicability.
Since 2000, the Serpentine Gallery in London has commissioned a yearly pavilion to be built and displayed during the summer months. A renowned international architect is chosen to design the installation, the only condition being that whoever is chosen has not completed a project in the UK at the time of invitation. These exciting commissions must therefore balance the opportunities for experimentation that a temporary structure affords against an extremely short timeframe: every pavilion must go from initial concept to completion onsite in less than six months.

The 2016 Serpentine Pavilion, designed by BIG (Bjarke Ingels Group) and engineered by AKT II, presents a compelling case study in the use of parametric modelling and advanced structural analysis tools in undertaking such time-constrained projects.

Concept and form
The pavilion centres on a (deceptively) simple concept: two 30m-long sinusoidal walls – one concave and one convex – undulate towards one another, before merging into a single interlocked form at their apex (Fig. 1). Each 14m high wall is comprised of open-ended boxes and set in an inverse checkerboard pattern to its neighbour, enabling the upper reaches of both walls to overlap and interlock into one continuous cellular grid. Back at ground level, the stepping and staggering of these 40cm tall boxes creates a “pixelated” external landscape open to climbing and sitting, while inside BIG has taken the opportunity to sculpt a series of differently scaled spaces intended for seating, a bar and live performances.

This formal ambiguity is reinforced by the use of open-ended boxes: when viewed longitudinally, they appear solid and substantial; however, as a visitor passes through and around, they turn face-on and seem to dematerialise down to mere grids of lines and moiré interference, enabling views through and out of the pavilion to the park landscape beyond (Fig. 3).

Parametric workflow
To realise such a large and structurally complex pavilion, it was necessary to go from concept design to fully
coordination of production information in less than three months. In addition to these time pressures, budgetary constraints necessitated that material topologies and quantities be optimised as far as possible without compromising the ambition of the design.

For these reasons, the BIG and AKT II design teams chose to generate the entire geometry through parametric design processes. This enabled the rapid evaluation of different options for the underlying grid early on, testing the relative merits of rectangular and square grids at different scales, as well as more complex pin-wheel and reciprocal arrangements and square grids at different scales. The resulting forms can be optimised as far as possible without compromising the ambition of the design.

Material development

From the earliest stages of the project, BIG emphasised that they wanted to experiment with glass fibre-reinforced plastic (GFRP) manufactured using the ‘pushtrusion’ process. GFRP is a composite material formed of glass fibres impregnated with the resin matrix that typically has a strength comparable to that of steel, but with only around a quarter of the weight. This high specific strength has made GFRP an attractive material in instances in which weight is critical, such as aerospace and automotive applications, but the labour-intensive manufacturing process of manually placing glass fibres into custom-made moulds has historically made GFRP only attractive in niche areas of structural and civil engineering. Manufacturing GFRP using automated processes has been of increasing interest recently as a route to unlocking the benefits of using it at a lower cost. Pultrusion is one of these processes, involving the use of a mould through which the glass fibres are pulled and impregnated with the resin. The resulting material can be produced on a large scale, with a high degree of consistency and at a low cost.

To support our explorations with this material, BIG invited Fibeline Composites A/S to join the project. Fibeline are one of the leading suppliers of pultruded GFRP, and have developed several GFRP products with beneficial structural properties as well as unique colours and transparency levels. Initial discussions with Fibeline focused on the possibility of forming the entire pavilion from a single type of GFRP element – a bespoke extrusion designed specifically for this project that would incorporate both the open box form and corner connections. However, for speed and economy reasons, the design team instead chose a kit-of-parts solution, where each box is assembled from four GFRP plates, with GFRP angles glued in each corner to increase lateral stability and vertical load-bearing capacity. By utilising this system, the project benefited from the very fast production line Fibeline already has in place for manufacturing sheet materials, and a high-dimensional tolerance in the resulting boxes could be assured.

In parallel with this development on the GFRP boxes, the design team considered a number of different options for connecting them. They ran tests on GFRP, carbon fibre and steel connectors before settling on a 10mm-thick cruciform-shaped aluminium that provided the necessary weight to strength ratio.

With over 95% of the pavilion made from only these two simple elements, the expression and detailing of the design were critical. The design team worked through several different options before finally selecting one suggested by StageOne: a bespoke flat headed bolt and sleeve that could be held in place asymmetrically on each box’s inside face during tightening, consequently enabling a smaller offset from the neighbouring GFRP angle face. By minimising this offset, the design team could specify shorter ‘arms’ for all of the connector cross-sections across the pavilion.
entire structure, resulting in faster production times, significant cost savings and reduced weight of box clusters. Advantages of cumulative effects like these were sought at every stage of the design process.

Structure design and physical calibration

Throughout the discussions with Fiberline, the previously established parametric models were used to test and provide feedback on different configurations. With Re.AKT in place, each option could be analyzed simultaneously at multiple scales – both globally and locally (Fig. 5). High resolution non-linear finite element analysis (FEA) mesh models of single boxes were generated at first, and later small clusters containing up to a dozen boxes – these were then used to calibrate global 2D and 3D frame models. This process enabled generation of schedules for all three elements, assigning unique bolthole positions (Fig. 2), with the Re.AKT workflow already in place it was straightforward to automate the production of schedules for all three elements, assigning unique codes to aid in fabrication, transportation and assembly sequencing (Fig. 6).

The existing design guidance relating to GRFP is not widely recognized in its application to primary load-bearing structures, outside of highly specific and specialized applications. To resolve this, a series of physical material tests were undertaken by Fiberline in order to provide further calibration and confirmation of the digital models. With the global models calibrated, it was clear that three thicknesses of box could be utilized: 10mm, 6mm and 3mm. This would provide the necessary stiffness where forces were concentrated, while minimizing overall weight and cost and maximizing the degree of translucency desired by BIG. Likewise, the varying forces present at the connection points could be transferred using either one, two or three pairs of bolts between adjacent boxes.

The final optimised design thus comprises 1,800 boxes of 16 different lengths, as well as 3,000 connectors of 126 different types in addition to more than 25,000 bolts (Fig. 4). Although almost every single box and connector is unique (54,000 connectors and 9,000 bolts positions (Fig. 2), with the Re.AKT workflow in place it was straightforward to automate the production of schedules for all three elements, assigning unique codes to aid in fabrication, transportation and assembly sequencing (Fig. 6).

At StageOne, the arriving boxes were grouped by wall, and assembled into modules across several rows at a time. These modules were necessary given the significant logistical challenges that the Serpentine site poses. The Central London location immediately rules out the use of any special order vehicles and significantly constrains the time window each day during which lorries can access the site. Furthermore, the site’s small footprint limits the volume of material that can be stored between deliveries. In response to these constraints and also the truncated programme of the project, the entire structure was prefabricated offsite at StageOne, and a ‘just-in-time’ delivery system brought small modules to the site on a daily basis. The size of these modules incorporated many factors: incoming material delivery dates, packing efficiency during transportation, reach and load capacity of the onsite mobile crane and stability of the pre-assembled modules during lifting. From this analysis, a 3 x 4 module was found to be optimal.

Even with this method established, the translation from atomized components into the final pavilion appeared to be a daunting hurdle. Setting out the 4-24 boltholes for each box and the 8-24 boltholes for each connector across the entire structure was a task inherently suited to computational working rather than human intuition. However, physically aligning and setting out these
components into the complex, non-repetitive form of the pavilion required significantly more dexterity and flexibility than digital fabrication could provide. This seeming paradox was overcome by fusing CNC and manual fabrication. The manageable size of each connector and more constrained bolt locations made them ideally suited to fabrication using CNC techniques. Once cut and drilled, these elements then became the template used to manually drill the more varied holes for each box. By using a single type of clip-on jig that aligned connectors against their neighbouring boxes, the setting out was simplified by an order of magnitude. This process had to be carried out in phases, as even StageOne’s facilities could only accommodate a few rows at a time. Once a set of rows was complete, they were all shipped to the Serpentine (except the uppermost row of boxes) the temporary bolting between modules was removed, and each one was made self-stabilising using ratchets and wooden props to support it during delivery to the site in London. The retained uppermost row of boxes was placed down on the ground to ‘reset’ the datum level – positions were checked and, using them as for setting out, the next set of rows began above. Construction

Onsite, the lowest row of boxes for each wall was set out individually and bolted into a raft slab foundation using around 300 post-fix bolts. These connections ensured a high degree of tolerance and created a definitive datum above which the first modules could be craned into place and rapidly bolted to their neighbours. The north and south walls rely on each other to provide stability in the form of an arching action in the final condition. While it would have been possible to design the structure for these ‘cantilever’ forces in the temporary condition, the increase in material thickness required was not economically or aesthetically desirable. Instead, once the pavilion reached a set height, a grid of Layher adjustable scaffolding was utilised to temporarily support specific boxes. This system enabled small adjustments to be made to the position of specific boxes and ensured a good fit where the two halves of the wall merged together. Once the structure passed above the merge zone, the pavilion was self-stable and the scaffolding could be removed. This allowed the wooden flooring to be laid inside at the same time that the final fully merged rows were added above. Just a few hours before the opening party, the last module was craned into position and the pavilion superstructure was complete (Fig. 7). Over this phase of the project, approximately 300 modules were delivered to the site and connected together in just 25-days.

A rewarding collaboration

A holistic design approach was vital in realising this challenging concept in the time available. The collaboration that emerged between different design disciplines was of itself very rewarding, and was strengthened further by the positive critical and public reception that the 2016 Serpentine Pavilion has received since opening. Just as significantly, it also seems that the pavilion will continue to advance conversations on material, form and structure in the future. Research is currently being undertaken on live monitoring of its GFRP elements, and the entire pavilion looks likely to tour multiple cities across the world over coming years.

Acknowledgements

We would like to acknowledge and thank the rest of the Serpentine 2016 design team for their unfailing enthusiasm, expertise and commitment throughout the project.


Designer: BIG (Bjarke Ingels, Thomas Christoffersen, Maria Lola Kraus, Rune Hansen, Max Mirvish, Claes Thomas, Kristian Kjeldberg, Mariakristin Als Clæst, Lornicher, Weehe, Tine & Kai Peter-Petersen).

Superstructure engineers: AKT II (Hanif Kara, Ricardo Baptista, James Kingman, Jon Dudley, Krystof Zabokrtsky, Edouard Tiburzi, Lorenzo Grice, and the team).

Foundation engineers: AECOM (Jon Leach, Amy Koerbel, Michael Orr, Jack Wilshaw, Francis Keirdy and Kate Leszczynska, Max Girn).

Material supplier: Fiberline Composites A/S (Stig Krogh Pedersen, Preben Vena Nielsen and Fritz Viviers).

Fabricator: Stage One Creative Services Ltd (Ted Fairbrother, Alan Doyly, James McIntosh, Mike Wade).

Technical advisor: David Glover.
Mario Carpo

Mario Carpo is a Professor of Architectural Theory and History at The Bartlett School of Architecture, University College London. His research is at the intersection of architectural theory, cultural history and the history of science. His work explores how the practice of architecture is shaped by the broader forces of culture, society and political economy.

After studying architecture and history in Italy, Dr. Carpo was an Assistant Professor at the University of Washington, Seattle, from 1992 to 1994. He is the author of The Digital Turn in Architecture (MIT Press, 2001) and numerous articles and essays and articles have been published in journals such as the Architectural Review, Domus, Azure, and Wired.

Carpo’s research and publications focus on the relationship between architectural theory, cultural history and the history of science. He is also the Chief Executive Officer of ArchDaily, the world’s largest online architecture platform.

Jenny Sabin

Jenny Sabin is an architectural designer whose work is at the forefront of new directions for the future of architectural practice – one that investigates the intersections of architecture and science and applies insights and theories from biology and mathematics into the fabrication of buildings.

Sabin holds degrees in architecture and interdisciplinary art from the University of Washington and a Master of Fine Arts from the University of Pennsylvania where she was awarded the Architectural League Prize for Emerging Talent in Architecture. She has been awarded a residency fellowship at the Art Institute in Toronto and was named a Young Talent Fellow in Architecture, one of 50 artists and designers recognized nationally by the Whitney Museum. She was recently awarded the prestigious Arch League Prize for Emerging Talent in Architecture and was named the 2019 inaugural NY Innovator in Design.

She has exhibited nationally and internationally, including in the acclaimed 45th Annual Triennial Exhibition at the Museum of Modern Art in New York. Her work has been extensively published, including in the New York Times, The Architectural Review, Azure, ArchDaily, Metropolis Magazine, and an American Journal of Phytology. She has also conducted research and written for the Whiting Fellows program at the Cooper Union.

Building Design Research: Architecture and Biology, co-authored with Peter Lynch, Jones, will be published in 2021.

Ronal Bael and Virginia San Fratello

Rael and San Fratello are Professors at the University of Arizona and Faculty at the Southern California Institute of Architecture. Bael was a Senior Designer at Caltrans in Sacramento where he was responsible for developing the Strategic Highway Research Program. San Fratello was the Director of the School of Architecture at the University of Arizona, where she was an associate professor as well as the founding director of Arizona State University's School of Architecture and Urban Design.

Bael and San Fratello are the authors of Designing the City: A New Public Agenda for Transport and the Environment, which explores how urban design and transportation planning can work together to create more sustainable cities.

Monica Ponc De Leon

Monica Ponc De Leon is an architect and educator who has been awarded several prestigious awards for her work in promoting sustainable and innovative architectural design. She is the Dean of the College of Architecture at the University of Michigan, where she leads a team of architects and designers who are working to bring new ideas to the field of architecture.

Ponc De Leon is a frequent speaker at conferences and events, and she has written extensively on the role of architecture in shaping the future of cities.

Carl Bass

Carl Bass is a member of the AutoCAD board of directors and is presently serving as an advisor to the company. During his 25-year tenure at Autodesk, he has held a series of executive positions, including President and Chief Executive Officer, Chief Technology Officer and Chief Operations Officer.

Bass is currently the CEO of McWane, Inc., a company that is acquired by Autodesk in 2013. Bass also serves on the boards of directors of HP Inc., Autodesk, Inc. and Ventana, a company that is acquired by Autodesk in 2014.

Antoine Picon

Antoine Picon is an Associate Professor at the Harvard Graduate School of Design where he teaches on the intersections of architecture and digital technologies. His research focuses on how digital tools can be used to explore the potential of architecture as a means of understanding and shaping the world.
MARIO CARPO
Where is your work heading right now? What are the key ideas?

JENNY SABIN
As you know, one of the driving questions and obsessions in my work is fuelled by the diminishing gap between design intent and that which is materialised – what is modelled, rendered, etc. through scripts and algorithms – and how that meets the material world via issues of fabrication and material constraints. I am really interested in that operating as a loop, both in the way I think through a design process and in the way it impacts on the tools that I produce and the projects that I generate. And at the core of that loop – which has driven an ongoing interest in, say, textiles and weaving and the origins of digital space – is, very importantly, the presence of the human and often the human hand (at least within the analogic prototyping stages).

Right now, my work is really about interventions within that loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms. The latest paper to come out of my lab is RoBo-sense: Context-dependent loop generating feedback mechanisms.

A second project I just opened recently, which continued an ongoing collaboration with Dr. Peter Lloyd Jones, is a project installed in Philadelphia called The Beacon. In the project, we worked with drones to dynamically weave a second exterior skin around a 20 ft tall modular steel structure over the course of 10 days. The project looks at the intersection between medicine, architecture, and emerging technologies, and at the future of these. The drones and the Beacon project overall served as an analogue and marker for discussion, and also as a public spectacle. It was exciting to take on something new, where you aren’t restricted to the six axes of a robot but are completely freeform in space as the drones deposit threads in a generative fashion. We had some failures, but I see it as an experimental act that will be looping back into the ongoing research trajectories within my lab.

When we started to deal with computation for the manipulation of complex materials, i.e. of non-standard materials with non-linear behaviour, there was this idea that we could at long last engage with the indeterminacy and complexity in a sense, at least to the extent needed for some practical purpose – not reversing but fulfilling the dream of a nineteenth-century engineer. Twenty years ago, we thought we were doing the opposite. When I look at the work of some of our friends, I have an impression that the discourse they were doing the opposite. When I look at the work of some of our friends, I have an impression that the discourse they were doing the opposite. When I look at the work of some of our friends, I have an impression that the discourse they were doing the opposite. When I look at the work of some of our friends, I have an impression that the discourse they were doing the opposite. When I look at the work of some of our friends, I have an impression that the discourse they were doing the opposite.

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...and responsibly embed them into our design process. Complexity of these effects, so that we could meaningfully material scientists, to simulate and approximate the. We developed our own tools, working side by side with material scientists, to simulate and approximate the complexity of these effects, so that we could meaningfully and responsibly embed them into our design process. Having said that, I don’t think we are quite there yet. Another intriguing example relates to one of my pavilion projects – a recent commission for the Cooper Hewitt, titled PolyThread. I wanted to dig into the behaviour of the knitted material, to the randomness, or the animation, of the material which is the same all over because mechanical machines cannot deal with anything else. But sensors and computers can now increasingly interact with irregular machines traditionally couldn’t work this way, so we invented plywood or we converted timber into an industrial material which is the same all over because mechanical machines cannot deal with anything else. But sensors and computers can now increasingly interact with irregular materials almost as well as a skilled artisan could. But the point is that there are not many skilled artisans that can still do that, whereas every computer can with the right programme. So that is our advantage today. And it is a reversal of the traditional science of materials. Until recently, the rule was to make materials standard; and now it is to take them as they are, and-prediction methodology, we end up with two games that co-exist. Which is more important in your work? Do you want to play with the cat? Or do you want to tame it? JS I am partial to the unpredictable cat. I am intrigued by the unexpected, and the agency of the material that one must respond to in the design process. I think in both my core research and applied projects, there is also a process that is slow, analogue and about the integration of the human hand. This usually happens at the prototype phase and is so crucial to allowing for the emergence of the unexpected, which I then opportunistically tame, but only in pursuit of the next potential scalability. So I would say I never want to fully tame that unpredictability. It is crucial to the innovation and to beauty. MC And this is where digital tools afford a level of interaction with the naturalness of the material which until recently only an expert artisan would provide. An expert artisan can deal with whatever irregularity is found in a chunk of timber because that is his skill, his intuition – he doesn’t need to make an x-ray of a log. If the log has a hole inside, he can just feel it or, by just tapping on it, can hear the reverberation of the sound. Likewise, if a particular log has some irregularity, he can work around it. Machines traditionally couldn’t work this way, so we invented plywood or we converted timber into an industrial material which is the same all over because mechanical machines cannot deal with anything else. But sensors and computers can now increasingly interact with irregular materials almost as well as a skilled artisan could. But the point is that there are not many skilled artisans that can still do that, whereas every computer can with the right programme. So that is our advantage today. And it is a reversal of the traditional science of materials. Until recently, the rule was to make materials standard; and now it is to take them as they are.
Images: Courtesy Cooper Hewitt Design Triennial.

### PolyBrick 1.0


### PolyBrick 2.0


Images: Courtesy Cooper Hewitt Design Museum.
specialist in any of these fields. This is still a role for which some architects are uniquely prepared, but it is a rare position. Of 100 of our students, 95 will become specialists, and they will not specialise in a specialised marketplace to earn their living. The remaining 5% will be those who will have this general holistic view of how we make things. We train them knowing that most of them will end up being specialists and a few will end up being architects. And this is good, because we need the generalist and the specialist.

JS So what you are stating is that we need both?

MC Well, 90-95% of our students will only be as good as they need to be to become specialists. But it was always that way. Is 5% pessimistic? You train designers – I only teach history, so I don’t know.

JS I would say the number is higher in terms of those who become architects – whether they are acting within an office or leading projects, or whether they go off to start their own practices. I hesitate to put a number out there, but I definitely see some architects – whether they are acting within an office, or leading projects, or whether they go off to start their own businesses. So I don’t know.

MC Yes, because now, in many ways, the distance between the designers who make the notation but don’t materialise it and the builders who materialise the notation but don’t invent it is being eliminated by the technical logic of digital tools. With digital design and fabrication, this distance has already collapsed. And so we go back to the medieval and pre-notational way of thinking and making at the same time – this is what we call digital craft, which is why I think we are much closer to the way we made physical things 500 or 600 years ago. We are revisiting a pre-Renaissance, pre-Albertian, pre-Brunelleschian way of making. I think we are closer to the model of a medieval city where master builders were members of guilds, who had to conceive and make at the same time. The separation between the thinker and the maker – this great invention of modernity – was not yet there. We are now reverting to this intellectual model, and I wonder if we are also revering the social and political model which went with it. That would be an interesting parallel, because in a sense the first phase of the digital age turned over the industrial revolution, eliminating the need for mass production, standardisation and economies of scale. Artificial intelligence now suggests an almost pre-scientific, intuitive approach to making. We really don’t know much about this magic power of digital intuition. From a distance, it is clear that its closest parallel is not the nineteenth-century engineer, it is not the twentieth-century designer, it is not the modern scientist – it is the medieval master builder, the artisan who can manipulate materials and can conceive and make without designing. Paradoxically, we are returning to this.

JS I think of many of us engaged in this type of work have a strong interest in the return to the site – I think that’s also why in so many projects the work exists currently within either a gallery or a museum as an installation, because we are still at the nascent stage of how this can move into the built environment as architecture. There are still so many constraints. I would like to go back to the turnip. I can’t remember the last time I initiated a design process with plan, section and elevation. Sure, I still use these techniques and notations because they are necessary in the way we communicate, but that is not how I work at all. Effectively, Brunelleschi turned the turnip into a piece of technology that allowed him to communicate information about form. MC Yes, noting a three-dimensional model was difficult at a time when parallel projections did not exist. But then he had another problem: he wanted these instructions to builders to remain secret, which is why after drawing the turnip he ate it! And the builders would need him on the scaffolding, onsite, every day – he was a modern designer, but he was designing as a medieval artisan and not like a Renaissance architect. That would come one generation later with Alberti. Alberti came up with the idea of making as many drawings as needed, then putting a name and date on them, so the builders would just follow the drawings. And when the building really looked like the drawings, then the designer can claim: “It’s my building, not because I made it, but because I made the drawings.” This is the act of foundation of the modern architectural profession. Brunelleschi was not yet there, because he wanted to have the building built according to his ideas, but he didn’t want to make drawings – he wanted to keep his ideas as secret as possible. He still had the mentality of a medieval craftsman, which he was – he was a goldsmith by training. And by the way, we still don’t know how he built the dome – it was a secret, still!

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MARILENA SKAVARA: Welcome to each of you and thank you for making time for this conversation. Our wish is that you develop a conversation between you. As convener, I will only prompt you here and there if necessary. To get started, maybe I ask a straightforward opening question: where is your work heading right now, what are the key ideas and questions driving it?

RONALD RAEL: We ask questions about material—particularly in terms of material provenance—in other words, where materials come from, where they are going and how they are filtered through various kinds of media. We are on a continual journey of exploration as we think about how particular materials—such as salt, recycled grape skins, recycled car tires—could be used in 3D printing to make building materials. To demonstrate this, we are doing several proof-of-concept pavilions, as well as integrating them more and more into architecture.

VIRGINIA SAN FRATELLO: We are trying to find practical applications for 3D printing in the near future, and we also want to start putting these materials together in the same building. With so much 3D printing, it seems that only one material is used at a time. We are developing a small house that uses several different 3D printed materials, including 3D printed clay and 3D printed cement, and we are even thinking about several different 3D printed materials, including 3D printed paper, 3D printed tiles and 3D printed cement, and we are even thinking about how to mix materials within one print, which is not something that has happened much yet beyond metals.

MONICA PONCE DE LEON: I am interested in the fit between technology and construction, and how everyday construction is affected by the realities of technology and the myth of technology. We tend to think that technology provides a certain level of precision, but in reality both it and the way we deploy it are imprecise.

VSR: You are widely recognised as a pioneer in applying robotic technology to fabrication within architectural education. How do you imagine buildings will be made in the next hundred years? And what are the changes that need to happen for these predictions to come true?

MPdL: I cannot predict the future at all. If you had asked me to guess where the discipline would be today 20 years ago, my guess would probably have been far away from where we are now. One of the exciting things in architecture is that there is no formula, and when you think everything has been exhausted, people come along and provide new twists and turns. So I don’t have predictions. I am interested in how, through building projects in the gritty-gritty of the everyday, that puts pressure on the kind of research that we do in academia. Ron and Virginia are very interested in real projects, whether they are test cases for a particular exhibition or whether they are for clients with budgets. Often, clients do not want the kind of material that one is researching, and you have to convince them that your research is culturally relevant for them and for the discipline at large.

RR: I think about past projects of yours such as Casa la Roca – that was an amazing project because it almost predicted things that people are attempting to do today with technology, but in traditional ways. Can you tell us about that?

MPdL: We were very much thinking parametrically—the kind of rule geometry that generated the figures of those walls and the layout of the bricks of those walls is part of the DNA of what came afterwards. It is interesting to see those same explorations executed through robotic fabrication, as opposed to by hand, and to see the research coming out of ETH Zurich, where robotic fabrication was used to do the geometry we had imagined with a different technology. This goes to show that there is again a loose fit between technology, execution and the culture of contingency that was intended for the house in Venezuela, which used vernacular materials—with terracotta tiles and terracotta bricks everywhere.

RR: What does that say about the development of architecture? Are we moving forward but yet not moving forward at the same time? That project in some ways is much more advanced in terms of thinking about parametric brick stacking, and yet the way parametric brick stacking has now entered into the profession is very banal—we’d much rather have a robot that stacks straight bricks in straight courses—so it is almost retrogressive. How does technology help us move forward? How does it prevent us from moving forward?

MPdL: Your hacking of technology poses an alternative to the status quo. I think there is a difference between accepting tools as they are and misusing the tool—and in misuse, the tools create a new way to think about materials, the relationships between them and their culture and context. This is one of the things I love about your work—you are always misusing the materials, misusing the technology, destabilising materials and methods of fabrications. The history is still embedded, but we’re asked to think about it differently. I think this offers a way to bring technology into question, and to destabilise the way we think about building in contemporary culture.

VSF: I’m reminded of the Helios House and the Tectonic Argument at MoMA, and how those projects referenced fashion design—and I’m thinking about overlaps between architects and other design disciplines including computer science, perhaps in a way of destabilising building or missing material. On your website, you say you work with
product designers and fine artists — I was wondering how interdisciplinarity affects your work and research?

MPdL: If we are going to misuse material and technology, I think it’s helpful to look outside the discipline for techniques that can be appropriated and reinvented within architecture and construction. I tend to work opportunistically — if I see something in a different field that looks like it might work, I try to adapt it. Like tailoring, for example, that’s something I pursue. There are also different relationships between how one draws a project and how one builds a project. I think drawing is a way of bringing techniques from different disciplines into architecture. Through model-making you can bring analogous techniques from other disciplines as a way to explore cultural concerns. I think you do this extremely well — the way you have reinvented the vernacular by applying techniques that do not necessarily belong to the history of a material. You mention 3D printing and how, by hacking the equipment, you use materials that would not normally be 3D printed — this is another version of using techniques outside of a particular mode of construction.

RR: We have also looked closely at building traditions — one of the things we did prior to 3D printing was travelling around the world to look at traditional vernacular buildings and learn from them. I think one thing that certain technologies have allowed us to do is figure out how to collapse many of the systems within-vernacular constructions into new systems; we came up with a brick that can absorb water and passively cool a space by having ventilation in it, but where that comes from is a much more complex and beautiful demonstration of many different techniques — the creation of wooden screens, ceramic vessels, traditions of collecting water, massive constructing rooms. In many ways, much is lost through these translations and much is gained. We always struggle when thinking about how old traditions are lost and new traditions emerge. What are the new traditions that will emerge in the technological era? I don’t believe in the idea that giant 3D printers will replace all the building traditions that exist. I think there needs to be an integration of older and newer traditions. In that hybrid moment, beautiful things emerge.

MS: What do you think are the most valid terms of reference to think about design? Is it performance, narrative or scarcity — or is it something else?

MPdL: One of the challenges, if you think about architecture only in terms of the immediate present, is that you end up with a series of buzzwords which can be very transitory. I can only imagine in the long run that scarcity, performance, etc, are not actually going to matter. What I always care about is whether a piece of work is culturally relevant and can be understood as part of a wider context, and for that it has to engage with a long understanding of a place, reflecting on the past, present and future. Architecture both constructs a particular idea of culture and reflects upon it. So in that sense, I think categories can sometimes get in the way.

RR: I agree; I was thinking about two particular categories that are creating a split in architecture culture. For example, there is a split between the social project and the parametric project — I understand those kinds of projects are divided, but why do they never attempt to cross-over?

VSF: That’s a good point — designing for performance using a particular Grasshopper script and merging that with social concerns about community or beauty, for example, might allow for new culturally relevant works to emerge.

RR: I think there are cultural tendencies toward technology that suggest that its output must do something or perform...
something – it should have feedback the way an iPhone does. I think always asking “why?” or “why not?” is important. Nothing makes me more impatient than when someone says something is impossible – well, why? Or when a student takes a particular direction – why? For me, a key component of architectural education is demystifying the process of design, fabrication and construction so that your student is really focused on imagining alternative scenarios, speculating hypothetically. This is particularly true outside city centres – the state of building today and the state of the landscapes and the sites around us is deplorable, so if we don’t teach our students different ways of operating within these conditions, and if we don’t push ourselves to imagine alternatives, then change won’t take place. For me, it’s not about becoming proficient with technology or methodologies, but actually demystifying all aspects of architecture so it opens up the imagination.

MPdL: Women have been around forever; we have been doing stuff forever. I was the Director of the Digital Fabrication Lab at Harvard in 2003, over 13 years ago – and I was working with fabrication prior to that. I became a Dean at Michigan eight years ago. The presence of women in the profession has a very long history – perhaps the media is highlighting it more today, so it seems as if we are more present. But I think women have been interested in technology from the very beginning, just as men have. Perhaps there is more of an effort now to make sure they are equally represented in the media, which may make it seem as if they are only now emerging in the field.

VSF: For me, the paradigm of fabrication has been very significant. It’s allowed me to be a craftsman and use materials that otherwise I had never worked with. I wonder if other women feel the same.

MPdL: I think we are all individuals. I worked in a mill workshop before studying architecture, so I have the opposite experience. I tended up pursuing digital fabrication because soon after I graduated I realised that the same mill workshops were no longer doing things the way I had done them myself, but yet this was not a conversation we had in academia. So I became interested in digital fabrication precisely because I saw it as an emerging context for the building industry that was being ignored by the academy. For me, it was not a way of enabling me to do things that I otherwise couldn’t. I think that your earlier question about Casa La Foca is very relevant, though. We were drawing by hand and then it became easy to draw with Grasshopper. But it is really a question of how long it takes – we are still drawing by hand, if it just takes five times as long. But I think that applies to everyone, men and women equally and all generations equally. One of the things I am very excited about is that combination between material invention and advanced technologies. I think one of the challenges for me, as a designer and educator, is that there has been a divide between material interest and advanced fabrication, it seems as if there are those only interested in advanced fabrication and those only interested in advanced materials. What I love about your work is that you are unapologetic about bringing together – and allowing the history of sourced materials to be understood as part of a continuum with the more recent generation of tools. That opens the door to a future which I think is very exciting; we no longer have to compartmentalise what is high tech and what isn’t. So there is a conflation of ways of looking at materials that wasn’t part of the disciplines before.

RR: Smithsonian magazine came out a couple of years ago with a list of the top 40 things you must know about the future, and number one was that advanced buildings would be made out of earth. This is not an anachronistic material – it is a technological material that has undergone 10,000 years of human development. If we look at every moment in history when there was some sort of global crisis, the scarcity of materials often asked humankind to review materials that they could already use. I think that we are now at that cultural moment. We are looking at materials that we are good at, and that’s why there is a tremendous interest in the relationship between ceramics and technology. We are talking about larger cultural connections and ecologies of material. This is one of those moments when we can stop and say: sure, it might be easy to put clay in a 3D printer or in a robot, but there are reasons why we are doing it culturally and historically – the availability and the plasticity of the material, but also our ability to achieve or attain because of its complexity, but this is also part of the demystification – asking how we can achieve the impossible. Another aspect of this might be the emergence of female leaders in the field (such as Jenny Sabin, Neel Cheman, Liz Diller) I was wondering if you saw this notion of demystifying, or changing societal forces, or even the paradigm of fabrication technology itself, as contributing to their strong and increasing presence?

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as humans to engage a material which has evolved with us over the course of human civilization.

**VSF** Perhaps the same can be said of salt. For example, in South America there are towns, hundreds of years old, built entirely out of salt. Salt is an ancient material that has the potential to be used as an advanced building material in the future in places around the world where salt is harvested. In the Bay area, it’s local, it’s renewable and there are both historical and ecological reasons for building with salt. Instead of shipping sand and cement all around the world to make concrete buildings, architects have new opportunities to revisit old materials and new manufacturing techniques for thinking about the evolution of material and building.

**MPdL** I am curious about your attitude towards precision. I have always been fascinated with the fact that architecture seems to rely on the concept of precision for its own disciplinary existence. You have the notion of tolerance and use certain details as a way of hiding the lack of precision – base boards are used to hide the gap between the wall and the floor, ground mouldings to hide the gap between the wall and the ceiling, and so on. We operate with tolerances, and in digital fabrication each tool has its own level of imprecision, and you are actually fabricating with a certain level of tolerance. In your use of vernacular materials, through the use of fabrication tools, I am wondering what your level of tolerance. In your use of vernacular materials, through the use of fabrication tools, I am wondering what your level of tolerance. In your use of vernacular materials, through the use of fabrication tools, I am wondering what your level of tolerance. In your use of vernacular materials, through the use of fabrication tools, I am wondering what your level of tolerance.

**VSF** I am talking about vessels – we call them the ‘G-code vessels’, which are mostly cylindrical in shape, and instead of modelling in form we use the G-code itself to design. And we have no idea how big these loops are going to be, or if the printer can do it, or if they’re going to break. And we are keeping pushing it until we see at what point it will fail. And at the same time, when we test print with cement, it is fairly accurate. We are currently working with engineers who are helping to develop a strong cement material which has more water in it, which can be crush-tested because we realise that the way we lay down ceramic material increases or decreases its strength, and this is all through a series of controlled errors.

**MPdL** I see them as all related. Perhaps the same can be said of salt. For example, in South America there are towns, hundreds of years old, built entirely out of salt. Salt is an ancient material that has the potential to be used as an advanced building material in the future in places around the world where salt is harvested. In the Bay area, it’s local, it’s renewable and there are both historical and ecological reasons for building with salt.

**RR** So do you see this as a larger critique of some of the agendas of fabrication that explore precision? Do you see it as a humanist moment in fabrication when many are attempting to achieve what is on the screen – hyper-smoothness, for example, or seamlessness – how do you see that?

**MPdL** One of the first exercises I give my students when we are working with a robotic arm is to ask them to design a stool with very few cuts and very little waste, and it is interesting to see how they struggle with the fact that the robotic arm is not actually as precise as they had assumed, and that it actually affects the size of the pieces. The more they had assumed that a piece of equipment was precise, the harder it is to deploy it, and the harder it is to come up with a cultural object, like a stool. So the critique is also embedded within the equipment itself – which means you have to predict that the piece of equipment is precise to even talk about precision. When one accepts the implications of the piece of equipment, you will end up with a more interesting conversation.

**RR** Given that we accept that there are not categories – not of curation, design or education – how would you define yourself as an individual in our field?

**MPdL** Architects are always curating and educating – whenever we choose one material or form over another, we are curating.

**RR** That’s beautiful. I love the way that it turns out all the same for you – it’s all about culture and imprecision and imagination!
ACHIM MENGES: think what makes the FABRICATE conference unique is that it brings together people from both academia and industry. It revolves not only around research findings, but also around projects. It’s not just about submitting a paper, but also about presenting your research or practice through the project, which is quite a unique format in our world. Being in Stuttgart, we tried to give it a special focus, presenting it as one of the heartlands of manufacturing and fabrication, with strong connections to industry. So we have also established special industry talks by cutting-edge companies – for example, the robot manufacturers KUKA.

So it is really about bringing together leading practitioners, companies – for example, the robot manufacturers KUKA. Also we have increasingly talked to cutting-edge companies – for example, the robot manufacturers KUKA.

BOB SHEIL: Looking back on the work you presented in 2014 and where your work is now, what do you feel has been the major stepping stone in the last three years? And where are you headed next?

AM: What we have seen is that computation is becoming closely related to materialisation, with the physical world rapidly emerging from within the digital domain. This is a very interesting situation. We have realised we cannot focus on computational design exclusively, but instead that it is inseparable from construction. This is the reason why we have changed our name to the Institute for Computational Design and Construction. We are working towards a higher level of convergence between design and making, with ramifications on how we conceptualise designs, how we work with materials, and how we understand digital fabrication.

Another profound change was the introduction of the micro-processor, so that you could now make high-quality, low-cost objects or products in small batches. As unique as a micro-processor, so that you could now make high-quality, low-cost objects or products in small batches. As unique as a micro-processor is fidelity between the digital and the real, as well as to gather performance and soon-to-be ubiquity of sensors. Something enabled us to tap into the potential of computation as it becomes increasingly ubiquitous, and to come up with something new.

Q&A 3
CARL BASS
BOB SHEIL
ACHIM MENGES

CARL BASS: To a degree, design has gone from documenting the design cycle. So if you look at computation for design and fabrication – this is the kind of landscape we are in.

When we look at technological developments, we note that there is an initial phase where new technologies are used to mimic old processes and products. This is true for almost all technologies; for example, material technologies – there are composite materials initially employed to mimic old processes and products – but it also applies to software technologies where, in the first generation of commercial CAD applications, the screen mimics the drawing boards and the mouse mimics the pencil. It is also true for production technologies. CAM was primarily used to automate and better control fabrication processes that existed before. One can argue that we are currently transitioning from this first phase of using digital technologies for designing and making things that are essentially pre-digital products to a second phase where we are beginning to explore processes and related products that are genuinely computational – things that are genuinely computational – things that we could not have made or even conceived of in pre-digital days. This enables us to tap into the potential of computation as it becomes increasingly ubiquitous, and to come up with something new.

Another profound change was the introduction of the micro-processor, so that you could now make high-quality, low-cost objects or products in small batches. As unique as a micro-processor is fidelity between the digital and the real, as well as to gather performance and soon-to-be ubiquity of sensors. Something enabled us to tap into the potential of computation as it becomes increasingly ubiquitous, and to come up with something new.
radically new ways of designing and making. This has great promise, but also offers quite a challenge because it means that we, as designers, have to adjust our design thinking. It is not just about updating the design tools and techniques; design thinking also needs to be fundamentally updated.

BS Do either of you envision a point in the future where we stop prototyping? In a sense, computation, simulation and the design process have become so complete that manufacturing is only about the delivery of the final piece. Or will prototyping remain as the middle ground between design and making?

CB I don’t think there’s an absolute. As people become more fluent and proficient with their digital facsimiles, they will be able to go without prototyping for things of greater complexity. At a certain point, this will break down and you will want to see, feel, smell or experience the thing you are building. If you look at CAD software, just like every other technology it tries to mimic, the technology that came before it found a life of its own – CAD technology started out mimicking the drafting table. Now, the goal of most CAD software is to build a digital model, a replica of the thing you are going to build. We are only partially there, but if you think about a building in CAD software, we now have a fairly good understanding of what it will look like, what that structure is, how the air will move in the building, how it will sound, how you feel when you move in the space or how it will react to environmental conditions. But there is no reason to presume that, over the next 10 to 20 years, we won’t be able to get very good approximations of the things we build. In essence, in manufacturing, I think prototypes that are small and manageable will continue to get built because it is easy. But many buildings, specifically any one-off building, are prototypes in themselves and we can only prototype parts of them. I think that is where we are headed.

BS Looking at your work, Achim, I enjoy what you say about adding the word ‘construction’ to the lab. Your recent work is becoming increasingly performative, in that the spectacle of making is a wonderful thing to watch. It shows that the performance of making is a part of design. This performance opens up the imagination for other things that we can make. Do you have a conscious view on performance as being part of the act?

AM Yes! I see it in two ways: 1) the performance of the process itself, and 2) the performance of the object or structure. Especially interesting is the way in which digital fabrication processes become more open-ended, flexible or, in other words, designable. When we talk about a prototype, we like to prototype not only the actual product, but the processes, too. Today, designers actively engage in developing new fabrication processes as part of the design process, instead of just using existing products and technologies. That leads to new modes of what one may call the co-design of processes and products, which is a different way of going about design. For me, this is one of the essential aspects of robotic fabrication – it extends your possibility as a designer beyond the product, beyond the building, to the processes in which the buildings and the products come about. We have a lot of collaborations here with production engineers – people that come from manufacturing – and it is interesting to see how designers bring a different agenda to the table as opposed to someone who is trained traditionally in this field. It really broadens the spectrum of what we refer to as ‘making’, to a kind of design thinking. The other aspect that is of interest to me is how we can conceptualise this convergence of design and making. In recent years, one of the most radical changes is that the line between what we call ‘making’ and what we call ‘design’ is beginning to blur. This relates to the prototypes, because the prototype is what

2. A generatively designed chassis of the Hack Rod, after the sensor points were fed into the programme. Image: © Autodesk.
3. A Hack Rod test drive in the desert.
we see as a step between design and making. With the arrival of what we here in Germany call ‘cyber-physical systems’, we see that design and making can happen in a kind of feedback loop, where they co-exist and co-evolve. This is also part of what Carl mentioned as the possibility to equip our fabrication environment with an abundance of sensors, which means that all of a sudden what you actually make becomes the model for what you want to make. This means that a machine is no longer just executing a control code taken from previously established models, but actually has a far more active interaction with the process of making, to the point where it can begin to make its own decisions, to the point where it can begin to make its own decisions so that the designer designs conditions and performances that need to be fulfilled, and a certain level of decision-making can happen on the level of the machine. Taking into consideration the fact that these machines are increasingly capable of learning sophisticated ways to operate in the physical world. So I think we can overcome this idea that design comes to an end, and then we prototype, and then we make – instead, these things start to co-exist in the same space. This begins to challenge some profound aspects of architecture, as well as our conceptualisation of what a designer is and does. CB There’s an example from some work we did recently which shows the way in which design and fabrication become more of an inter-related cycle. We wanted to build a new kind of vehicle chassis, so we built the frame of this car in a very traditional way and then hired a bunch of drivers from Hollywood to take it into the desert and drive it, aggressively, for 10 days. The vehicle was monitored for the duration. When we were finished, we had enough knowledge about the forces that acted during extreme stress testing. We took that information and put it back into an algorithm that generated an ideal structure for that vehicle, and then we added in three different fabrication techniques and said: given this idealised form, how would you realise it through different fabrication techniques? One was an improved version of something that was made out of tubing, and the others are these two wild-looking designs that were intended to be done with additive manufacturing, one out of chromoly and the other out of titanium. What’s interesting is that you have this form that you want to get to, and then you have these different kinds of material and processes to actually realise the design. AM One example that I like to mention from our work is one of our recent research pavilions, where we inflated a membrane to look like a big balloon which we then reinforced by gluing carbon fibre inside it, and therefore turned this floppy membrane into a building envelope that is actually supported by the fibres. The interesting thing is that during the fabrication process, the structure changes shape constantly, so you no longer have a finite design. In this case, the robot has the capacity to sense the stress in the membrane and actually sense where the membrane is in space, adjusting its carbon fibre layout path accordingly. So, there is direct feedback between the environment in which the robot operates, the structure it builds and the way it is controlled. This is something you cannot fully predict. It’s also something you can’t predefine in a sort of representational geometric model; it’s really about forces, structures and predictive simulation and also about real-time sensing. In that case, it is really interesting, because sometimes the robot makes semi-autonomous motions which obviously leave traces of carbon fibre, which become part of the design. It is difficult to determine where the design ends here and where fabrication starts – it is a kind of coalescing of the two. BS How can we look for a gear shift in the construction industry at a more general level, and how can a designer’s playfulness and inventiveness have an impact on a much
This is what we have to get industry to realise. In Germany, just as a kind of digitalisation of what you have done in the past. Technologies and you are short-served if you consider them this will be rewarding, because these are truly disruptive research and will take more time. However, ultimately I think now. This is something that needs a more profound rooting in technologies? Obviously this is not something you can resolve today. This is a kind of digitalisation of what you have done in the past. What is this? What is this? A kind of digitalisation of what you have done in the past. This is what we have to get industry to realise. In Germany, this is not so easy, because there is a very strong construction industry and not a lot of incentive to change established business models. Computational technologies have incredibly disruptive potential and inevitably the construction industry will have to reinvent itself. We need to lay the foundation for this and, at least from my academically biased perspective, make sure we can tap into its true potential – not just its design potential but also the ecological and environmental perspectives, which very much need addressing in the construction industry very soon. We will not be able to go on as we do, because we consume more than half of the resources and energy on the planet. So we need that long-term vision and your projections and forecasts for design experimentation at a much greater scale?

CB: I don’t have the same prejudice as Achim, because I am not in Germany. I am slightly more optimistic, due to the timeline. The construction industry is bottom-line driven, so whenever we can build better things more cheaply, construction will pick it up. Yet construction companies are actually very resistant to change. If you look at job sites today, they look nothing like job sites thirty years ago — the skills, the people, the tools they use, the processes, the materials they are working with — they move with the times quite effectively. There is a kind of capitalistic tech approach that serves as a counterpoint to what happens in architectural artistic practices. Just as I can go to my workshop and dream up and build any crazy thing I want and it does not have to make economic sense — I think many firms can build that way, and I love this experimentation and it should continue. On the other hand, the construction industry offers a check and balance on this, saying what makes sense and what is sustainable. In that sense, I am pretty optimistic about construction companies moving forward with digital fabrication, because the right incentives are underlying their choices. BS: Do either of you see a future in which the construction industry gets challenged by lots of micro design and maker industries, similar to the way in which artisan beer makers are prepared to take risks based on notions of quality and distinction as opposed to mass production and profit?

CB: My initial response is no. What I would say is that spending six dollars for a beer instead of three and a half is a decision that millions of people can make every day. The stakes involved in the cost of a building are so much higher and what was when things become more expensive and discretionary is that the number of owners who are willing to incur that extra expense are very few and far between. Obviously there are all kinds of wildly innovative projects being built, but I don’t think it could ever become a mass market thing. However, once we get to a point where we can build more unique designs for the same kinds of prices, then all bets are off.

BS: Is this prospect on the horizon?

AM: Well, I also have quite an optimistic outlook on how the construction industry might change. Very often, we have the hand-laid brick wall and the robot-laid brick wall, which is something you have mentioned. It boils down to which is cheaper to produce. I think the real question to ask is: does the robot really want to build a brick wall? And the answer is: probably not. I think the construction industry needs to benchmark digital processes on pre-digital construction systems. But as we are just making the transition from the stage where we employ computational technologies to mimic traditional processes to the stage where we start to uncover radically different solutions, we need to challenge norms and established ways of doing things. How do we want to build when we have computational construction, cyber-physical systems and man-robot collaboration? Obviously, the goal cannot just be the automation of the building site and the automation of existing offsite processes. Accordingly, how do we move it towards following the logic of economics of the digital age? This is where we really need to get the construction industry to. This is a challenge, but also a new opportunity — we might perhaps be able to democratis what the ordinary
The rise of digital fabrication represents a major turning point, even if there are still a lot of ideological discourses that obscure the path it is taking. Not everyone will become a ‘maker’. I also think that the notion that thanks to digital fabrication the designer will become a kind of postmodern craftsman is also ideological. Comparing oneself to Ruskin seems to me to be profoundly dubious.

What lies ahead?

Another crucial evolution will stem from the urgent need to reconnect the digital with the quest for sustainability. Also, what does it mean to design in a true context of augmented reality – at the level of the articulation of atoms and bits?

What are the most valid terms of reference for new ways to think about design?

As I have argued repeatedly, one of the main consequences of the digital revolution is to make design appear more strategic, commensurate with a form of action, rather than being about the revelation of some pre-existing formal idea. Design becomes synonymous with event-making and with the production of scenarios. Making and speculating tend to become more and more intimately linked, but not in a ‘craftsman’ way. They are linked more by a common inquiry into the foundations of materiality.

Nostalgia is inevitable, since the digital has separated information from matter while pretending that it does the contrary. Material computation is actually permeated with nostalgia. For me, this is part of what makes it interesting beyond its claim to a new objectivity.

We are delighted that you have agreed to be a keynote at FABRICATE 2017, extending the tradition, which began with Mario Carpo at FABRICATE 2014, of having a historian speak. Where is your work heading right now – what are the key ideas and questions driving it?

Between 2010 and 2015, I devoted three books to looking at how the rise of digital culture links to transformations within urban architectures: Digital Culture in Architecture (2010), Ornament (2013) and Smart Cities (2015). These books identified a series of theoretical issues that I would like to concentrate more specifically on in the years to come, such as the question of materiality and the links between the evolution of architecture and subjectivity in the digital era.

Alongside these lines of investigation, I plan to focus on techniques themselves – on software in particular and its influence on the design process. If the first line of inquiry is akin to a philosophical investigation, the second would be closer to an anthropology of techniques.

How have your work/interests evolved over the past decade?

I have gradually shifted more towards urban and societal issues. For instance, the need to reconcile the quest for sustainability with digital advances appears to me to be a major challenge. More generally, I am perhaps less interested in architecture as such and more in broader issues of space, technology and society.

Looking ahead to the context of FABRICATE and your forthcoming keynote, do you believe we are witnessing a new era in computation/design/making?

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So what lies ahead?

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Rethinking Additive Strategies
The research presented in this paper, based on two projects, investigates design methods for discrete computation and fabrication in additive manufacturing. The first project, CurVoxels (Hyunchul Kwon, Amreen Kaleel and Xiaolin Li) introduces a discrete design method to generate complex, non-repetitive toolpaths for spatial 3D printing with industrial robots. The second project, INT (Claudia Tanskanen, Zoe Hans Thoe, Xiaolin Yi and Qianyi Li) proposes to make this discrete process physical, suggesting a fabrication method based on robotic discrete assembly. This discrete design and fabrication framework aligns itself with research into so-called digital materials — material organisations that are physically digital (Gershenfeld et al., 2015). The suggested methods aim to establish highly complex and performative architectural forms without compromising on speed and cost. Both projects propose design and fabrication methods that are non-representational and do not require any form of post-rationalisation to be fabricated. The research argues that, compared to 3D printing, robotic discrete fabrication offers more opportunities in terms of speed, multi-materiality and reversibility. The proposed design methods demonstrate how discrete strategies can create complex, adaptive and structurally intelligent forms. Moreover, by moving computation to physical space, discrete fabrication is able to bridge the representational gap between simulation and fabrication. This representational gap is a result of a two-step process usually associated with computational design strategies, where a design is first developed digitally and then passed on to be fabricated.

Analogue and digital fabrication

The projects described in this paper are produced in a research-through-teaching context within The Bartlett Architectural Design Programme (AD) — Research Cluster 4 (RC4). RC4 is a part of BPro, an umbrella of postgraduate programmes in architectural design at The Bartlett School of Architecture, UCL. The research can be situated in the context of robotic manufacturing and the automation of construction processes. The two projects presented are based on the use of industrial robots, but these are assumed as abstract, notional machines. The projects could potentially be more efficiently implemented with other types of custom-made robots, but the research in question here is first and foremost focused on design methods. Both projects should effectively be understood as research into design methods, rather than as research into robotics and manufacturing itself. In terms of fabrication, both projects are additive fabrication processes: CurVoxels (Fig. 2) is a 3D printing process, and INT (Fig. 3) is an additive assembly workflow.

There have been significant research efforts into robotics and automated construction, especially in the context of additive processes. Gramazio Kohler has developed additive projects such as The Programmed Wall (2006), Complex Timber Structures (2013) and Mesh Mould (2014). However, these attempts to automate construction have had little impact and are caught in a conflict between complexity and speed (Gershenfeld et al., 2015). Neil Gershenfeld argues the need for digitising not just the design but also the materials (Gershenfeld et al., 2015). In this context, The Centre for Bits and Atoms has developed the notion of digital materials — parts that have a discrete set of relative positions and orientations.

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Gershenfeld et al., 2015). These materials are able to be assembled quickly into complex and structurally efficient forms. These digital materials establish material possibilities that remove representation, resulting in structures that are not continuously differentiated, but discrete and limited. After the toolpath is tested for a single curve- or point-based print, the voxel is rotated to connect to the line in the previous voxel. In principle, there are a few resolutions possible but a number of these are not printable, and a resolution tool would interact with the curve. The logic of combining separate toolpath fragments is essentially combinatoric: there is a discrete set of options for how curves can connect without losing continuity. The printing process cannot be prototyped on a few very small test samples. The fabrication procedure proposed by INT aims to resolve some of the problems associated with continuous additive manufacturing, such as the lack of speed and mono-materiality (Fig. 5).

Towards discreteness

In the first instance, this research is driven by the question of how the notion of discreteness can make the automation of construction processes more efficient while also allowing for more complexity and differentiation. It attempts to combine the efficiencies of digital materials with combinatorial design methods. Secondly, as a broader question, the projects presented develop design methods that remove representation, resulting in structures that are not continuously differentiated, but discrete and limited. After the toolpath is tested for a single curve- or point-based print, the voxel is rotated to connect to the line in the previous voxel. The printing process is based on a tool head, mounted on a robot arm, extruding hot plastic along a spatial vector. This method saves a lot of time in comparison to layered methods. Preferably, the robot does not stop during the process, but continuously extrudes material. Robot-based printing has a number of limiting treatments, the most important being that the robot can never interconnect with previously deposited material. There are also structural constraints: material can only be extruded at the air for a limited range – at some point, support structures are needed. Therefore most digital printing projects make use of a highly repetitive toolpath organisation, based on parallel contours, connected with a triangular toolpath. The formal possibilities are limited, and the toolpath organisation is not very complex.

CurVoxels and INT

CurVoxels is a team of students in RC4 who developed the project Spatial Curves (2014-15). The project is a continuance of research into spatial printing, which started with a previous team of students called Filaments (2013-14). Spatial printing is a new method for robotic printing, but first appeared in the Mesh mould project (Gardner, Lauer, Gramazio, Kohler, 2014). The printing process is based on a tool head, mounted on a robot arm, extruding hot plastic along a spatial vector. This method saves a lot of time in comparison to layered methods. Preferably, the robot does not stop during the process, but continuously extrudes material. Robot-based printing has a number of limiting treatments, the most important being that the robot can never interconnect with previously deposited material. There are also structural constraints: material can only be extruded at the air for a limited range – at some point, support structures are needed. Therefore most digital printing projects make use of a highly repetitive toolpath organisation, based on parallel contours, connected with a triangular toolpath. The formal possibilities are limited, and the toolpath organisation is not very complex.

CurVoxels developed a design method which is aimed at combining the toolpath constraints and developing new freedoms within these constraints. CurVoxels’ computational approach is based on discretisation: a voxel space is developed, where every voxel contains a toolpath fragment. It was decided to use a Bézier curve as a unit to compose the toolpath. The team then developed a process that cycles through the voxel space in a layered and linear fashion, simulating the trajectory of the robot. Every time a voxel is accessed, the Bézier curves inside the voxel is rotated to connect to the line in the previous voxel. In principle, there are a few resolutions possible but a number of these are not printable, and a resolution tool would interact with the curve. The logic of combining separate toolpath fragments is essentially combinatoric: there is a discrete set of options for how curves can connect without losing continuity. The printing process cannot be prototyped on a few very small test samples. The fabrication procedure proposed by INT aims to resolve some of the problems associated with continuous additive manufacturing, such as the lack of speed and mono-materiality (Fig. 5).
The next project, INT, combines discrete design with discrete fabrication. Similar to CurVoxels, a combinational unit is developed, but this time as a physical building block that can be aggregated and assembled. This unit is able to combine with itself in different ways and can be robotically assembled. Similar to Neil Gershenfeld’s digital materials, the unit is serialised and has a discrete set of connection possibilities. The digital building block, or tile, has a geometry which can be inscribed in a voxel space; one L shaped unit is comprised of three voxels. The tile is further defined by a series of subtractions so that it can be picked up by a gripper tool in different orientations. It is also marked with multiple reflectors that help a camera system to track the elements in physical space. The project is based on multiple scales of CNC milled timber blocks. The smallest can be gripped at the outside boundary, and the largest from inside. The use of heavy, compression-based material introduces difficulty to the assembly process, presenting a whole range of structural problems. More significantly, the project makes use of joints, but in the end a substantial glue in order to be assembled. The use of glue prevents the reusability and reversibility promised by the project. The problem with the joint is one of the main limitations of discrete fabrication: the smaller the elements, the more joints are required. Potential solutions could attempt to make the element itself interlocking, but this would inevitably increase the complexity of the robotic assembly process and again severely limit the formal possibilities.

Discrete fabrication

The design methods developed in the CurVoxels and INT projects have significant implications for additive manufacturing, the automation of construction and architecture. The proposed combinational design methods establish a series of efficiencies while also enabling complex serialised organisations. The shift from continuous fabrication to discrete fabrication moreover introduces a series of advantages, such as multi-materiality, structural performance, speed and reversibility. The proposed combinational method allows for discrete fabrication in comparison to the repetitive character commonly associated with digital materials. Formal differentiation no longer relies on the mass customisation of thousands of different parts, but can be achieved by the recombination of cheap, serialised units (Fig. 1). The use of cheap, prefabricated building blocks, in combination with increased assembly speed, reduced error space and vast formal possibilities, provides a rich ground for additive manufacturing.

The potential for reversibility has implications reaching far beyond automated construction. Architectural building elements that are recombinable could significantly change the lifecycle of buildings. The combinational aspects can help to introduce complexity and adaptability in prefabricated building systems, without losing the benefits of seriality and standardisation.

References

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Throughout nature, hair-like structures can be found on animals and plants on many different scales. Beyond ornamentation, hair provides warmth and aids in the sense of touch. Hair is also a natural responsive material that interfaces between the living organism and its environment by creating functionalities like adhesion, locomotion and sensing. Inspired by how hair achieves those properties with its unique high-aspect ratio structure, this project explores ways of digitally designing and fabricating hair-like structures on the surfaces of manmade objects. Material science and mechanical engineers have long been investigating various methods of fabricating hair-like structures. In this paper, we present Cilllia, a digital fabrication method to create hair-like structures using stereolithographic (SLA) 3D printing.

The ability to 3D print hair-like structures would open up new possibilities for personal fabrication and interaction. We can quickly prototype objects with highly customized fine surface textures that have mechanical adhesion properties, or brushes with controllable stiffness and texture. A 3D printed figure can translate vibration into a controlled motion based on the hair geometry, and printed objects can now sense human touch direction and velocity. In this paper, we will focus on introducing the fabrication pipeline and the emerging mechanical adhesion property of the printed hair surface.

The 3D printing revolution
3D printing is rapidly expanding the possibilities for how physical objects are fabricated. Its layer-by-layer fabrication process has tremendous potential to enable the fabrication of physical objects not previously possible. High-resolution 3D printers have become increasingly affordable and widely available, enabling the fabrication of micro-scale structures. Cilllia is a bottom-up printing pipeline intended to fully utilize the capability of current high-resolution photopolymer 3D printers to generate large amounts of fine hair on the surfaces of 3D objects. We introduce methods, algorithms and design tools for the fabrication of Cilllia and explore its capabilities for mechanical adhesion.
In this paper, the following contributions are presented:

1. A bottom-up approach for generating 3D printable micro-piller structures.
2. A simple graphical interface that allows users to easily design hair structures.
3. Examples of encoding mechanical, electrical or biological properties into hair-like structures.

As high resolution 3D printers become increasingly available and affordable, we envision a future where the lack of an efficient digital representation of CAD models with a fine surface texture is no longer a limiting factor. We introduce a bottom-up approach to 3D printing hair-like structures on both flat and curved surfaces.

The algorithms described in this paper generate readable files that reconstruct hair-like structures. The method can be viewed in three layers:

1. A single hair’s geometry (1D): height, thickness, and angle.
2. Hair array on flat surfaces (2D): varying single hair geometry across the array on a 2D surface.
3. Hair array on curved surfaces (3D): generating hair array on arbitrary curved surfaces.

Single hair geometry

Compared to other surfaces textures, such as the wrinkle, hair is more complex to describe mathematically. It usually comprises a high aspect ratio cone that is vertical/angled to the surface, although the height, thickness, and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continuously decreases from the base to the tip. However, the smallest unit in the DLP printer is a pixel. Therefore, each pixel of the bitmap is one pixel of the surface, although the height, thickness and profile might vary. As we know, the diameter of a cone continues...
Printing with laser beam-based SLA

1. Bitmaps of hair structures:

There are three advantages when directly generating length correspondingly (Fig. 3). In our test, we successfully printed 20,000 strands of hair on a 30 x 60mm flat surface. In our experiment, we directly manipulate the exposure time on a laser beam-based SLA printer (Form1+). In the experiment, a pair of hair panels (30 x 30mm) were glued onto a solid truncated pyramid (30 x 20 x 30mm). We pushed the hair surfaces against each other and measured the force that was needed to pull them apart. Our test shows that as the tilting angle of the hair increases, the adhesion force rises as well.

Successful fabrication of customised hair-like structures

To summarise, we present a method of 3D printing hair-like structures on both flat and curved surfaces. This allows a user to design and fabricate hair geometry at the resolution of 50μm. We built a software platform to let one quickly define a hair’s angle, thickness, density and height. The ability to fabricate customised hair-like structures not only expands the library of 3D printable shapes, but also enables us to design surfaces with mechanical adhesion properties.

While we demonstrated methods and a possible design space for 3D printed micro-pillar structures, we are aware that the technique is very much limited by the physical constraints of current SLA 3D printers. For example, if we had to create an arbitrarily shaped object fully covered by hair, we would have to split the object so that the curvature of the surface could still be printed without a supporting structure. The printable materials are also limited in terms of colour and stiffness. Our current algorithm for generating hair on curved surfaces is also highly dependent on the amount and distribution of the triangles of the CAD model. This means that to print high quality hair requires either a clean mesh model or a preprocessing step for the model. In the future, we will add re-mesh functions to our software platform to control hair distribution. It would also be very interesting to test if tilted hair is mechanically weaker than straight hair, as there is less contact area for each layer of the voxel.

Notes

The aim of this project paper is to present new findings in the implementation of a design for fused filament fabrication (FFF) and custom material development methods, alongside a stimulus-responsive 3D printed prototype (Fig. 1). The project demonstrates control in the design and manipulation of new composite materials to create architectures capable of complex kinematic deformations in response to environmental stimulus. The project highlights hygroscopic, doubly-curved, shape change apertures capable of autonomous climate-adaptive kinematic response.

While recent research into stimulus-responsive materials (SRM), such as timber composites (Wood et al., 2016), bimetals (Sung, 2008) and multi-material composites (Tibbits, 2013), have had to rely primarily on multiple fabrication steps in order to assemble structures capable of double curvature shape deformations, the presented research can build custom directional deformation within a single fabrication process. Moreover, unlike Poly-Jet matrix approaches to SRM, the presented FFF method, using fibrous fillers, enables anisotropic properties through the deposition and the make-up of the material itself. The project showcases a methodology that couples a design-oriented and computationally enabled method that integrates 3D printing via FFF, custom SRM composite polymers and bio-inspired material syntax strategies. The project highlights precise kinematic geometric deformation with multi-directional curvature made possible via a precise understanding and negotiation of the material properties and behaviours inherent to the FFF process. Variations on material properties through the development of a custom polymer composite provide an outlook into the capacity to programme differentiated kinematic response times and material performances for bespoke applications. The research builds upon over seven years of previous work by the authors into hygroscopic actuators using wood composites and bio-inspired 3D printed architectures, furthering this research by transferring and expanding the functional principles and material intelligence of these mechanisms.

Double curvature as a functional principle

The primary research question for this project concerned the integration of double curvature as a functional...
principle into the development of a multi-hierarchical system architecture. Previous research by the authors for 3D printed SRM presented reliable shape change actuation with single curvature deformations using wood fibre composites (Correa et al., 2015). Early tests highlighted that enabling shape change curvature direction could be further directed into controlled twisting angles through the differences in the dominant angle of deformation orientation of each layer (Fig. 2) [Correa et al., 2015]. Similar to previously developed woven composite laylours (Reichert, Menges & Correa, 2013) or hygroplastics (Eli et al., 2013), varying the angle of deposition can enable twisting of the sample through global manipulation of the composite architecture. That is, the changes in material orientation apply homogeneously across the whole sample. The key principle that allows SRM composites to shape change is the ability to direct small expansion forces from the SRM material over a non-SRM substrate. Therefore single curvature shape change deformations are most effective when all expansion forces are directed along a single axis. To achieve double curvature, it is therefore necessary to further expand the understanding of these principles by investigating material organisation methods and composite architectures that can negotiate the interaction of expansion forces in multiple directions. For the presented project, the development of an architectural aperture capable of double curvature shape change was selected as the medium to investigate multi-component interaction and mechanism scale.

New insights through collaboration

Using a customised additive manufacturing process, the double curvature in the hygroscopic-responsive SRM flap is achieved in a single step. Fabrication of the complete multi-aperture assembly involves two steps: first, the printing of the SRM flaps with the fastening support attachment; and second, the printing of the non-responsive understructure that positions the flaps into apertures. Research into two-stage, double-curved pin scale actuation, in collaboration with the Fluid Biomechanics Group at the University of Freiburg provided novel insight into the kinematics and functional material differentiation that allows double-curved shape change in pin scales (Poppings et al., 2021). This functional principle of double curvature actuation was abstracted into a double-curved flap component with two integrated curling axes. Consequently for each individual flap, the performance goal is to have a dominant and a secondary curling axis. The primary axis is responsible for the opening of the aperture, while the secondary axis facilitates the lateral expansion and the resulting double-curved shape. As the flaps are configured concentrically within the aperture, their lateral interaction is facilitated by this secondary double curvature deformation. In this design, the double curvature deformation allows for the aperture to form a segmented dome geometry while in the opening state the flaps push each other further into the open position, enabling a wider aperture diameter. Moreover, the flap actuation within the aperture is further supported by a secondary functional region located at the base/stem. This region is hot only responsible for the fastening of the flap to the aperture understructure and also designed to have a single curvature shape change along the dominant curling axis. For the hygroscopic shape change actuation, the composite architecture of the flap is constituted of a hygroscopic SRM material and a secondary constraint material, which has negligible hygroscopic expansion characteristics. While several FE plastics with a limited moisture expansion coefficient can be used, acrylonitrile butadiene styrene (ABS) filament was selected in order to facilitate fast bounding of the flaps to the aperture understructure. For the hygroscopic SRM material, two materials were tested: commercially available wood composite polymer (WCP) filament and a custom developed cellulose composite polymer (CCP). Both materials make use of the shear-induced alignment of the fibres in the 3D printed flaps to define the anisotropic properties of the composite architecture. While single curvature deformation only requires a primary angle of material deposition perpendicular to the shape change axis, the presented double-curved flap mechanism must negotiate different directions of expansion and corresponding constraint. Early tests indicated that positioning two mirrored angles of deposition at 15° from the main curling axes was effective in achieving double curvature, but it achieved a limited curling angle along the primary axis. It was speculated that the central region, along the central axis, did not provide enough material alignment perpendicular to the primary axis. In this initial test, the stem region was designed to be longer in order to compensate for this limited curling angle along the primary axis (Fig. 3). While this is an effective strategy for the aperture opening, a second approach was developed that could subsequently change the deposition angle to meet both axis requirements. In this second approach, a paraboloid curve was implemented in the toolpath that allowed for the material to be deposited at 90° from the main axis, at the apex; the deposition angle then changed to meet the 15° angle for the lateral sections. This approach functionally distributed the material in relation to the desired curvature and reduced internal stresses resulting from single axes of expansion meeting at a narrow angle along the central axis. As a result, the flaps were successfully able to achieve a narrower curling shape change angle along the central axis, without compromising curvature changes on the secondary curling direction (Figs. 4 and 5). After achieving the target performance for the main functional region of the flap, the stem region was reduced in order to be more seamlessly integrated within the substructure; it therefore plays a more limited role in the overall angle of opening of the aperture. For the non-hygroscopic constraint components, the material organisation along both the primary and secondary axes followed the same corresponding functional distribution. The main constraint material beads are deposited in line (5°) with the primary curling axis, while the secondary constraint follows a 90° angle. Additionally, in order to better integrate the stem and the main flap region, a boundary edge is implemented. While the WCP provided the desired hygroscopic shape change performance for the double-curved mechanisms, a second custom SRM material was developed and tested. A cellulose composite polymer (CCP) filament was developed, using isolated cellulose filaments embedded in a proprietary co-polymer. It was of interest to test the effect that the isolated cellulose filaments had in relation to the SRM composite response time and shape change characteristics. Furthermore, using a second composite polymer with hygroscopic characteristics, we aimed to test the effectiveness of the previously developed shape change methods. The design of a bespoke composite filament allowed for the verification that the cellulose filaments that were added did not directly or indirectly affect the performance of the SRM polymer. The material differentiation of the material falls outside of the scope of this project paper, empirical tests, with both isolated single-curved samples and with the presented double curvature aperture, indicate a small increase in moisture absorption and desorption in the samples, resulting in a faster stimulus response time. However, the colour change resulting from the removal of the lignin appears to have an impact in tests using radiation from light sources. As opposed to the darker WCP samples, the
white CCP samples can reflect most wavelengths of light, resulting in reduced temperature increase. Due to the complex interaction that relative humidity, radiation and localised surface evaporation can have in moisture description, the samples have unique different performance profiles. When subjected to moisture desorption tests, the WCP samples can have a faster response time under exposure to light radiation due to their colour, while the CCP samples can be faster in low light environments with equivalent low relative humidity.

The ABS 3D printed substrates was designed to provide a support structure for a composite three scales of flap mechanisms ranging from 38 to 72mm (measured along their primary axis). The piece is composed of two halves, containing a total of 14 apertures. Small changes in angle direction allow the piece to generate a sense of enclosure while exposing each aperture to slightly different light angles.

Developing a new ‘smart’ material

Wood composite 3D printed filament enabled the application of a found material ‘wood’ into a new fabrication process, using a thermoplastic polymer to bond the particles and enable the deposition of the material in a directed and controlled matter. In other words, the method hijacks the precise deposition of the FFF 3D printer and the hygroscopic properties inherent in the material to enable the development of a new designed meta-material/‘smart’ material. By isolating cellulose, the active hygroscopic component of wood, the new custom cellulose composite highlights the possibility of selectively choosing desired performance properties. In collaboration with material science experts and industry partners, additional aesthetic or functional performance characteristics can be further integrated to meet desired applications. The integration of ‘smart’ functional material performance into a multi-hierarchical architectural system, enables closer insight into the perception of truly smart and adaptive buildings, whereby the function, material and form are intrinsically programmable to respond to and anticipate user performance needs.

In this context, it is evident that in addition to furthering research into SKM shape change architectures, more research and testing is needed for the adequate characterisation of both composite filaments and the resulting meta-material composites. The potential of FFF for form generation continues to be widely investigated, but the physical and material intrinsics resulting from the material interactions of FF layered deposition remain poorly understood. While there is substantial research into the base constituent polymers used in FF plastics, little is known about their final physical performance once they are chemically modified/optimised for FFF criteria. Current efforts are dedicated for Seams’ strength, material fatigue or UV decay will be required in order to be able to consider possible technical applications. Moreover, meta-material composites with SKM multi material architectures offer additional layers of complexity and opportunity requiring a wider scope of investigation in a multidisciplinary context (Le Duigou et al., 2016).

New directions for material intelligence

This novel approach in presenting shape-changing architectures for FFF provides new opportunities for design that can further access material intelligence through a programmable and adaptive responsive systems. The competence of architects lies in the conception of material organisation strategies that are functionally integrated through geometric and material interdependence. Reciprocity in form, structure and material differentiation require a sound conceptual understanding as a formal and material assembly, in order to implement effective and adaptive multi-hierarchical functional structures capable of performance-driven spatial differentiation. Nevertheless, the challenge for architects and designers is that while material science forms a critical component of material-orientated architectural research, it does fall outside its core field of expertise and professional scope. It is only through a truly interdisciplinary research approach that both competencies and professional expertise can yield innovative approaches and applications.

The outlook of this research presents the possibility of applying and expanding the presented FFF methods into other interactive mechanisms with additional curvature direction or the integration of synthetic and antilastic curvature changes within the material of a single piece. Additionally, material development of the composite filament offers great potential to include bespoke performance characteristics that can enable further control of the actuation response. Development of testing methodologies to evaluate feasible applications into architectural applications can foster better understanding of desired technical performance and limitations. Moreover, considerations of the lifecycle of the material systems is of particular concern; further studies into the incorporation of bio-based polymers and additives that can also be biodegradable is of critical importance for this research.

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3D metal printing is developing rapidly into a viable structural technology for architectural and sculptural projects. The benefits of 3D printing can be married with the strength of metal to achieve high performance levels. Successful implementation requires the development of new computational design and analysis tools that become integrated into the design process, as well as an understanding of metallurgical processes for controlling material properties. We have pushed forward with this on two projects: one sculptural and the other architectural. In both examples, the standard approach would have been cost-prohibitive or physically impossible. This paper covers the technical background and the detailed design process for using 3D metal printing as a structure.

There is an ongoing convergence of low-end and high-end 3D printing technology that has a far-reaching impact on the structural performance of sculptural and architectural projects. At the low end (defined here as ‘low’ structural strength and ductility), we have seen the rapid rise in accessible cost levels, so the market continues to expand in both volume and quality. At the high end, we have seen specific uses of medical and aerospace designs with an accompanying high cost of design development and production for the unique performance market; so far, this market has been limited by cost.

This is a prime time to take advantage of this current convergence, and we have developed computational approaches, designs and prints for real projects as proven examples. Below, we outline the current state of 3D printing for the AEC industry and provide details of two case studies.

A vision for 3D metal printing in the AEC industry

The upfront benefits of 3D printing (mass customisation, complexity at low/cost, reduction in assembly effort, production of forms previously not feasible, etc) are valuable to the AEC industry, in which most projects are essentially one-off unique buildings, pavilions, sculptures, etc. Uptake in the industry has been slow, as the material and design technologies have had to develop to match need.
How can these benefits be made real on AEC projects?

As stated above, there are real benefits to 3D printed structural components that are valuable to the AEC industry, including mass customisation, complexity, low/no cost, reduction in assembly effort, production of forms previously not feasible and others. We see two areas of technological development that can make the benefits of 3D metal printing real:

1. Development of integrated design tools: most structural software is focused on analysis only and is inflexible to the changing design process. For 3D printing, the generation of a form and its iterations are intrinsic to the process, so new methods and approaches are required.

2. Understanding of the metallurgical process: currently, the resulting printed metal is not identical to metal product and design standards that previously did not exist for 3D printed metal. Hence, to provide an equivalent performance, the metallurgical process and its effect on the design must be understood and interpreted accordingly.

Overall, there is no better learning than doing. We have worked on two recent projects, one sculptural and one structural, to address these issues head on and drive the technology forward.

Sculptural project: Schwerpunkt at MIT, Cambridge, Massachusetts, USA

Helmick Sculpture was commissioned to create a 3D anamorphic sculpture for MIT’s McGovern Institute for Brain Research in Cambridge, MA. The sculpture is comprised of a hundred individual neuron sculptures ranging in size from 305mm to 915mm in the longest dimension, and suspended in a three-storey atrium with viewpoints throughout the space. The individual neuron sculptures must ‘read’ from every direction, with primary views from below and the exterior entry points on main pedestrian and vehicular artery of the area known as ‘Technology Square’. The composition not only had to ‘read’ from every viewpoint, but the sculpture were simple and concerned only with ‘proof of concept’ rather than sculptural complexity. Once we began 3D modelling each of the neurons in Rhino, we realised that preserving the dynamic of the sculpture from all angles would require increasing the palette of forms. Any repeat forms, notwithstanding changes in size and orientation, became visually apparent. Over time, the creation of the culminating brain image required specific shapes from various dendrites to create a unique collection of forms from various viewpoints.

From a formal perspective, unique neuron forms, and specifically coarse dendrites, would be the clearest and most successful approach to the sculpture design, but the fabrication of a hundred unique organic forms using traditional methods was daunting. Previous Helmick sculptures with similar forms were made using bronze casting, although this still allowed for specialization and one-of-a-kind pieces without prohibitive pricing. After creating a physical suspended 1/8 scale 3D sketch of the entire sculpture in the studio, we also explored other methods such as a ‘kit of parts’ approach, but we found the number of components needed in order to achieve the appearance of individuality made the kits impractical in scale. In it we is if you produce three each of three hundred parts? It may be, but it’s certainly not an efficient or cost-effective kit.

Finally, we turned to the possibility of direct 3D printing.

3D metal printing and design

Helmick Studio has long combined digital tools – 3D laser scanning, rapid prototyping, CAD modelling – with traditional sculptural methods, but this approach created an entirely new fabrication sequence for us. Instead of starting with a hand-sculpted object and digitising it, we would start with a digital object and hand-finish it. Helmick Studio modelled each neuron individually in Rhino, and Simpson Gumpertz & Heger (SGH) expanded the same model to include both the existing structure and real-time structural analysis within the Rhino model itself. Through an iterative approach, the Helmick-SGH model combined the existing structure, the entire sculpture in the studio, we also explored other methods such as a ‘kit of parts’ approach, but we found the number of components needed in order to achieve the appearance of individuality made the kits impractical in scale. In it we is if you produce three each of three hundred parts? It may be, but it’s certainly not an efficient or cost-effective kit.

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Finally, we turned to the possibility of direct 3D printing.

3D metal printing and design

Helmick Studio has long combined digital tools – 3D laser scanning, rapid prototyping, CAD modelling – with traditional sculptural methods, but this approach created an entirely new fabrication sequence for us. Instead of starting with a hand-sculpted object and digitising it, we would start with a digital object and hand-finish it. Helmick Studio modelled each neuron individually in Rhino, and Simpson Gumpertz & Heger (SGH) expanded the same model to include both the existing structure, the entire sculpture in the studio, we also explored other methods such as a ‘kit of parts’ approach, but we found the number of components needed in order to achieve the appearance of individuality made the kits impractical in scale. In it we is if you produce three each of three hundred parts? It may be, but it’s certainly not an efficient or cost-effective kit.
4. Wind forces and stresses on simplified model
5. Defined topological optimization and finite element analysis
6. 3D images of final stainless steel print connector

4 The pieces direct printed in a bronze/Stainless steel alloy. This approach had several advantages: we maintained weight tolerances for each neuron by hollowing larger pieces and making smaller neurons solid, we made the cell bodies to dendrite connections structurally robust in a quantifiable way; we labelled each individual component in CAD for easy assembly and tracking, and we were able to fabricate a hundred unique organic sculptures at a significantly lower cost than creating the same pieces using traditional sculpture fabrication methods.

Once printed, the neurons were hand finished, assembled, primed and finally goldleafed, again by hand.

The final result is a sculpture that would not have been assembled, primed and finally goldleafed, again by hand.

This approach had several advantages: we maintained weight tolerances for each neuron by hollowing larger pieces and making smaller neurons solid; we made the cell bodies to dendrite connections structurally robust in a quantifiable way; we labelled each individual component in CAD for easy assembly and tracking; and we were able to fabricate a hundred unique organic sculptures at a significantly lower cost than creating the same pieces using traditional sculpture fabrication methods.

The SGH team focused on developing design and analytical approaches that could provide valuable insight and information on the connectors without limiting design creativity and iteration, and where the resulting designs could still be analysed to an accuracy required for refined shape-forming and printing. The team realised that the integrated and unique nature of architectural and structural requirements for these components would need addressing during the design process rather than being left to a delegated design procurement method. Although we noted above the potential cost benefit of using titanium, we chose stainless steel for the material design to provide a more direct connection to the building façade geometry as input to automatically generate a finite element analysis.

The result of this stage was a series of 3D-related forms that satisfied overall structural requirements but would need more design and analytical refinement.

Workflow 1: the ‘quick and dirty’ method. This approach followed from the above family of 3D-related forms and design discussions with the team, and allowed for design and analytical refinement. The resultant geometry from the optimisation process is ‘pixelated’ and therefore produces a rough surface finish. We imported the geometry into Rhinoceros to smooth the surface profile and clean up the mesh. We then brought the form back into ANSYS for mesh refinement and final sign-off against load capacity criteria.

3D metal printing

As proof of this approach, we selected one connector to print in stainless steel. We worked closely with Addaero Inc. of New Britain, Connecticut, during the Workflow 1 stage. The authors wish to thank Richard Merlino of Addaero Inc. for his technical advice and production of the façade connector print.

The resulting printed connector is a hollow volume with a shell thickness of only 0.05 mm optimised for architectural and structural performance. Printed at the same time as the connector were test coupons which are being used for tensile testing at our in-house machines lab to review for strength and ductility. This work is ongoing.

The technological development of metal 3D printing processes is at a rapid pace. The benefits afforded by 3D printing have significant value to the AEC industry. Our vision outlined in this paper to deploy 3D metal printed components in architectural and sculptural applications takes advantage of these benefits to remove the limits of current fabrication methods and enable new structural forms. Continued development of computational tools and materials specifically designed for these applications is best served through project experience, where a goal drives focus and drives progress forward, especially with production and performance of forms previously not feasible.

Acknowledgements

The authors wish to thank Richard Merlino of Addaero Inc. for his technical advice and production of the façade connector print.

Notes

2. 3D-printed jet engine http://hype.com/3D/3D-print world’s largest commercial jet engine using 3D-printed metal parts.
8. 3D Printing: APT (accessed 16 October 2016).
10. Stylus, Parallel Mechanisms (used with permission of creator).
11. ANSYS Workbench Mechanical Enterprise, release 17.0.
12. Rhinoceros, version 4.0.
In the past decade, robotic fabrication in the field of architecture has developed rapidly, opening up new possibilities for architecture and design. New fabrication techniques allow the utilisation of materials like fibre composites in the field of architectural construction by employing qualities of the material that were previously not feasible. However, the equipment used for material exploration in the field is often standard industrial machines, originally designed for assembly line applications, which have scale and process limitations. Introducing a new generation of mobile construction machines capable of operating onsite would allow expansion of the capabilities of currently developed fibre composite fabrication. This research proposes a multi-robot system of cooperative, mobile machines operating within the context of the surfaces of existing architectural environments: façades, walls, ceilings. Anchoring new tensile filament structures to these surfaces activates a new layer in the architectural environment, building upon and modifying it to current spatial requirements in real time (Fig. 1).

Using custom mobile robots

The presented project aims to expand the scope of robotic fabrication for filament and composite fibre architecture through the introduction of custom, cooperative mobile robots. Over the past decade, a significant body of work related to applying fibre composite materials to architecture and design without the need for elaborate moulds or formworks has been developed (Menges & Knippers, 2015). Simultaneously, advancement in mobile robotics and autonomous control have become more prominent in relation to design and fabrication through research projects (Jokic et al., 2014). Developments in technology and methodology in these fields allow this research to take things one step further, through the introduction of mobile collaborative robots for fibre composite fabrication. Mobile machines are directly matched to the unique affordances of fibre composites: lightweight properties of the material as well as the process of phase transition from soft filament to cured structure allow for low payload agile machines iteratively applying layers of fibre to create a structure.
Exploring the potential for in situ fabrication through the introduction of machines capable of operating in architectural environments would expand robotic fabrication processes beyond the constraints of the production hall. This expansion exposes the possibility of urban and interior environments as the unique framework for onsite fabrication. Multi robot systems have the potential to provide larger solution spaces and design potentials than traditional robotic fabrication. Small machines enabled with locomotion allow fabrication in environments that are not – and could not be – equipped to house industrial-scale machines. Significant conceptual differences between operating mobile and standing machines require a distinct change in all stages of fabrication and development, starting with design. In this work, new design (CAD) and manufacturing (CAM) processes are to be developed in order to fully take advantage of new hardware tools for construction.

A new approach to fibre composites in construction

Developments in mobile robotics and autonomous control systems allow for automation of various tasks in industrial and household applications (Novikov, 2015). Companies such as Amazon have implemented mobile robots for the automation of manual labour required at their warehouse facilities (d’Andrea, 2012). Complex locomotion systems are being developed in order to operate in dangerous and unreachable environments, such as earthquake sites (Zhang, 2007). Quadrupeds have replaced complex equipment in the filming industry. Surface-climbing robots are used for the maintenance of building façades (Mahajan & Patil, 2013). In the field of digital fabrication, projects like the Aerial Construction research at the Gramazio Kohler Research group of the Eidgenössische Technische Hochschule in Zurich (Mirhan, Gramazio & Kohler, 2015) demonstrate that the application of collaborative mobile machines to construction with lightweight materials is very promising.

The integration of fibre composite materials into the architectural construction process has been a focus of exploration for designers and researchers since the late 1950s. High performance of these materials has promised a revolution in construction and design possibilities. Multiple attempts at fabrication with fibre composites at a large scale, such as the Monsanto House in California in 1957 (Phillips, 2004), influenced discourse but failed to find a foothold in the construction market. Standard fabrication techniques for fibre composites imply a serial production scale which became undesirable in a “society that increasingly valued individualism” (Knippers & Menges, 2015). The necessity of creating large complex moulds for such fabricated piece made it inefficient for the fabrication of unique elements.

Today, we see a new approach to fibre composites. A body of work developed at the Institute for Computational Design (ICD) and Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart suggests a new way of building with fibre composites using industrial robots. Through iterations of research pavilions (Menges & Knippers, 2015), endless filament winding (Prado et al., 2014) and integrated framework (Vassy et al., 2015) methods have been developed. These methods embrace the quality of filament materials as objects of infinite length and introduce techniques that reduce necessary moulds down to cheap and reusable formwork through continuous winding strategies. The fabrication strategies that a robot provides allow the creation of complex geometries without requiring a solid mould.

A unique property of fibres filament material is its virtually infinite length. The material can span large and small distances, which means it can work at both local and global design scales within the same system. The latter enables its use in various contexts, including furniture, interior spaces and global architectural applications.

Tensile filament systems require anchoring to solid formwork to be stable. Using the existing surfaces of an architectural environment instead of constructing new ones would create a new layer of architectural complexity in existing habitats. An industrial arm, designed to work on a production line with car-sized objects, does not provide this level of scalability and flexibility of environment interaction.

Constructing a system for complex environments

The first stage of research focuses on conceptualizing and developing a locomotion system that would suit our research goals. As the aim is to develop a system for constructing complex shapes in three dimensional space, a simple wheeled robot would not be efficient. The system needs to provide functionality for operating in complex environments, and for converting the façades, walls and ceilings of architectural surroundings into fabrication anchor surfaces. Alongside the development of mechanical locomotion solutions, software for control and real-time process analysis are required for performance in unstructured environments.

1 Human-scale structure prototype fabricated using the system
2 Series of mobile robotic prototypes for the mobile robotic fabrication system for filament structures
3 Exploded diagram of the final robotic prototype

Images: Maria Yablonina, Institute for Computational Design, University of Stuttgart, 2015.
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Once the locomotion system is developed, additional features of the machine need to be conceptualised. How exactly does the material interact with the environment, and what functions does the machine require in order to be able to perform the interaction? A solution for transforming an existing architectural environment into a framework for a tensile structure needs to be developed: anchor points and an attachment mechanism.

A fabrication process involving multiple robotic units requires the development of an interaction system between the independent machines on both hardware and software levels. This ties directly into the way the machines are controlled. A strategy involving perception, actuation and localisation is required.

Developing and controlling the robots

The proposed hardware system consists of multiple robots that can be used in an interior environment. A wall-climbing prototype was developed to demonstrate basic locomotion functions and prototypes were developed iteratively to evolve the design into the way the machines are controlled. A strategy involving perception, actuation and localisation is required.

In order for the machines to navigate in unpredictable environments, a control system capable of localisation and real-time path correction was developed. Since mobile systems move, it is hard to predict an inability to directly relate motor movements to the actual distance travelled. A feedback loop for local vector correction is required: Visual sensors (cameras) and the control unit are positioned externally to the bodies of the robots, allowing the system to capture the whole fabrication space simultaneously by sending data and commands back to the machines. Path planning (Bencina & Pajarinen, 2005) is used to navigate three-dimensional spaces across anchor points and the material. For global navigation, an A* pathfinding algorithm (Hart, Nilsson & Raphael, 1968) is employed. Once obstacles and restricted areas are defined by the user on a localisation site map, the algorithm defines the most efficient path for the machine to move along.

A custom robotic effector was developed to efficiently attach and detach materials to anchors and pass the thread hold-in between robots. The mechanism allows the bobbin to be wrapped around slender anchor hooks. It is actuated with a single motor through a set of gears (Fig. 3). A material bobbin is mounted onto a circular rotating plate with a slit on one side. As the robot approaches an anchoring hook, the rotational element is placed into the capturing position so that the hook slots into its centre. Actuating the motor causes the bobbin to spin around the anchor, wrapping the thread around it. Each robot is equipped with a set of electromagnets that allow each of them to pass or receive the fibre bobbin to or from other robotic units.

Once the fabrication process begins, all of the robot movements are choreographed autonomously. However, a safety mechanism can be implemented. Whenever the operator spots a problem or a mistake, the system can be switched into troubleshooting mode and the robots can be operated manually from a pendant. This switch between autonomous and manual control can be made at any time during the whole process and allows smooth continuation from the previous point thereafter.

Global geometry, size and position of anchor surfaces, number of anchors and the sequence in which they are connected are defined by the user prior to fabrication.

Once the software receives the information, it computes the working space, location of the anchors and movement sequence for each robot.

Assessing the basic functions of the system

This system has been successfully tested in a scenario of interior environment fabrication process with two surface climbers spanning a simple human-scale structure made of nylon thread between two anchor surfaces (Fig. 4).

Throughout the test, the machines successfully performed locomotion, interaction and anchoring. The fabricated prototype has been designed to test basic locomotion features of the system rather than to explore design possibilities (Fig. 5). The result is a 2.5-m-long and 0.9-m-diameter double-curved hollow fibre structure capable of supporting a human. It consists of 35 layers of thread anchored at 26 anchors. The total count of loops and the total length of thread used is approximately 850m. The winding process took approximately 20 hours.

This proposed mobile robotic system is therefore successful in working with filament materials in conditions of onsite fabrication. While these machines cannot compete with industrial robots in payload and precision, they open up the possibility of building entirely new structures that would be impossible otherwise. The ability to interact with onsite environments as well as the potential for various scales of fabrication make this process extremely useful for in-situ interior and urban-scale fabrication.

Increasing the number of machines involved in the process could allow more complex multi-surface areas to be utilised, as well as increasing the speed of production. The currently existing constraint of 90° surface orientation can also be avoided through the modification of the effective base plate. Simultaneously upgrading current hardware could in turn make the system far more efficient.

The vacuum motors being utilized have a high power demand, which makes it necessary to supply power via a cable. Using more efficient vacuum motors along with powerful batteries would allow the robots to work entirely wireless and thus to move with more freedom during fabrication. Once the robots can manoeuvre between previously laid fibres without the risk of crossing, complex fibre interactions, where subsequent layers shape the previous ones into a new condition, can be achieved.
Having proven the feasibility of the proposed system, further research is required in order to achieve a more robust fabrication strategy and to explore new design and construction potentials. Further development of current design software would allow the creation of more performative fibre patterns and structural composite spaces. Embodiment tools for editing winding syntax and anchor placement would allow for planning the output to a finer degree of detail. Introducing elements such as openings, branches and space dividers would be a possible next step.

Potentially the system could occupy the external surfaces of urban environments, using building façades as formwork. The architecture that would be created would be a possible next step. Introducing syntax and anchor placement would allow for planning the output to a finer degree of detail. Introducing elements such as openings, branches and space dividers would be a possible next step.

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References


The wider aim of this research is to explore the architectural potential of additive manufacturing (AM) for prefabricating large-scale building components. It investigates the use of AM for producing building components with highly detailed and complex geometry, reducing material use and facilitating the integration of technical infrastructure.

In order to achieve this, the concept of stay-in-place 3D printed formwork is introduced. AM is employed to produce sandstone formworks for casting concrete in any shape, regardless of geometric complexity. This approach explores the synergy between the geometric flexibility of 3D printing sand formworks and the structural capacity of concrete. It allows the production of composite components with properties superior to either individual material.

This new fabrication method is demonstrated and evaluated with two large-scale 1:1 ceiling slab prototypes (Figs. 1 and 2), which are described in this paper.

Large-scale binder jetting technology in architecture

3D printing, or additive manufacturing, refers to the process of producing artefacts by successively adding material using a computer numeric control (CNC) system. A digital 3D model of an artefact is created and sliced along a vertical axis. The data about each slice is then translated and fed to a 3D printing machine, and the machine creates the artefact by building up material layer by layer.

There are a few different types of AM technological processes. In the context of architecture, the interest lies in the AM processes that enable the production of large artefacts onsite and prefabricated components offshore. This research focuses on binder jetting for prefabrication (Fig. 3). Binder jetting is an AM process in which a liquid bonding agent is selectively dropped on thin layers of powder material to bind it.

Several characteristics of binder jetting make it interesting for prefabrication in architecture. Due to the nature of the process, binder jetting can theoretically...
be used with any powder material that can be bonded (cement, plaster, ceramic, metals, sand, sugar, plaster, etc; Rael & San Fratello, 2011). Moreover, this process has the advantage that, within a set bounding box, increasing geometric complexity results neither in longer production time nor in higher cost. Complex castable/wearing forms and even interior structures can be 3D printed without auxiliary support, because the powder bed itself performs this function. Lastly, there are a number of larger-scale facilities that use binder jetting technology to produce large-scale artefacts. An example is the D-shape system designed by Enrico Dini (Dini, 2009). This is one of the largest 3D printers in the world, but unfortunately this system only reaches a limited resolution. This resolution depends on the grain size of the powder, the layer height and the resolution of the print head. In contrast, there are industrial 3D sand printers that can produce parts that are both large and highly detailed. Currently, they are used by the foundry industry to produce moulds for metal casting. These moulds can be printed at a very high resolution, in the range of a tenth of a millimetre, and at a maximum volume of 8m³.

The project Digital Grotesque by Dillesburger and Hausamyer (2012) demonstrated the potential of 3D printing sand for the fabrication of highly detailed, freeform components in architecture, yet the use of 3D sand printing in architecture has barely begun to reach its potential. One reason for this is that large-scale 3D printed sand parts are too weak to operate as a building material - the bending strength of 3D printed sandstone is very low. As a result, the current applications are limited to building components which are mostly under compression.

The advantages of 3D printed sandstone

The central question of this research is how to use the unique advantages of 3D printed sandstone and overcome its limitations in order to enable the fabrication of large-scale building components. The research introduces and examines the concept of stay-in-place 3D printed formwork and the performance and efficiency (functional, structural, material) of the resulting load-bearing building components are investigated.

• How do concrete and 3D printed sandstone interfaces?

To answer this question, the fabrication constraints of 3D printed formwork and the performance and efficiency (functional, structural, material) of the resulting load-bearing building components are investigated.

• What is the impact of this new fabrication process and geometric freedom on the design of architectural components?

One reason to search for new ways to fabricate complex forms with lower constraints is that doing so allows us to reduce material use through the optimised design of components. Well-thickness can be adapted and undercuts, microstructures and complex branching topologies can be fabricated. With its excellent geometric flexibility - recesses, undercuts, internal voids and tubular structures are possible – 3D printed sandstone formwork lends itself well to the production of such complex architectural elements. The main means of demonstrating the feasibility of this construction method in this research is the production of two large-scale 3.1 m² prototypes.

The two prototypes investigated forms which were found by computational strategies (e.g. topology optimisation).

The target objective of the optimisation was to reduce material use and efficiently distribute the remaining material in order to maximise the slab’s strength.

Prototype A (Figs. 1 and 5) is a slab designed for a load case with three supports in the centre. This slab folds into a hierarchy of ribs that give stability to the large cantilevering areas. Prototype B addresses a load case of four peripheral support points (Fig. 2 and 4). It features a sophisticated topology of tubular elements branching in three dimensions. The amount of concrete contained within (50 litres) corresponds to a solid slab a mere 3 cm thick.

To produce the large prototypes, the following steps were taken:

• Compression and bending tests of combinations of different types of powders and binders.
• Structural tests of different concrete mixtures considered for potential combination with sand-print.
• Rheology studies of casting concrete in sand-printed formworks of different geometries to derive a formal workflow as a design guideline (Fig. 6).
• Exploration of various computational design strategies to optimise the use of the chosen fabrication method with respect to the structural limitations of the material.

Because its main use is casting moulds for metal, relatively little was known about the structural properties of 3D printed sandstone. A series of tests was therefore initiated to measure its resistance to compression and bending forces. The tests showed that 3D printed sandstone has reasonably good resistance to compression, but is brittle when exposed to bending forces. Below is the list of parameters involved in the compression and bending tests:

Parameters of the compression tests:

- Size of the specimens: 50 x 50 x 50 mm.
- Binders used: phenolic and furanic resin,
- Spatial orientation in the printer bed: X, Y and Z.
- Number of specimens per combination: 3.
- Total number of specimens: 36.

Parameters of the bending tests:

- Size of the specimens: 50 x 50 x 50 mm.
- Three-point bending, supports at 200 mm distance, central point load.
- Same binders, orientation and number of specimens as the compression tests (36 specimens in total).

The compression and bending tests were also applied for parts with different types and binders - as the table on page 215 shows, the difference between binder types is only marginal, apart from the bending strength of unbonded parts. This is because the sand is less densified during printing, and heat curing vaporises more of the liquid. As a result, more resin infiltrates the part. As expected, additional binderhardening has a significant and increases its strength.

The behaviour of 3D printed sandstone in combination with ultra high performance fibre reinforced concrete (UHPFRC) was investigated in partnership with the
Develop a concrete recipe with adequate admixtures that has the desired rheological properties.

Adjust the length and content of the steel fibre reinforcement to achieve ductile behaviour while maintaining the ability to cast in narrow channels.

Understand the impact of the porosity and sorptivity of the 3D printed sandstone formwork (how do the capillary absorption and transmission of water of the 3D printed sandstone influence the hardening of the concrete?).

Mechanically test the bond between the two materials as a composite.

The details and results of the study are documented in ‘3D Sand-Printed High Performance Fibre-Reinforced Concrete Hybrid Structures’ (Stutz, Montague de Taisne, 2016).

From a design perspective, an important finding of this thesis project is a series of formal guidelines. According to these, cavities and tubular structures in the formwork can be dimensioned in relation to both the length and the volumetric content of the fibres in the concrete mixture. These guidelines informed the design of the two prototypes in terms of dimensioning and controlling rheological aspects with regard to the concrete casting process. Moreover, both prototypes exploit the entire size (180 x 100cm) of the Ex-One S-MAX 3D printer bed.

Production of formworks with a high degree of detailing and precise geometric features for large concrete components is very challenging – and sometimes impossible – if using other formwork fabrication methods such as robotic wire-cutting, 3- and 5-axis CNC milling and fabric formworks. The described 1:1 slab prototypes show how 3D printing can facilitate the fabrication of such formworks.

3D printing is particularly suitable for producing stay-in-place formwork. This is because the bond between the sandstone formwork and the UHPFRC is very durable. Mechanically removing a 9mm-thick layer of 3D printed sand completely requires pressures greater than 3,000 atm with a water jet. Removable temporary formwork is possible (and was successfully tested in another project) but requires a coating treatment of the formwork which closes the pores to prevent the concrete from percolating through the sandstone formwork. The geometry of the formwork and the minimum dimensions of its hollow features were dictated by the constraints of the fabrication processes, post-processing of the 3D printed formwork and the rheological properties of the concrete mix.

Parameters related to 3D printing sand

The post-processing involved removing loose sand from and infiltrating the outer surface of 3D printed formworks. Thus the geometry and diameter of the hollow features had to be designed in such a way as to facilitate removal of the loose sand (Fig. 6). The thinness of the 3D printed formwork as it relates to the fabrication process was also studied. This dimension was tested from 6 to 10mm, and thinner walls were found to be unstable during the removal of loose sand (due to erosion from compressed air jets or vacuuming) as well as during casting (as hydrostatic pressure built up in deeper channels and penetrated the thin formwork walls). At 1.8m², the overall size of the components also approached a limit in terms of both the manipulation of the formwork and the stability of the 3D printed piece. While smaller parts can increase the complexity of the assembly, they are easier to handle. Therefore, the dimensioning of the parts is always a trade-off between weight, number of connections and logistical factors.

The tests revealed the fact that the friable nature of the 3D printed sandstone needs to be carefully considered, especially when scaling up the manufacturing process and fabricating components in larger volumes.
to avoiding damaging the formwork before casting by integrating a protective layer of unbonded sand contained within a closed 3D printed box that also provided auxiliary support during casting was successfully tested (Fig. 9).

Parameters related to concrete
The specific post-processing operations of the 3D printed parts (i.e. vacuuming loose sand, infill of the outer surface of the formwork) and the rheological properties of concrete dictate minimum dimensions for the hollow features. UHPFRC mixes work well with 3D printed channels with diameters as low as 20mm and bending radii of 10mm. For features below these minimum dimensions, the stay-in-place sandstone formwork can take the role of an ornamental exposed surface that does not necessarily transfer all the details to the cast concrete inside.

A full complement of structural tests is scheduled for the next stage of the research, but the empirical tests performed so far by applying a 2,500KN/m² distributed load on a concrete component with an average concrete thickness of 100mm were encouraging. The indication is that material savings of up to 70 percent are achievable.

Successful printing of composite building components
- The proposed method advances the idea of using 3D printing as an indirect fabrication method for producing composite building components with elaborate geometry. Potential applications are in the realm of one-of-a-kind, extremely thin or highly complex concrete structures. While further tests are necessary to conclusively quantify the advantages of this fabrication process in comparison to others, the prototypes have performed so far by applying a 2,500KN/m² distributed load on a concrete component with an average concrete thickness of 100mm were encouraging. The indication is that material savings of up to 70 percent are achievable.

Additional functionality: as a consequence of the durability of the concrete-sandstone bond, the 3D printed formwork is ideally suited to stay in place and host additional functions. Acoustic surface treatment, heat transfer-regulating geometry and detailed ornamentation are possible, as is the integration of enclosures for mechanical and electrical services. This opens up the possibility of fabricating smart, integrative building components.

Fabrication process development: up to this point, the research has relied on commercially available generic 3D printers. Nevertheless, this research hints at certain improvements to the technology that would benefit this specific application, such as new powder and binder combinations and the integration of post-processing.

Digital design tool: the findings from all the experiments are to be compiled in a computational design tool specifically dedicated to the design for indirect binder jetted fabrication. This application will incorporate relevant design constraints and optimisation procedures.

The results suggest that indirect fabrication approaches can be generalised to other types of 3D printing technologies. The solution relies on a hybrid fabrication process in which a precious material is used minimally, only where necessary, and relies on another strong material to perform structurally. Digital fabrication is used to produce a minor proportion of the final product, but has a major impact on its performance and behaviour.

Acknowledgments
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References


New developments in digital workflow

Research at ITE aims to bring computational design, digital fabrication and new materials together. The main interest in a so-called digital workflow is to develop innovative and resource-efficient building components, building systems and fabrication processes.

In past decades, we have lost structural intelligence for economic reasons; today, we mostly realise buildings of simple geometries with high-mass structural elements. By using the potential of digital planning and digital fabrication, we will in the future be able to design innovative customised structures that will be efficient economically as well as in terms of resources.

In fact, the main research focus at ITE is based on the potential of ultra-high performance concrete (UHPC) for new kinds of sustainable structures and architectures. The enormous compressive strength of this material promises a large reduction of structural material for future buildings without loss of performance, as well as the fabrication of innovative lightweight concrete structures. Conventional fabrication technologies in concrete industries do not work with this high-tech material, as geometries have to become much more complex in order to exploit this material’s potential. As concrete is a mono-material, and more importantly a complex compound system with graded properties of different components, new ways of fabrication have to be taken into consideration. Conventional casting technologies cannot be used for customised concrete structures, as they are limited to planar geometries with high element thickness. New optimised materials and developments in digital fabrication are opportunities to rethink the production and design of reinforced concrete structures. They can overcome geometrical limitations and lead to a completely new design space for the use of concrete (DBZ, 2016).

So, for instance, future load-bending effects of building elements can be taken into consideration at the planning stage and can be compensated by an individual adaptation of the element curvatures using shell effects. In the fabrication of non-standard concrete structures, currently mostly customised one-way formwork is used.
In this paper, the robotic controlled production of non-standard double-curved fibre-reinforced concrete panels by using an adaptive mould needed to be investigated further in order to create a coherent process chain of production. The described research idea deals with a lot of parameters and constraints that have to be taken into account. To automate these complex and manifold fabrication processes, they need to be divided into several process steps and tackled independently. This strategy enables a process without complex programming, the use of sensors or complex adaptation systems. In addition, the collaboration of man and machine as a key factor insures as it creates a very powerful combination, in which both machine and human can act to their strengths. The robot is unbeatable in accuracy and humans are able to make flexible decisions. This creates a completely new workflow, in which physical results may be unexpected but may also lead to a new appreciation of the process and its formal traces.

The topic of advanced moulding systems for complex concrete elements has been previously addressed in different research initiatives and projects. In this respect, we would like to mention the TailorCrete project ‘Industrial Technologies for Tailor-Made Concrete Structures’ (ETH, 2010-15), where the research team used an adaptive mould that stabilized a wax cast to create precise surface geometry and form individual concrete elements. Within this context, the team from the Amsterdam Station project in the Netherlands presented ‘Design to Installation of a Free-form Roof Cladding with a Flexible Mold – Building the Public Transport Terminal at Amsterdam Central’. The information derived from the digital model of each roof panel was projected on a metal mould to give the height values for the adaptable ribs that would individually calibrate the surface to produce the concrete roof panel. In addition, two directly related projects need to be mentioned, too – the ‘Robotic Clay Molding’ (ETH Zurich, 2012) and the ‘Prozedurale Landschaften 2’ (ETH Zurich, 2012) workshops where, together with the research team, students developed different robotically controlled methods for the surface treatment of a clay mould and sand mould for the surface treatment of concrete elements.

The next steps

How are we able to take the reference projects a step further? How is it possible to create a full process chain for the production of a double-curved fibre-reinforced concrete panel in a reusable mould? This paper investigates the interdependent relationship between production and design, in this case a coherent unit that needs to be evaluated as one. With which tools and with which specific materials are we able to produce a double-curved fibre-reinforced concrete panel in a sustainable manner with the least amount of material? The envisioned production process results from a link between the functional and structural criteria of a freestorm concrete element and its design. What does the process chain look like and what impact does it have on the architectural appearance of the final element? Is it possible to express new design ideas through technology and through the choice of specific materials? What is the impact of these factors on the final appearance? Can a production process be the driver of an overall new architectural expression?

The 4C/ITE Research Pavilion 2012 team at Achim Menges and Jan Knipperhaus at Arnhem Station project in the Netherlands presented double-curved reinforced concrete elements was developed by the research team at ITE. The method is divided into six individual steps which all involve a 6-axis robot in combination with different end effectors combined with human interactions. The base mould material is a special mixture of sand, oil and potato starch. At the beginning, a framework will be created by the robot pushing the sand compound from the centre to the edges of the sand mould. This creates a rough approximation of the desired surface. Additional sand or resulting sand heaps can be added or removed by hand. In a previous step of the process chain, the deviations of the actual surface and the planned surface were tested. In the next phase, a 3D camera scans the sand surface and compares the data with the digital model of the planned surface. By evaluating the areas with too much sand and the areas with not enough sand, the geometry can be iteratively corrected and the sand compound placed in the exact shape required. By scooping from the low to high areas, a rough mould is prepared. The results satisfy, but the digital process was too complicated and therefore too time-consuming in comparison with the manual workflow.

After this first rearranging of the sand compound is finished, a pneumatic cylinder connected to the robot is developed to stamp the surface and compress the sand mixture. Depending on the tool head and the surface curvature, the tool prints a so-called digital pattern into the mould which can be adjusted by the frequency of the up-and-down movement of the tool, the robot movement speed and the angle of the end effector according to the surface. The pneumatic cylinder minimizes the robot movement and adds a significant amount of speed to the process. In preliminary tests, the cylinder acted as an independent tool and performed its up-and-down movement without being coordinated to the robot's movement. Later, the movement of the cylinder and the robot were connected so that the robot stopped for a second whenever the cylinder compressed the sand. This helped to create a more accurate surface finish by not scooping sand with the extended tool.

This fabrication technology is very cost-intensive and slow and produces a lot of waste, while the reinforcement process is very complex and produced elements are limited to a large material thickness. This paper presents a method to build up customised double-curved fibre-reinforced concrete panels in a very short time without creating any waste of formwork material. The process is sequenced in several fabrication steps and involves a robot for human-machine interaction (HMI). The method is still in its testing phase, but the present results already show significant potential with regard to conventional casting techniques.

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Whenever the curvature was getting too strong, the meshes were not flexible enough to adapt to curvature or complex geometries. This method was only successfully applied to planar geometries because the meshes were not flexible enough to adapt to curvature or complex geometries. Whenever the curvature was getting too strong, the meshes were folded back into planar mode and could not reinforce the concrete in the right location. Alternative prefabrication strategies of double-curved reinforcement were tested in an earlier DFB-studio, described in the IASS 2016 paper “DFB-studio - Evaluation and Development of Research Topics through the Application of Advanced Fabrication Technologies” (ITE, 2016).

The newly developed method shows a lot of potential for placing the fibres, especially for double-curved surfaces which allow the fibres to stay exactly in place where they need to be (Fig. 5). One of the main benefits of this method is that it can be used as a material and aesthetic expression of the design of the surface appearance, as a result of a highly optimised fabrication process. Similar to growth processes in nature, these fabrication constraints becomes itself a new kind of architectural expression. One can’t be done without the other. Fabrication and form have to be in balance. Design processes and production methods need to be specifically designed for the material and the manufacturing process. The newly developed method shows a lot of potential for placing the fibres, especially for double-curved surfaces which allow the fibres to stay exactly in place where they need to be (Fig. 5). One of the main benefits of this method is that it can be used as a material and aesthetic expression of the design of the surface appearance, as a result of a highly optimised fabrication process. Similar to growth processes in nature, these fabrication constraints becomes itself a new kind of architectural expression. One can’t be done without the other. Fabrication and form have to be in balance.

Moving forward

The latest DFB-studio combined the experience of the 2014 and 2015 teams working with HMI robots (IASS 2016, DFB-studio - Evaluation and Development of Research Topics through the Application of Advanced Fabrication Technologies) to create thin, structurally optimised concrete elements. The goal was to build a complete structure out of several-unique-fibre-reinforced concrete sheets (Figs. 1 and 7). The shingle design consists of four surfaces: two trepanned, and two rhombuses on the side. The trepanned is twisted (double-curved) in contrast to the rhombuses, which are designed to always form a planar surface. The planar surfaces overlap with the neighbouring planar surface. Due to the convex-concave relationship, this setting forms an interlocking element between the shingles.

To keep the elements positioned in a longitudinal direction, every single piece needed to have an additional nose, allowing the detail of a classic roof shingle. In order to create the shingle nose, two methods were tested. The first one was to remove sand from the mould on the desired edge and compress the gap in the mould again.

The cavity could then be filled with concrete and worked as an additionally moulded form added to the shingle in the form of an extended nose. The second method was the result of the casting process. By scooping leftover mortar from the proppin rim started to pulp up against the mould edge. By applying extra material and programming an extra offset to the edge, the nose of the shingle was created without any extra mould.

The idea of the mockup was to evaluate the full potential of this method and to explore its limits with students. By producing the shingles either with the front side in the sand or the back side in the sand, both processes (casting and filling and bilining) could be displayed, showing their individual formal expressions and aesthetic value (Fig. 4).

With a well-connected production chain, 64 individual concrete elements were produced within 60 days. The results were quite convincing, although there is still a lot of potential to improve the method. It allowed us to produce a wide range of geometrical possibilities. Double-curved, single-curved and planar elements with concave and convex sections in a continuous thickness could be produced and could even be very flat and fine-tuned according to the structural needs of each single piece. Reviewing the results of the mockup shingles and study objects produced earlier shows the potential of the process. Compared to earlier investigations with more curvature, the shingle geometry does not differ enough from an actual planar surface and therefore the process traces appear like an irritation on an almost even surface rather than a tolerated process trace. Either this can be optimised in further post-production steps, or the nature of the surface has to be integrated in a more integrated part of the design process and the process logic to form the optimal geometry in terms of stiffness, material behaviour and production method.

New steps for the production chain

The promising results of the latest mock-up encourage the transfer of the production chains to the new Digital Building Fablab, a collaborative laboratory (DBFL) which was introduced at the beginning of 2017 by the ITE. A scaling process to a 1:5 prototype robot with a full automation of the process. The previously tested production steps, such as the 3D scanning of the surface, could become valuable additional functions of this design chain. An optimised fill-in height could result in an improvement of production speed and improved accuracy of the concrete elements. An important issue will be the surface finish. Integrating the design of the surface appearance, as a result of a flexible process and production technique, will lead to new perceptions of the material and its manufacturing and will give the designer a layer expression.

Traditional moulding techniques in concrete industries have led us to a limited and complicated geometry. They have been optimised to perfectly replicate the design of formal architecture via top-down processes and to find a compromise between design and structural properties. By reaching the limits of material properties for conventional and sustainable production with the new fabrication methods, as described here, the digital workflow from the early design stages to final shapes has to be expanded. As the optimisation processes of building elements in the fabrication stage have reached a big impact on the final design, and also because architectural design ideas could not directly lead to a final building shape, recursive feedback loops have to be established in the design process. Similar to growth processes in nature, highly optimised fabrication processes in architecture as a genotype lead to a unique phenotypical shape. Following up these bottom-up principle aesthetics from these fabrication constraints forms a new kind of architectural expression. One can’t be done without the other. Fabrication and form have to be in balance.
Novel design and fabrication strategies

Ongoing research conducted at the University of Stuttgart is focused on material-efficient construction through the development of novel design and fabrication strategies for fibre composite lightweight construction systems. In a long-term, bottom-up development across multiple demonstrator projects, the underlying structural principles of fibrous lightweight structures in nature have been investigated in interdisciplinary collaboration with biologists, leading to the development of building technological advancements which allow the transfer of biological lightweight construction principles into technical fibre composite structures (Menges, 2015, Dörstelmann, 2015a, Van de Kamp, 2015). A series of prototypical demonstrator projects have showcased a higher degree of material efficiency and functional integration than current building methods.

The presented project continues this line of research in a site-specific installation at the Victoria and Albert Museum in London. The project aims to further develop the previously prototypically tested processes at a larger

EL YTRA FILAMENT PAVILION
ROBOTIC FILAMENT WINDING
FOR STRUCTURAL COMPOSITE BUILDING SYSTEMS

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scale, with additional functional capacities being embedded and ultimately constituting a fibrous building system that is suitable for niche applications. Developments in robotic fabrication methods, embedding of sensory systems into the fibre composite building parts, integration of construction detailing and interfacial design should be feasible within building systems such as façade and ground anchoring, structural simulation methods, reconfiguration and expansion capacity based on a sensor-informed learning system in combination with a local fabrication setup. The focus of the presented paper is the advancements in robotic fabrication methods for bespoke fibre composite parts.

Fibrous composites are versatile and structurally performative materials, useful for many architectural applications. They have been utilised in many performances, useful for many architectural applications. They have been utilised in many constructions (LeGault, 2014). Early experiments with hand-laid fibres that can be automated for speed and efficiency in industrial production (Peters, 2011). Fibre orientations can be controlled, which makes this process more adaptable to the structural requirements and changing boundary conditions of architectural projects. While the previously mentioned fabrication process was capable of a high degree of morphologic freedom (useful when creating geometrically specific structures or expanding the design potential of the system), for smaller applications this process could be refined to reduce complexity and increase fabrication efficiency. While the Edinburgh Filament Pavilion proposed an adaptive, reconfigurable construction set with structural components that could be rearranged or grown into various configurations, this resulted in a refined edge condition for each component, making a reconfigurable frame unnecessary while still allowing for unique, individualised geometries and fibre arrangements to be created. More research interest was placed on the refinement of the fabrication scenario and the performative component geometries suitable for this design implementation.

The development of a versatile fibrous building system requires further consideration in several areas beyond that of morphological freedom. First, to show its applicability as an architectural system, it must be used at a larger architectural scale. More specifically, in the case of the Edinburgh Filament Pavilion, the scale required longer spans and cantilevers to test the use of the structural system in various scenarios. Furthermore, beyond purely structural considerations, a fibrous building system should be able to integrate, incorporate or interface with other building systems such as the roof enclosure, wall façade construction, floor or foundation, which are important preconditions for wider application in the building industry.

The development of integrated design, engineering and fabrication methods that allow the harnessing of the material characteristics of fibrous materials for building construction while reducing the need for surface moulds (Dörstelmann, 2015, Wernet, 2013). The ICD/ITKE Research Pavilion 2013 showed the ability to make a dual-layered structural system from highly differentiated components using a ‘coreless filament winding’ system and reconfigurable winding points (Prado, 2014). This project pushed for the possibilities for morphological exploration and novel fabrication techniques.

Two synced industrial robotic arms fitted with reconfigurable frames created a highly adaptable fabrication setup, where geometric articulation and morphologic differentiation were key areas of investigation. This project showed high potential in both the developed dual-layered structural system and the coreless filament winding process.

While the key components of the pavilion building system include (from top to bottom) the malleable cladding panels, coreless wound fibre composite cores, bolted component-to-component joints, integrated lighting and sensor systems, coreless wound fibre composite columns, halved bolts supporting columns, malleable support brackets, core-enclosing membrane, core steel frame, foundation plates and bearable basement, many of these elements are common within the building industry, but as no standard interface details exist for coreless wound fibre composite components, these were developed alongside the fabrication process.

Fibre composite building system

Small-scale pavilions have historically often served as vehicles for highlighting innovation in design, material or fabrication, while research, explorations and fundamental requirements allow a focus on specific research questions. Similar past projects, such as the ICD/ITKE Research Pavilion 2012 and the ICD/ITKE Research Pavilions 2012 and 2013-14 (Knippers, 2015, Dörstelmann, 2015), were scientific demonstrators built on the campus of Stuttgart and thus did not require significant interface with other building systems. In comparison, the Edinburgh Filament Pavilion was formed from different components interrelated with multiple other material systems.

Additionally, being sited in a prominent public space, it was required to pass through the rigorous certification process required for an inhabitable architectural structure.

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Robotic fabrication process for coreless filament winding

The presented fabrication process utilized a refined custom production set-up as well as further developments in the coreless filament winding process. An 8-axis robotic set-up consisting of a 6-axis industrial robotic arm linked to a 2-axis turntable, which carries a multi-part fixed frame, was used for winding (Fig. 3). For offshore production, a custom resin bath and spool holder which could carry up to six carbon fibre spools simultaneously was utilised for higher production speeds, while for onsite production (Fig. 5), pre-impregnated fibre spools were used. A higher degree of integrated construction detailing was enabled by advancements in the robotic coreless filament winding techniques. A multi-stage winding process was developed, which relied on several phases of frame assembly and disassembly throughout the winding process in order to wind fibres in specific configurations (Fig. 4). With this technique, embedded connectors and structural spokes could be created to interface with a transparent shingled roof enclosure system. Through adaptations in the robotic fabrication process, the construction of a wide variety of component geometries with tailored structural performance is possible on a simplified winding frame. The differentiation in system morphology which would not be possible with standard FRP fabrication techniques, showcases the refinement and control of the coreless winding system. The surface curvatures and the size of the aperture could be controlled for each component. Expanding beyond simple surface topologies (embellishments of fabrication techniques requiring a mould) enabled a hierarchical organisation of volumetric form, including a global layer structure. This structural system, used in previous research, was refined to create larger diameter components with a thinner structural depth to cover more area with less volume. This made the system highly efficient, requiring less material for a larger structure.

Another evolution in the structure was the development of the closed body reinforcement at the component scale. This created two interconnected hyperbolic surfaces which enclose a complex structural volume. With traditional mould based fabrication techniques, these geometries would be impossible to manufacture unless the winding core remained in the finished piece or was sacrificed completely. At the material scale, coreless winding techniques were developed to control local fibre density and thus enable increased surface depth. This process, similar to three-dimensional weaving techniques, builds height from alternating dense fibre directions and a low-density, counter-directional stabilization layer. This refinement was further demonstrated in the variation of fibre resolution, providing more control over the structural filigree.

Improved manufacturing efficiency

The refined fabrication process allowed for highly efficient production of unique roof and column components. Optimised winding times range from 4 to 9 hours per component, which were then cured and tempered overnight before being removed from the reusable winding frame. The process was highly automated and could be performed with a single robotic operator. Material handling, resin mixing and frame assembly are still manual processes in this scenario, though using industrial solutions for these could further improve manufacturing efficiency.

The Elytra Filament Pavilion cells are formed from a mix of unidirectional carbon and glass fibres roving to tailor structural efficiency. The stiffer carbon fibres provide the primary load paths within the cells, while the glass fibres create the required geometry, distributes load and stabilizes the carbon fibres. The flexibility of the fabrication setup enables variation of the cell aperture size, changing the resulting performance of the structure. A small aperture uses more material in the top and bottom surfaces of the component, resulting in a heavier but stiffer element (Fig. 5). The cell’s corners, which include connection points to its neighbours, then receive a variation in carbon material quantity based on the amount of load to be supported, with higher forces requiring greater localised stiffness and strength.

In certain critical parts of the structure, the whole cell is reinforced with a layer of carbon fibres to provide improved load transfer and strength. These strongest cells are capable of supporting a load of up to 250kg in a catenary loading condition. In earlier cellular prototypes, the free edges arising from this base geometry were susceptible to buckling issues, but this was eliminated in the final demonstrator through the closed outer body reinforcement mentioned previously (Fig. 4). The pavilion cells are therefore torsion-like beams that, when joined, create a continuous double-layer shell without free edges but with significant shear connectivity (Figs. 1 and 7). Apart from geometric variation, the additive nature of coreless filament winding allows for a highly efficient use of the raw material.
of material, placing fibres of different types only where they may be best used. With the possible variations in cell geometry and parameter known, a computational tool was developed to determine material placement, balancing stiffness and local distribution across the structure while achieving deflection limits (Fig. 5).

The project uses the integrative capacity of fibrous building systems to embed a sensor system that monitors weather and local conditions while achieving deflection limits (Fig. 5). In combination with an onsite fabrication set-up, the project showcases the potential of fibrous lightweight structures to become responsive learning systems that expand and reconfigure as expanding structures and space.

Fibre optical sensors allowed for the monitoring of internal stress states of the composite structure, while thermal imaging enabled the gathering of anonymous statistics of viscous utilisation of the composite. Local weather data and climate simulation processes allowed predictions of local microclimatic conditions. Interpreting these data sets’ interrelations allowed for reactive or proactive expansion and reconfiguration behaviours of the canopy and deriving of the respective fibre layout and fabrication data for new components. During the run of the exhibition, new components were produced at specific onsite fabrication events. The onsite fabrication set-up utilised the compactness of industrial robot arms and the fibre composite materials. After assessing the structural capacity of the global system and local loading conditions, the new components were produced with even more material, continuing to push the boundaries of lightweight construction throughout the ongoing research process. The produced components were added during onsite reconfiguration events, resulting in two cantilevers reaching out by 5.5m and 6m from the next support, highlighting the structural performance of the implemented fibre composite building system.

The Elytra Filament Pavilion was installed in the John Madeley Gardens at the Victoria and Albert Museum in London in May 2016. In its starting configuration, the fibrous canopy was constructed from 40 differentiated roof components resting on seven columns. It covered an area of 200m², which was extended to 220m² during the exhibition run. The fibre composite structure weighs only 35kg/m², while the entire canopy weighs 2.5 tonnes. This project showcases the future potential of fibrous building systems and how integrated design, engineering and fabrication strategies allow for simultaneous advancements in building technology and building culture.

Future fabrication scenarios

Future research will focus on the upscaling of building parts while maintaining the level of detail and resolution in design and local distribution across the structure while achieving deflection limits (Fig. 5). The project uses the integrative capacity of fibrous building systems to embed a sensor system that monitors weather and local conditions while achieving deflection limits (Fig. 5). In combination with an onsite fabrication set-up, the project showcases the potential of fibrous lightweight structures to become responsive learning systems that expand and reconfigure as expanding structures and space.

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Computational design commonly focuses on the synchronisation of advanced manufacturing technology and material behaviour. This allows for technical specificity, or instrumentalisation, to be achieved in material, structural and architectural performance. The research discussed in this paper extends such a material-based practice by utilising aspects of sensorial experience to drive the design and engineering of material performance and architectural responsiveness. This is explored as part of the Social Sensory Architectures research project, through the articulation of textile hybrid structures and their application to the development of skills in motor control and social interaction for children with autism spectrum disorder (ASD). The research is developed at the University of Michigan, through a collaboration between the Taubman College of Architecture and Urban Planning, the Department of Psychiatry and the School of Kinesiology. This alignment of disciplines integrates material research with methodologies for assessment of social function and kinesthetic activity.

This interdisciplinary research is described, in this paper, through the development of the sensorial PLAYSCAPE prototype. The prototype, as a malleable multi-sensory architecture, seeks to unravel associations between deficiencies in motor planning and processing of sensory stimuli with limitations in social function for children with autism. Defined as a spectrum disorder, a hallmark of autism is the highly unique and specific sensory and behavioural issues related to each individual. This is captured in the commonly used phrase “when you’ve met one person with autism, you’ve met one person with autism.” Accordingly, a significant criterion for the prototype is to enable the child to instrumentalise the sensorial experience of the architecture to suit their particular preferences. The intentions are to develop skills in motor planning that will assist social functioning through collaborative play. Navigating through the tactile architecture simultaneously reinforces such physiological and social activities through the sensorial adaptability of the architecture.
This research concentrates on tailoring the hierarchical relationships between the various multimodal sensations triggered via the interactive textile hybrid environment. Tactile, visual and auditory stimuli are activated through physical deformation of textile surfaces and movement through the intricate spatial arrangements of the playscape prototype (Fig. 3). This requires the priority of the textile hybrid system to move beyond spatially resolving the stresses of internal material behaviour and structural forces, where minimal load-bearing reserves remain. Through advancements in the use of CNC knitting of the textile, structural interface and laminate of bending-active glass fibre-reinforced (GFRP) beams, the highly variable and dynamic loads incurred as a structural landscape for play are enabled.

**Nexus of movement and social function**

Autism is a neurological disorder affecting 1 in 68 children and involving global impairments in communication, social interaction and the regulation of physical and emotional behaviour (Baas, 2014). An underlying yet prevalent factor is the difficulty to receive, sort and integrate sensory information related to social and environmental stimuli (Spalding & Brady, 1999). Such ineffective means for integrating sensory information prevents the learning of adaptive, generalised behaviours and coordinated movement. Such ineffective means for integrating sensory information related to social and environmental stimuli (Spradlin & Brady, 1999).

Specifically, atypical tactile sensory processing is often a characteristic in children with autism (Koegel et al., 2001). The development of fine and gross motor skills are also commonplace, hindering fine motor skills for grading of movement, the ability to assess and execute the appropriate amount of pressure needed to complete a task. Yarn, variegated stitch structure and the calibration of tactile forces generate an increasingly more tactile feedback as one pushes on the textile surfaces to greater depths (Fig. 3). Another level of engagement corresponds to movement of the body through space and time, the proprioceptive and vestibular senses that guide movement and posture. The calibration of the pre-stressed textiles, laminated GFRP beams and spatial arrangement generates the combined experience of localised pressure at different positions and minimised (though recognisable) deflection at the scale of the entire material system (Fig. 3). Elasticity is tailored to satisfy deeper sensations of touch and register fine and gross movements. Correlation with the visual and auditory landscapes fosters continued variability and saliency.

**Textile hybrid sensoryPLAYSCAPE prototype**

A hybrid structure denotes a system which integrates more than one foundation (Cascio, 2010). The textile hybrid incorporates tactile form-active textile surfaces and boundary elements stiffened through their configuration into curved bending active geometries to generate a structural form (Lienhard et al., 2012). Specifically, through this research at the University of Michigan, the hybrid system is uniquely comprised of seamless CNC-knitted textiles and bending active GFRP rods laminated into curved structural beams (Ahlquist, 2013) (Fig. 4). In the design, engineering and manufacturing of the playscape prototype, the topologies of the textile architecture and rod configurations are articulated through simulation in the Java-based springFORM software (Ahlquist et al., 2014). Bending-active laminated GFRP beams

The active bending of the GFRP rods in a textile hybrid serves to maximise stiffness and simultaneously activate tension in the integrated textile surfaces. Traditionally, the relationship between the GFRP rod cross-section and desired stiffness is designed solely to satisfy a target geometry. Unfortunately, this leaves little in structural results for bending active geometries to be achieved when the bending active GFRP boundary is comprised of a simple rod cross-section. Cross-sections inter-connected with form-active CNC knitted textiles.

1. Study of the illuminated prototype at the HandsOn PLAYSCAPE at the University of Michigan, the McClean Event for Children with autism. Image: Sean Ahlquist, University of Michigan.
2. Projected photograph and a photograph of spatial configurations of the textile interface with the multi-scale multi-sensory roles of the prototype. Image: Sean Ahlquist, University of Michigan.
3. Direct COLSOF interface development tool generates colour based on the location and amount of pressure applied to the tactile textile system.
In response, GFRP rods are strategically bundled and laminated in their bending-active state to form curved beams with clean-stiff connections. A critical advantage is gained in geometric freedom, where individual rods of minimal cross-section can be used to accomplish a wide range of radii, and in structural stiffness, where, once laminated, strength is increased by a factor of 10.

The overall textile architecture is dictated through extrapolating geometry and relative force calculations from the springFORM model in comparison to knitted 1:1 textiles swatches. The knitted swatches utilize a multi-topology yarn with an alternating tuck-tuck-stitch structure knitted on every other needle (referred to as one-by-one) of a 14 gauge CNC knitting machine. The primary method of extrapolation is approximate, as the stitch structure is developed in the final textile via shaping of the overall form and manipulating the stitch length, in order to accomplish certain conditions such as achieving maximal stretch to fit across the joints in comparison to the structure. The performance of the tensioned textile surface is defined primarily by providing a high degree of adaptability, which is achieved in the textile interface. Yet this is still in balance with its service to the textile hybrid system, where the CNC-knitted textiles improve the overall structural stiffness by approximately 15 percent.

The method of sensing functions as a standalone algorithm outputting data for location and depth of interaction with the textile surface. The system is utilised for a lower resolution chassis to track interactions on a two-dimensional surface.

To embed visual and auditory interactivity, the prototype in combination with the various software modes for multi-sensory feedback. Through an ongoing pilot study with the Spectrum Therapy Center in Ann Arbor, the stretchCOLOR interface is utilised to attend to the development of skills for grading of movement. Where poor signalling from the somatosensory system and lack of muscle tone may contribute to diminished sensory capacity and output and analysis of diagnostics, the sensoryPLAYSCAPE provides more intimate interactions, where a quick touch distorts a free-floating school of fish, while a long touch generates an attractor for the fish to stirle around, also triggering a randomised soundscape of wind-chimes.

Therapeutic capacity of sensory architectures

Two primary skills are being addressed – motor planning and social function – through the sensoryPLAYSCAPE. Where it is branched from the bottom surface at one edge, the tubular portion is both iteratively interlocked textiles, the tubular portion is both iteratively interlocked (co-mingled elastic nylon and spandex core) yarn with an alternating tuck-tuck-stitch structure knit on every other needle (referred to as one-by-one) of a 14-gauge CNC knitting machine. The primary method of extrapolation is approximate, as the stitch structure is developed in the final textile via shaping of the overall form and manipulating the stitch length, in order to accomplish certain conditions such as achieving maximal stretch to fit across the joints in comparison to the structure. The performance of the tensioned textile surface is defined primarily by providing a high degree of adaptability, which is achieved in the textile interface. Yet this is still in balance with its service to the textile hybrid system, where the CNC-knitted textiles improve the overall structural stiffness by approximately 15 percent.
Projected colours, based on depth of touch, and resistance.

The social component of this research is assessed by Dr. Richard Solomon and focused on modes of play emerging through the child’s own unique physiological experience, an understanding of motor planning and sensory processing capabilities. Data are collected through the software, capturing location, depth and scalar tactile qualities with modes of interaction that encourage communication and social interaction through the child’s own unique physiological experience as the primary performative constraint by which material, spatial, visual and sonic landscapes are actively and dynamically articulated its material and visual stimuli. This is generated through following an activity attractive while also providing a positive reinforcer to the child and fostering social interactions.

Acknowledgements

This research is being developed at the University of Michigan through funding from the McAgauo program for the project ‘Tactile interaction and environment for developing motor skills and social interaction in children with autism’. The principal investigator is Prof. Sean Ahlquist, Prof. Costanza Cascio, and Toddler Development for measuring motor skills and the social component of this research is assessed identifying developmental delays. The social component of this research is assessed by Dr. Richard Solomon and focused on modes of play emerging through the child’s own unique physiological experience, an understanding of motor planning and sensory processing capabilities. Data are collected through the software, capturing location, depth and scalar tactile qualities with modes of interaction that encourage communication and social interaction through the child’s own unique physiological experience as the primary performative constraint by which material, spatial, visual and sonic landscapes are actively and dynamically articulated its material and visual stimuli. This is generated through following an activity attractive while also providing a positive reinforcer to the child and fostering social interactions.

Working with the sensory experience to create new architectures

The researcher describes the foundation for an architecture that sets the sensory experience as the primary performance constraint by which material, spatial, visual and sonic landscapes are instrumentational. Yet perception of space and time, in social and environmental constraints, is largely atypical for children with autism. In response, those who engage with the architecture are given considerable agency to actively and dynamically articulate its material and immaterial natures. Performance of the prototype is defined by the measured understanding of the physiological and social human behaviours that occur within it. The manner in which the architecture is transformed communicates the individualised nature of the socio-sensory experience.

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BENDING-ACTIVE PLATES
PLANNING AND CONSTRUCTION

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Bending-active plate structures

In 2015, researchers at the University of California, Berkeley, and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart collaborated with the aim of contributing to the current research on bending-active plate structures. They placed particular emphasis on the further development of the formal and structural potential of this relatively new structural system and construction principle. In general, bending-active structures are fascinating because they take advantage of large elastic deformations as a form-giving and self-stabilizing strategy. Previous research has mainly focused on a bottom-up form-finding approach, in which typical characteristics of plates or strips were predefined first and the global shape of the structure resulted from the interaction of assembled parts. In contrast, the main emphasis of this work will be on demonstrating a possible top-down approach that is based on form-conversion.

For bending-active plate structures that implement form-conversion, the process starts with the design...
offers several benefits and opens up a larger design space than a bottom-up form-finding. However, the key challenge remains - and essentially boils down to - the question of how to assess both the global shape and the local features of the constituent parts for structures in which geometric characterization and material properties are inevitably linked together and similarly affect the result.

To demonstrate the potentials and challenges of the form-conversion approach, the authors will discuss this research method in general and show its feasibility in the planning of two built case studies in particular. Each structure explores a different aspect of this design approach. While the first case study takes advantage of translating a predefined shape into a self-supporting woven pattern, the second case study gains significant stability by translating a given form into a multi-layered shell. Finally, the means of architectural prototyping will provide proof of concept. By reflecting on how these case studies were actually constructed, the authors will give valuable insights into the opportunities and limitations of designing bending-active plate structures by form-conversion, and will hopefully spark further research in this direction.

Breakthroughs in modelling tools

In recent years, the architecture community has witnessed astonishing changes in digital design and modelling tools. With programs such as Kangaroo, Fyna, Keradec and Sopftik, new types of versatile tools have become widely accessible, enabling the creative design of highly complex geometrical models and also allowing for the integration of real-time, physics-based simulations in common CAD environments. Thus equipped, it is nowadays possible to rapidly form-find and freely interact with particle systems, or accurately analyse and optimise structures by means of the finite element method. Due to these changes, one can now describe and evaluate the mechanical behaviour and structural capacity of a model under simultaneous consideration of external forces and internal material stresses. In response to these developments, architects and engineers are rediscovering a widespread interest in structural systems in which form and function cannot easily be predicted, but result from a delicate balance between geometry, interacting forces and material properties. In this context, bending-active structures are perfectly suited to illustrate the innovative potential that physics-based simulations can have in the design process. As a relatively new typology, bending-active structures are characterised by the clever integration of large elastic deformations of initially plane building materials in order to generate geometrically complex constructions (Knippers et al., 2012). While the conventional maxim in engineering is to limit the amount of bending, this structural system promotes the opposite approach and instead harnesses material flexibility for lightweight designs. This idea is as simple as it is versatile. It can be used, for example, in a form-giving and self-stabilizing strategy in static structures, as suggested by Lienhard (2014), or be considered for the design of compliant mechanisms and kinetic structures, as shown by Schleicher (2015).

Bending-active structures can generally be divided into two main categories, which relate to the geometrical dimensions of their basic building blocks. For instance, one-dimensional systems can be built from slender rods, while two-dimensional systems employ thin plates. While extensive knowledge exists for 1D systems, with elastic gridshells as their most prominent application, plate-dominant structures have not yet received much attention and are considered more difficult to design. However, what makes this subset of bending-active structures particularly interesting is the fact that plates have a clear scale separation. They are typically very large in one dimension and progressively smaller in the other two. Their length is specified in metres, their width in centimetres and their height only in millimetres. This hierarchy makes it easier to assess the structural behaviour and accurately anticipate the plates’ deformed geometry with digital simulations. Among the most prominent examples for bending-active plate structures are Buckminster Fuller’s ‘plydomes’ or the ICD/ITKE Research Pavilion 2010. While the first example follows a rational geometry-based approach in which the shape of a sphere is approximated with a regular tiling of identical plates (Fuller, 1959, Marks, 1971), the design of the second example explores extensive structural simulations and takes advantage of computational mass customisation (Lienhard et al., 2012, Fuchsberger et al., 2012).

The design space of bending-active plate structures is limited by material formability. The only shapes that can be achieved within stress limits are those that minimise the stretching of the material. For plate-like elements, these are reduced to developable surfaces: cylinders and cones. Attempting to bend a sheet of material in two directions will result in either irreversible plastic deformations or ultimately failure. Due to these constraints, designers mostly follow a bottom-up form-finding approach, which usually starts with planar sheets and recreates the bending process digitally (Lienhard et al., 2011). By using the method of digital simulations, one can deform multiple plates and couple them to form complex structures in equilibrium. Depending on the simulation software used, this method can be very quick and interactive or particularly accurate and reliable regarding its results. The drawback of form-finding, however, is that the final shape and the caused stresses are often not known from the start. A designer will only find a certain shape in mind would therefore have to conduct multiple simulations with gradually changing parameters to approximate a target design (Fuchsberger et al., 2015).

Design space

1 Berkeley Weave installation at UC Berkeley’s College of Environmental Design (CED). The ultra-thin bending-active shell, assembled out of 3mm birch plywood, demonstrates the potential of bending-active structures.
2 Form-conversion process and analysis of Berkeley Weave.
3 Architecture students at the College of Environmental Design (CED) analysing Berkeley Weave. Image: Simon Schleicher.
The constraints related to form-finding raise the burning question of whether a radically different approach could give the designer greater control over the final shape while at the same time guaranteeing that components are only bent within permissible limits. In an earlier publication, the authors introduced a different approach and coined for it the term ‘form-conversion’ (La Magna et al., 2016). Here, the design process is top-down and begins with a predefined target surface or mesh, which is then discretised further into smaller bent tiles based on the flexibility of the plate material used. Investigating this strategy further allows for the possibility of significantly expanding the feasible design space of bending-active structures.

Multi-directional bending

The key conceptual idea behind form-conversion is to overcome the obstacle that a plate can only be bent in one direction and will not easily be forced into double curvature without stretching or plastically deforming the material. To achieve multi-directional bending, one needs to remove material strategically and thereby free the plates from the stiffening constraints of their surroundings. As a result, one would get single-curved developable surfaces with no or very little Gaussian curvature. A similar approach was presented by Xing et al. (2011) for more complicated geometries. This principle can be integrated into the subdivision of virtually any freeform surface. In order to prove this point, the authors applied this method to the design of two exemplary case studies.

The first case study that follows a form-conversion approach is called Berkeley Weave. This project considers not only the effect of bending of slender strips but also their torsion. A saddle-shaped design, based on a modified Enneper surface (Fig. 2a), was chosen because of a challenging anisotropic geometry, with locally high Gaussian curvature. The subsequent conversion into a bending-active plate structure followed several steps. The first one was to approximate the surface with a quad mesh (Fig. 2b). A curvature analysis of the resulting mesh reveals that its individual faces are not planar but double-curved (Fig. 2c). The planarity of the quads, however, is an important precondition for the later assembly process. In a second step, the mesh was transformed into a four-layered weave pattern with composed strips that feature pre-drilled holes. Here, each quad was turned into a crossing of two strips in one direction, with two other strips at a 90° angle. The resulting interwoven mesh was then optimised for planarity. However, only the regions where strips overlapped were made planar, while the mesh faces between the intersections remained curved (Fig. 2d). A second curvature analysis illustrates the procedure and shows zero Gaussian curvature at the intersections of the strips, while the connecting faces are both bent and twisted (Fig. 2e).

Specific routines in the form-conversion process guaranteed that the bent zones stayed within the permissible bending radii. In the last step, this converted shape was used to generate a fabrication model that featured all the connection details and strip subdivisions (Fig. 2f). To allow for a proper connection, bolts were only placed in the planar regions between intersecting strips. Since the strips were composed of smaller segments, it was also important to control their position in the four-layered weave and the sequence of layers. A pattern was created which guaranteed that strip segments only ended in layers 2 and 3 and were clamped in between continuous strips in layers 1 and 4. A positive side effect of this weaving strategy was that the gaps between segments were never visible and the strips appeared to be made out of one piece. The resulting challenge, however, was that each segment needed a unique length and required individual positioning of the screw holes.

The second case study called Bend9 showcases another take on form-conversion. This project is a multi-layered
permissible stress limits with respect to bending and critical areas to improve the global resistance of the building. As in the previous example, the offset of the surfaces changes along the span of the bending moment calculated from the preliminary analysis, the offsetting of the mesh to create a second layer. Analysis of the structure was conducted and informed by the shape alone, the choice of using extremely thin reinforcing to provide further load resistance. These plywood elements achieved consistent stiffness when jointed together, as the pavilion, although locked into position once it was fastened to its neighbours, still one of the best ways to quickly validate assumptions, prototyping. Constructing with the actual material is proof of concept, the authors referred to architectural prototyping. To evaluate these case studies and to demonstrate proof of concept, the authors referred to architectural prototyping. Constructing with the actual material is still one of the best ways to quickly validate assumptions, gain intuition about practical design issues and lay the foundations for future research. The first case study was constructed in the dimensions of 4m x 3.5m x 1.8m and was exhibited at various occasions at UC Berkeley. The structure was assembled from 420 geometrically different plywood strips that were fastened together with 420 bolts. The material used was 3mm thick plywood with a Young's modulus of $E_m = 16,715\,\text{N/mm}^2$ and $E_m = 1,025\,\text{N/mm}^2$. Dimensions and material specifications were employed for a finite element analysis using the software SOFiSTIK. In consideration of self-weight and stored elastic energy, the minimum bending radius in both the digital simulation and the built structure were no smaller than 0.25m and the resulting stress peaks were below 60 percent of the permissible stress limits with respect to bending and torsion. The resulting tiling logic that was used for both layers affected the size of the members and guaranteed that each component could be best into the specific shape required to construct the whole surface. More precisely, this was achieved by strategically placing voids into target positions of the master geometry ensuring that the bending process could take place without prejudice for the individual components. Although initially flat, each element underwent multi-directional bending and was locked into position once it was fastened to its neighbours. To exploit the large deformations that plywood allows for, the stiffness of the shells was increased to the minimum leading to the radical choice of employing 3mm birch plywood. Since the resulting asseems were very flexible, additional stiffness needed to be gained by giving the global shell a peculiar geometry, which transitioned from an area of positive curvature to one of negative curvature. This pronounced double curvature provides additional stiffness and helps avoid undesirable deformation of the structure. Despite the considerable strength achieved by the shape alone, the choice of using extremely thin layers of plywood at such scale necessitated additional reinforcement to provide further load resistance. These needs were met by a double-layered structure with two cross-connected shells. As in the previous example, the first step of the process was to convert the base geometry into a mesh pattern. In the next step, a preliminary analysis of the structure was conducted and informed the offsetting of the mesh to create a second layer. As the distance between the two layers varies to reflect the bending moment calculated from the preliminary analysis, the offset of the surfaces changes along the span of the arch. The offset reflects the stress state in the individual layers, and the distance between them increases in the critical areas to improve the global resistance of the system. The subsequent form-conversion process was carried out numerically by material/constrains and lay the foundations for future research. Material utilisation. The structure was assembled from the centre outwards, and during the construction process it was interesting to experience how the global stiffness increased the more elements were added and the more the structure was forced into its double-curved configuration (Fig. 3).

Similarly, the second case study was also constructed in the original scale and was shown at Autodesk's Pier 9 and at UC Berkeley. The built structure employed 196 elements unique in shape and geometry (Fig. 3). 76 square wood profiles of 4cm x 4cm were used to connect the two plywood skins (Fig. 6). Due to the varying distance between the layers, the connectors had a total of 156 exclusive compound mitres. The whole structure weighs only 10kg, a characteristic which also highlights the efficiency of the system and its potential for lightweight construction. The smooth transition and the overall complexity of the shape clearly emphasise the potential of the construction logic. Furthermore, both implemented form–conversion processes can be applied to any kind of double-curved freeform surface, not the ones presented here.

Prototype

To evaluate these case studies and to demonstrate proof of concept, the authors referred to architectural prototyping. Constructing with the actual material is still one of the best ways to quickly validate assumptions, gain intuition about practical design issues and lay the foundations for future research. Material utilisation. The structure was assembled from the centre outwards, and during the construction process it was interesting to experience how the global stiffness increased the more elements were added and the more the structure was forced into its double-curved configuration (Fig. 3).

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Feasibility for the future

The two case studies clearly illustrate the feasibility of form-conversion for the planning and construction of bending-active plate structures. Both structures are directly informed by the mechanical properties of the thin plywood sheets employed for the project. Their overall geometry is therefore the result of an accurate negotiation between the mechanical limits of the material and its deformation capabilities.

The assembly strategy devised for both prototypes drastically reduces fabrication complexity by resorting to exclusively planar components which make up the entire double-curved surfaces. Despite the large amount of individual geometries, the whole fabrication process was optimised by tightly nesting all the components to minimise material waste, flat-cut the elements and finally assemble the piece onsite. The very nature of the projects required a tight integration of design, simulation and fabrication processes can be applied to any kind of double-curved freeform surface, not the ones presented here.

For the Berkeley Weave installation, the authors would like to thank Anne Orozco, Andrei Nejur and Rex Crabb for their support. The Bend9 pavilion would not have been possible without the kind support of Autodesk’s Pier 9 and its entire staff.

References

The primary focus of this research project is the fabrication and joining of thin-walled, double-curved prefabricated concrete elements. By using a process-based approach, many different research questions were combined into one interdisciplinary project. The material technological aspects led to the search for interesting architectural uses for ultra high performance concrete (UHPC). It is extremely well-suited for thin-walled, double-curved prefabricated elements; however, use in highly efficient structures is only imaginable once appropriate joining methods have been developed.

Modern possibilities in digital design and manufacturing in combination with industrial robots raise questions about alternative shaping methods that could achieve a higher quality and efficiency in the production process of structural elements. These fundamental ideas were investigated over a period of three years by a team of architects, civil engineers, material engineers and mechatronic engineers. The result was a production process that covered every step from the first design ideas all the way to the final product.

In the last hundred years, concrete has greatly influenced building culture worldwide. Today it is one of the most used consumer goods. UHPC is unique due to its quasi non-porous structure and its high compressive strength, which ranges up to 200N/mm². Due to its material properties, it is ideal for use in light structures and structures which span large distances. The sophisticated processing of the raw materials into UHPC is very similar to that of standard precast concrete production. Joining precast elements using mechanical screwing systems and press-fitting the contact surfaces is extremely effective when compared to conventional methods of filling the joints with in-situ concrete. It also creates a new and different feeling for concrete structures.

The heyday of the concrete shell structure is long gone. However, it is just as relevant today that a structure which is engineered efficiently can transfer loads mainly as membrane forces. This, in turn, means that slender elements can be produced and material utilisation optimised. This is not the case with standard flexural concrete elements, and most concrete elements that are designed are flexural elements. The historical decline in
Concrete shells is usually blamed on the large costs associated with their production. This is illustrated by the fact that the largest portion of Felix Candela’s structures was built in the 1950s-60s, and the increase in the Mexican minimum wage was responsible for the end of this boom. The high costs involved in producing complex, time-consuming formwork compared to the costs of the cheap materials used to produce concrete are obviously unfavourable. After the first patent application from Wallace Neff, a new branch of research was born. This concentrated on principles of pneumatic formwork – the most well-known of these being the BiniShells. Pier Luigi Nervi (1891–1979) suggested an alternative. After he founded his building company in 1920, he developed a building system based on semi-precast panels which were supported by a falsework and finally finished in situ concrete. These three examples show that examining the building method is the key to a re-evaluation of concrete shell production. These three different approaches show that there is a connection between the history of shell constructions and the search for an efficient production method.

Research context

Because of the rapid developments within architecture in digital fabrication and robotic production, questions regarding the efficient production of double-curved elements are increasingly in the spotlight. Numerous questions have been posed, with solutions and strategies varying considerably. One such project was TailorCrete. This involved pouring the concrete onsite into a milled foam formwork. A part of the project introduced a variable moulding table based on adjustable pixels and an elastomer mat. The formwork was then created using wax and the parts were cast conventionally. The steel rebars were then bent and welded automatically using robots. A similar method was also developed by the AXXA, which made it possible to create double-curved shell elements. This method was also based on a flexible membrane, which was shaped using adjustable pins. The PhD thesis ‘Double-Curved Precast Concrete Elements’ presented a variable moulding table and a complementary concrete mix whereby the shape was adjusted after the initial setting time. This meant that no counterformwork was necessary. The problem of joining precast concrete parts is usually solved, in the same manner as in Nervi’s structures, by pouring concrete into the joints onsite. The project ‘Lokale Lasteinleitung… mit Implantaten in Bauteilen aus ultra-hochfestem Beton’ proposed a steel connector for thin concrete elements. These are suitable for tension, compression and shear forces.

Digital fabrication for concrete shells

Taking current research aspects into account, the following goals were defined. Concrete shell structures should not be cast individually using large, complex, onsite form- or falsework, but constructed by joining elements that have been accurately prefabricated. This requires the double-curved surfaces to be divided into a number of individual elements. The dimensions of these elements are based on the boundary conditions of the laboratory where they are produced, as well as the possibilities for transportation.

If it can be assumed that the structure is a freeform one without any type of symmetry, a large number of irregular elements will be produced and few, if any, of them will be identical. As soon as the formwork cannot be produced using flat panels, the question of alternative production methods is even more relevant. The structuring of this question was based on the production chain, from the first concepts through to the final joining of the elements. The main aim was to design a flexible formwork which could be controlled by a robot and would be robust enough to survive in a prefabric concrete factory. The requirements of the concrete element, including the carbon fibre reinforcement grids and steel fibres, called for the expertise of concrete technologists.

It was also necessary to consider alternative joining techniques for these slender prefabricated ultra high performance concrete elements. The conventional joining method, such as that used by Nervi, involving filling the...
5. Evaluation of the deviation from digital model to one of the fabricated elements

4. Fitted joint surfaces

5. Evaluation of the deviation from digital model to one of the fabricated elements

All the building elements that were analysed and all the freeformed, wave-like roof structure of the fictitious hall. The size of the elements were investigated by using the finite element software. The calculation of the reinforcement and the contact surfaces were then pressed together (Fig. 1). The calculation of the reinforcement and the design of the screw connectors were carried out using finite element software.

By evaluating the results obtained from experiences in other projects, not only does this method consume large amounts of resources but it is also not very economical. For example, to achieve a fair faced concrete, long milling times are necessary and therefore the cost of manufacture increases dramatically. This is why a variable moulding table was favoured in this project, making it possible to produce different double-curved surfaces simply. From the very beginning, one of the primary goals was to create a simple, robust tool which had a long life expectancy and was appropriate for use in a precast concrete factory environment without breaking.

Two different moulding tables were investigated: a so-called pin field and a so-called pixel field. Both of these can be controlled or adjusted by an external, industrial robot. The robot can be used for other parts of the production process, as its separate and not fixed to the moulding table. The pin field has a formable surface connected to joint-mounted heads. These heads are connected to the pins, which are evenly distributed across an orthogonal field. The double curvature is then produced by moving the pins along their longitudinal axis and deforming the surface. On the other hand, the pixel field is made up of a number of plastic rods, each with a square cross-section, which can be slid along their longitudinal axis (Fig. 2). In this case, the industrial robot pushes the plastic rods into the correct position for the final precast concrete element shape. The panels are then fixed and used as the basis for the elastic mat. When considering the fastest reuse of the panel field, as well as the separation of the concrete casting process from the moulding table, it became clear that an additional step was necessary: taking a negative form made of quartz sand. Here, a layer of bonded sand was put on the astaxanthin mat and compacted, as is usual in casting techniques. This has many advantages: the sand adheres to shape quickly and therefore only needs to be on the panel field briefly. The quality of the surface is also very high. According to what is known today, there is hope that with this bonded sand a formwork material has been found which expands the possibilities for fair-faced concrete formworks (Fig. 3). A UHPC concrete with steel fibres from Dyckerhoff was used, with Nanodur Compound 5941 binding material. This was combined with two layers of carbon fibre grid mats. In this project, spacers were developed which could be clamped between the two sand forms. They held the carbon fibre reinforcement mats (CFRP) 5mm away from the surface as precisely as possible. After the concrete was poured and set, the edges were ground in a wet state. The connecting edges are extremely complex. They are spatially curved, stripe-like surfaces. An essential requirement for this step is the system of three points which are always in the same position relative to each other, which are integrated into the panels. These points are the interface between the reference points in the CAD/CAM files and the real plates. This makes it possible for the plate and edges to be spatially positioned correctly over and over again. At the momentary stage of development, it is necessary to remove 5mm from each joint surface. Approximately 1mm can be removed in each processing stage when using a water-cooled, diamond tipped grinding bit (Fig. 4).

The joints of the nine plates were pressed using the specially developed screw connection. The best results, which were anchored into the cross-section of the concrete plate, transformed the nine surfaces from pre-tensioned screw connections into the concrete and the contact surfaces were then pressed together (Fig. 1). The calculation of the reinforcement and the design of the screw connectors were carried out using finite element software.
Sensor-based evaluation
An important step in the development of the manufacturing process is the evaluation of the different manufacturing steps. The digital workflow process enables safe and accurate production. It is, however, interrupted by several intermediary steps. Firstly, this means that the two steps which are carried out by the industrial robot are at the beginning and the end of the production process. Secondly, the digital processes themselves can also deviate from the desired accuracy of ±0.25mm. To determine the cause of the size and shape deviations of the surfaces, every single step was recorded using measurement technology and checked: from the production and the robotic adjustment of the moulding table to creating the sand mould, all the way up to the final grinding of the joining surface (Fig. 6).

2. Tool/component interaction

Formatting the concrete panels using wet-state grinding is very dependent on the tool/component interaction. The combination of UHPC and steel fibres leads to wear on the tool. Within just one processing stage where the plate is reduced to an acceptable size within the tolerance range, the tool experiences significant wear. The wear on the tool is also dependent on the amount and direction of the steel fibres and therefore it cannot be estimated beforehand. A high-precision measuring device was installed on the robot, which checked the results after the processing step and decided if further processing steps should be carried out to correct discrepancies (Fig. 7).

The tool mentioned above for pixel adjustment makes it possible to control large numbers of pixels easily. During the pixel adjustment, the decision as to whether to proceed or go back and rework – and the iterative process of grinding, measuring and regrinding – are not particularly typical manufacturing cycles, but could help to develop new production concepts in the fields of civil engineering and architecture.

Collaboration between experts
Because the project introduced here was extremely broad, it was necessary for a number of different experts to work together on it. A process-oriented approach and the exemplary processing of the linked case study showed the method to be successful. By including digital manufacturing methods and robotic technology, it led to wear on the tool. Within just one processing stage where the plate is reduced to an acceptable size, the tool experiences significant wear. The wear on the tool is also dependent on the amount and direction of the steel fibres and therefore it cannot be estimated beforehand.

A practical case study, which the company Max Bögl is presently carrying out, should show that this method can be used for large format, ultra-thin prefabricated concrete elements. The case study is a slender roof construction made from four 10m-long, 2m-wide and 6cm-thick double-curved prefabricated concrete elements. This should also show that the technical innovations described will also find their way into the construction industry. Being able to build constructions out of concrete and reduce the amount of formwork will be the key to success.

Notes
The Seine Musicale by Shigeru Ban (formerly known as Cité Musicale) is envisioned as the flagship project for the urban renewal attempt of the Île Seguin in the west of Paris. Built in place of a former Renault manufacturing plant, the complex will host various concert and rehearsal spaces. The egg-shaped auditorium features a doubly-curved timber structure consisting of 1,300 individual glue-laminated and CNC-machined beam segments, as well as a secondary structure formed by 3,300 individual timber pieces supporting the hexagonal and triangular façade elements.

For fabrication and assembly of both timber structures, a fully parametric 3D CAD model was implemented, detailed down to the last screw and containing both the raw and final geometries of all timber elements. This model was the central node in the digital planning process. It was the origin of fabrication data for lamination and CNC milling of all timber pieces, acted as the basis for structural calculations and was used to simulate assembly situations throughout the whole structure.

This paper gives an overview of the digital planning and fabrication process of the primary timber structure of the Seine Musicale. The second part describes how Woodpecker, the timber fabrication plug-in for the parametric modelling environment Grasshopper, was further developed in this context.

**Topology and detailing**

The primary timber structure is a hexagonal grid consisting of 15 horizontal rings and 86 diagonals running around the egg-shaped building. Structurally, the rings are formed by up to 24m-long segments (Fig. 2), acting as tension or compression rings in the lower or upper building parts respectively. The diagonals are segmented into shorter pieces of 4-5m in length (Fig. 4), always spanning from one ring to the next. The whole structure rests on supports at the lowermost and uppermost rings with no additional support points in between.

In terms of detailing, there was a requirement by the architects to use as little steel as possible within the
timber structure. All the cross joints, as well as the longitudinal joints of the compression rings, were designed as lap joints, which is a traditional timber detail. Screws are taking lateral forces and beech dowels assure precise positioning. The ring/diagonal crossings also act as longitudinal joints for the diagonals. For the longitudinal joints of the tension rings, a splice joint was developed, featuring toothed inlays CNC-cut from beech plywood (Fig. 3).

Describing the structural properties of these details in depth would exceed the scope of this paper. However, for freeform projects, the purely geometric properties are equally important, namely to ensure the assemblability of all pieces (see F. Scheurer, H. Stehling, F. Tschümperlin, 2013, ‘Design for Assembly – Digital Prefabrication of Complex Timber Structures’, Beyond the Limits of Man, Proceedings of the IASS 2013 Symposium).

Assembly

Traditional lap joints have only one degree of freedom, meaning that there is exactly one possible assembly direction (‘from above’ in respect to the joint plane). With curved beam segments spanning over multiple crossings, many lap joints with different directions have to be engaged at the same time, blocking assembly altogether. This problem has to be solved in every freeform project, with solutions highly dependent on the respective geometric properties.

In case of the Seine Musicale, assembly was solved by slightly skewing the lap joint side faces depending on individual assembly directions for every beam segment. The diagonal segments were pre-assembled into X-shaped elements. Onsite, these elements had to be mounted by engaging two lap joints at the same time, leading to a pairwise assembly direction for these joints. For the rings, the assembly was defined as a circular movement rather than a linear translation. With this concept, the four to eleven lap joints of each segment could be engaged one after the other, rather than all at the same time.

Notably, the ‘toothed splice joint’ helped a lot in easing assembly, as it features a wide range of possible assembly directions. This is in contrast to a more conventional connection with slots, steel plates and steel dowels, which would have limited assembly direction to the plane of the slots/plates.

Assembly of every single segment was simulated in the 3D CAD model in order to detect and solve collisions and other issues blocking assembly.

Lamination

Beam segments for structures like the one discussed are usually CNC-milled from a mixture of straight, single-curved and double-curved glue-laminated timber blanks. The decision of which type of blank to use is a trade-off between structural strength, material cut-off and lamination costs.

For the Seine Musicale, a special constraint for the primary structure was that all timber beams be fabricated with the timber fibres exactly following the final geometry, in order
to reach a flawless appearance without any visibly cut glue seams. As the final geometry of all pieces was double-curved, this meant that all glue-laminated blanks had to be double-curved, too.

More than 1,000 pieces were laminated from stick lamellas with a cross-section of only 32 x 40 mm. Thus the typical piece consisted of about 110 lamellas which had to be precisely placed in the press bed, which itself had to be adjusted to the desired shape of every single piece. To streamline this process, a simulation of the press bed was implemented in the parametric 3D CAD model, permitting expert users to optimize and draw press settings and quality control. Due to the number of pieces, two different kinds of press beds were used, requiring different variants of setting data.

For some of the largest ring segments, lamination from stick lamellas was not feasible. Instead, these were produced with a more conventional two-step approach: straight planks are laminated into a single-curved beam on a conventional large-scale press bed for single curvature. The beam is then cut into strips crosswise to the lamination direction, resulting in single-curved plank lamellas. A second single-curved lamination process then yields a double-curved result.

To ensure precise placement of the up to 24m long beam segments in the CNC milling machine, despite lacking any plane face as reference, positioning points were defined in the 3D CAD model and exported along with the lamination data. These points were defined based on press bed positions and thus could be mapped on the pieces during lamination. As data for CNC milling were later generated from the same model, the positioning points could be referenced again and related to physical support points in the CNC milling machine. This process allowed for the minimum blank oversize to be no more than 10mm per side, which was necessary to meet the criterion of not cutting through the first lamella. This process allowed for the minimum blank oversize to be no more than 10mm per side. This process allowed for the minimum blank oversize to be no more than 10mm per side.

In conventional processes, this is mirrored on the software side, where every piece is individually prepared for CNC milling based on a CAD model showing the desired result in full detail. To streamline this process, a set of BTL (Building Transfer Language, see www.designmachine.com) files were exported for every piece. Described in more detail in the aforementioned FABRICATE 2014 paper, BTL allows the definition of fabrication operations based on geometry, machine features. So BTL does not remove the individual machining preparation of every single piece, but brings this set of operations in full detail. To streamline this process, a set of BTL (Building Transfer Language, see www.designmachine.com) files were exported for every piece. To streamline this process, a set of BTL (Building Transfer Language, see www.designmachine.com) files were exported for every piece. To streamline this process, a set of BTL (Building Transfer Language, see www.designmachine.com) files were exported for every piece.

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Especially for complex details like the benchtop shaped splosh joint, close collaboration between the parametric modeller (knowing all the details and their geometric range) and the fabrication operator (knowing the machine and its capabilities) is necessary in order to ensure an efficient process in fabrication preparation. In the case of the Seine Musicales, several test iterations were run until a satisfying data set was achieved, and improvements to the BTL layout were made even after production had already started.

Conclusion

For the timber structure of the Seine Musicales, a highly integrated digital fabrication process incorporating lamination and CNC milling has been set up. High demands in terms of aesthetics and detailing lead to innovations in the fields of lamination and construction details. Assemblyability is one of the key aspects (if not the key aspect) in timber projects and has to be taken into account as early as possible. The interface into fabrication can rely on established exchange formats and processes, but has to be further developed to meet the specific needs of each project. Optimally, a balance between automation and manual control is found.

Erection of the timber structure of the Seine Musicales finished in summer 2016. At the time of writing, the façade is being installed. The scheduled opening date of the building is April 2017.

Acknowledgements

Keeping it state-of-the-art – update on Woodpecker, the timber CAD/CAM interface for Grasshopper

The BTL has proven itself as a very suitable CAD/CAM interface format in many freeform timber projects, such as the DI Tower Canopys (Sinnverach, Dublin 2015), the French Pavilion at the Expo in Milan (X To, Milan 2015) or the ‘Haus des Brötz (House of Bread)’ (Carp. Himmelblau, Dau, Asten 2015).

Originally a side-product of project-specific implementations, a BTL export plug-in for Grasshopper was released by the authors in 2014 (see www.footloose.info/com/project/woodpecker). This plug-in features the most generic operations and allows the generation of BTL files including 5-axis contours directly from Grasshopper.

Since then, development has focused on projects such as the ones mentioned above, which were notable not done in Grasshopper but used the same BTL export code. In spring 2017, the first major update is being released as Woodpecker Version 2. As well as supporting a wider variety of BTL operations and a series of bug fixes and other improvements, the plug-in will allow the export of STLX. STLX is XMI-based and is meant to be a successor to the aged ASCII-based BTL format. Version 1.0 was released in 2015 and is gradually being adopted.

Woodpecker remains free for educational purposes.

The interface from the CAD model to the CNC machine is the critical point in any digital fabrication process (see H. Stöhlker, F. Schweier, J. Reulier, 2014. ‘Bridging the Gap from CAD to CAM. FABRICATE – Proceedings of the International Conference. Zürich: paa Verlag). While parametric modelling enables the definition of thousands of individual components through the same set of rules, in fabrication every piece becomes a physical instance which has to be laminated, machined, post-processed, transported and finally assembled.

While parametric modelling enables the definition of thousands of individual components through the same set of rules, in fabrication every piece becomes a physical instance which has to be laminated, machined, post-processed, transported and finally assembled.

5. Assembly concept for the diagramp. To facilitate the central clamping line of the legs forming the X it had to be calculated into two legs.

6. The erected timber structure viewed from the outside. The secondary structure transfers load to the lintel yet connected façade parts can be seen a top of the main beam segments.
At FABRICA'TE 2011, the authors of this article encountered two new research trajectories (Dombernowsky, 2011, Verde, 2011), on, respectively, the design of topologically optimised concrete structures and hot-wire-cutting of expanded polystyrene (EPS) construction elements. Over lunch, the potential for a synthesis was gauged. In the years that followed, the intense collaboration that ensued resulted in a number of projects and articles (McGee, 2013, Feringa, 2014, Søndergaard, 2016). The industrial merit of the approaches explored paved the way to further develop these at an industrial scale, leading to the founding of Odico Formwork Robotics in the spring of 2012 (Søndergaard, 2014). At Odico, the challenges faced when deploying and building with robotics at scale are addressed. Over the years, a range of novel fabrication processes have been developed in an industrial context.

Are quantity and quality mutually inclusive?

Automation is often discussed in the framework of efficiency – of increasing productivity at lower labour costs. This is to say that robotics is discussed in a quantitative framework, rather than a qualitative one. The potential quality that robotics has to offer the building industry is central to its further development. Architectural robotics has been enthusiastically embraced by the design-led research community, exploring specific traits of machining processes for their intrinsic or tectonic potential. The cultivation of new manufacturing aesthetics, precipitated by the new degrees of freedom and material control offered by digital machining, has been a central motif over the past decade. Performance is rarely addressed, especially in direct quantitative terms. So far, the literature lacks an accepted methodology and criteria to assess and contrast the relative merits of various existing technologies. Within internal technology research and development at Odico, quantity and quality represent the axes on which the merits of methods are plotted. The following criteria serve as guidelines to gauge the pertinence of technology:

- Transferability – does the approach translate across multiple applications, disciplines or material systems?

SCALING ARCHITECTURAL ROBOTICS
CONSTRUCTION OF THE KIRK KAPITAL HEADQUARTERS
ASBJØRN SØNDERGAARD / JELLE FERINGA
Odico Formwork Robotics
However, Odico’s experience with the test project suggested that RHWC could be a viable alternative for creating bespoke formwork. The company decided to engage the construction market for early-stage adoption and to mature the technology for large-scale impact in construction. Considerable attention has been directed within Odico to exploring its versatility, its mechanical principle of incremental material subtraction is inherently slow and thus not suited to scale economically beyond the exclusivity of high-profile construction projects. As such, the capacity of RHWC to cut through large volumes of expanded polystyrene (EPS) formwork for concrete casting pressures, while a relatively low-density EPS material was selected for the test where the traditional formwork dealt with deformation. Through this critical finding, Odico obtained a vote of confidence from the building contractor, Iorton, to go ahead and produce the formwork for the project.

The formwork system developed for the project entailed three primary variants. First, an in-situ prefabrication workflow, where polystyrene mould parts were inserted into a rectangular timber scaffolding box. This procedure was applied for onsite prefabrication of curved wall void walls, spanning vertically across all storeys. With dimensions varying from 7.4 x 2.8 x 5.2m to 4.2 x 3.2 x 5.2m, the volume of formwork to be produced would summarise 70-110m³ per storey section.

While building a test mock-up, traditional wooden moulds were contrasted with the EPS moulds supplied by Odico. The EPS moulds stayed more true to form under casting pressures, while a relatively low-density EPS material was selected for the test where the traditional formwork dealt with deformation. Through this critical finding, Odico obtained a vote of confidence from the building contractor, Iorton, to go ahead and produce the formwork for the project.

For robotic fabrication of such volumes, machining time replaces labour as the key cost factor and is a primary concern. While robotic CNC milling has long proven its versatility, its mechanical principle of incremental material subtraction is inherently slow and thus not suited to scale economically beyond the exclusivity of high-profile construction projects. As such, the capacity of RHWC to cut through large volumes of expanded polystyrene (EPS) formwork for concrete casting pressures, while a relatively low-density EPS material was selected for the test where the traditional formwork dealt with deformation. Through this critical finding, Odico obtained a vote of confidence from the building contractor, Iorton, to go ahead and produce the formwork for the project.

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Following the KKHQ project, Odico Formwork Robotics has seen a rapid expansion, completing over 200 projects in the four years since its formation, including several high profile commissions in the United Arab Emirates, the United Kingdom, Norway and Denmark.

One recent example was the design and production of EPS foam guides for the manufacturing of 2,000 uniquely designed glass façades of Opus Dubai, an iconic premium hotel resort designed by Zaha Hadid Architects in Dubai, UAE. In this case, enabled by the geometric coherence of the design scheme, a complete automation of the workflow was established. This enabled the entirety of profile geometries to generate mould design and resulting robot code in a single batch operation. This optimisation allowed for an increase of output from 80 unique units per 24 hours to 200-300 units, helping to accelerate the production schedule.

High volume applications, such as stairs, panels and structural components - as well as advanced infrastructural developments, where formwork expenditure represents a significant cost factor - form a testbed for the demonstration of the combined effects of the hot-wire machining speeds, the degrees of freedom offered in robotic control and the cost-effective EPS material. Indeed, this represents a viable pathway for a dramatic offsetting of costs in industrial concrete production.

The production of hot-wire-cut moulds for the KKHQ main structure corroborates that RHWC can act as a cost-effective method for the production of complex concrete moulds, applicable to a wide range of construction uses.

In such cases, as is typical for the majority of Odico’s projects, the primary threshold in the successful demonstration that the technology can be effectively applied to designs that did not anticipate the use of advanced robotic fabrication – or RHWC specifically – in the conceptual design phase.

Conversely, a growing interest from design partners in exploring the inherent vocabulary of RHWC concrete production is starting to complement these initial efforts. While robotically controlled hot-wire-cutting of concrete offers a distinct solution space in which novel design vocabularies can be explored, the mechanical concept per se can be extended across several domains of material processing and motion types. This line of thinking constitutes an important exploration within Odico’s internal development efforts. Over the course of four tool prototyping, robotic abrasive wire-cutting (RAWC) has been developed and implemented within Odico’s production.

While subjected to the same geometric and motion constraints as RHWC, abrasive wire-sawing enables the processing of hard materials such as marble (Feringa 2014), timber, non-flammable foams and ice (Fig. 5). In turn facilitates a conceptual shift from producing the intermediate product of formwork designs to the architectural component itself.

Adjacent to this strand of development, Odico recently began to explore the domain of ceramic brick fabrication. In collaboration with Steijeg Teig, a leading Danish producer of ceramic bricks, a robotic system was devised for production of bespoke tile designs. Early work on the topic (e.g. Adreano, 2012) indicated the architectural potential for bespoke ceramic tiles. Odico explored a different mechanical approach for processing the clay material due to the density of the clay utilised. By the development of an oscillating end effector, in which forward and quick lateral movement of a wire is combined, a rapid manufacturing process was devised, paving the way for rapid production while directly integrating with Steijeg’s manufacturing process. As such, the installation enables the production of uniquely designed tiles. This quality was explored shortly after the initiation of the facility for an interior wall cladding of Odense Theater by Cees Arntzenius A/S, emulating the undulating motion of the theatre curtain.

Double-curved formwork – blade cutting

Odico tendered in a consortium for the production of the formwork of the Vaalbrug bridge extension project by Zwarts & Jansma Architecten. The design required many thousand square metres of double curved formwork. The constraint of double curvature could not be met in a satisfactory way using ruled surface rationalisation and hot-wire-cutting, so that approach was dismissed in favour of timbers formwork, which meant that Odico did not participate in the realisation of the project. However, the tender did inspire an idea: by bending a blade, double curvature could be closely achieved.
Technology wants

The past decade has seen the genesis of a range of specific robotic construction technologies and processes — some of which hold promise for adoption in construction. Thanks to this accumulation of academic efforts, momentum is building. The critical test is whether architectural robotics can scale beyond the lab to the construction site and become a commercially sustainable industry, possibly breaking the current technological steam.

In What Technology Wants, Kevin Kelly offers a compelling perspective on the trajectory that drive technology: “The second great force pushing evolution on its immense journey is positive constraints that channel evolutionary innovation in certain directions. In tandem with the constraints of physical laws outlined above, the set of self-organisation swells evolution along a trajectory. While these internal ingestions are immensely important in biological evolution, they are even more consequential in technological evolution. In fact, in the technicism, self-generated positive constraints are more than half the story; they are the main event” (Kelly, 2011).

In the context of advanced architectural fabrication, we can observe the parameters that constitute the methods and techniques that are tangential to the demands of a progressive architecture, having the capacity to scale architectural artefacts of a novel character, while considerably challenging the price unreasonable cost penalty (Søndergaard, 2016, Brander, D. et al., 2016). This method is now under preparation for pilot production (Figs. 7 and 8), with expected construction cost reduction of Palmyra’s Arch underscores 4.

The challenges faced by large-scale automation in construction could be the call to disrupt the present order. “Not alone have the older forms of technics served to maintain, renew and stabilise the structure of the old order… Paleotechnic purposes with neotechnic means: the machine that builds the machine – the factory.” (Braud, 2011).

Notes
1. “To support the best way to exchange rich geometry-preserving parameterized models, the working schema includes several additional geometry types, such as advanced B-rep (NURBS), faceted B-rep and surface models, constructed solid geometry (CSG) and advanced sweeps, including tapering and presentation styles, such as colours and textures, which can be added to these geometries.”

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2. Not universal material B-splines.


Responding to climate and landscape

MPavilion is a unique architecture commission and design event for Melbourne, Australia. A new temporary pavilion is commissioned each year from a leading international architect by the Naomi Milgrom Foundation.

Each structure takes shape in the downtown oasis of Queen Victoria Gardens to accommodate a free programme of talks, workshops, performances and installations from October to February. Building on unexpected collaborations, MPavilion is a catalyst and a meeting place – an intriguing form, a temporary landmark, a spontaneous detour, a starting point and a base to explore design’s role in the creative city.

At the conclusion of its lifespan in Queen Victoria Gardens, the pavilion is demounted and gifted to the City of Melbourne for reassembly in a permanent location to create an enduring legacy.

The brief was an opportunity for a structure that responds to its climate and landscape, exploiting the temporary nature of the pavilion form and producing a design that speaks in response to the weather.

Rooting the pavilion in its parkland setting, the vision for MPavilion was to create the sensation of a forest canopy, with beautiful dappled light where visitors could see the sun and the sky – a dreamy atmosphere that could inspire a diverse programme of events for four months.

The design was driven by an ambition not only to integrate the pavilion with its parkscape environment but also to involve the wind, and sometimes the rain, as part of the experience. And so the structure needed to balance a degree of flexibility in its response to the atmosphere with subtle movements, with sufficient stability to safely host thousands of visitors over the summer. The pavilion would be a celebration of those natural shelters where people come together: an exceptionally light, open structure that sits gently on the land while affording protection from the unpredictable weather of Melbourne.
3D technology, advanced materials and engineering and the all-important ingredients of practical experience and construction management."

AL_A had a long history of working with boatbuilders, of which Australia has some of the finest. Initial inspiration was provided by the innovative materials typically used in aerospace and in the surfboard industry and the latest technology used in nautical engineering – in particular, the large sails utilised in high-performance yachts that afforded a sense of the possibilities in both aesthetics and material capabilities.

The overall design was optimised to keep the fabrication simple by using symmetry. Therefore the final design was limited to petals of just two different sizes, while still allowing for multiple configurations.

Establishing a framework

The ambition and contexts – conceptual, physical, material – established the framework for a series of questions that in their answering would define the success of the pavilion.

At its heart was the notion of how to dematerialise a structure, albeit a temporary one, and to make it feel and look less like a permanent building. The solution of a forest of petals surmounting impossibly thin columns in order to make it as transparent and as light as possible simply uncovered further questions as to its material composition and fabrication methodology.

Consequently, the challenge became one of achieving sufficient lightness and transparency or translucency in the form of the petals without compromising its twin natures of the seemingly ephemeral pavilion necessitated both swift construction and deconstruction methodologies while in its temporary home before becoming an embodiment of durability in order to persist in its permanent Docklands location thereafter.

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3. The petals disperse at the edges, blending into the parkland tree canopies. Image: John Gollings.

2 & 3. The making of a petal. Image: mouldCAM.


A balancing act

The success of MPavilion would be determined by the delicate equipoises of flexibility and strength, of the elements to participate in the performance. The achievement of the thinnest possible petals, with the greatest possible transparency, and the control of the entire project, necessitated a programme of comprehensive trials, of testing and prototyping composite materials. The ambition to dematerialise the structure and blur the threshold between pavilion and park was achieved by material innovation working in parallel with the overall design. Once the 3D computer model was complete, a new fabrication process was developed for camera tripods.

Placement was not only optimised for structural performance, whereby the lines of fibres are easier locked to allow for maximum efficiency, but also for the creation of a beautiful radial pattern that became the defining graphic of the entire project. This necessitated a programme of testing utilising different materials, as MPavilion proved.

Most significantly, it was decided to add external reinforcement in the petals to produce rigidity. These decisions were 45mm in diameter with 4mm wall thicknesses. Like the petals, they are the product of a process of research and development undertaken during their industrial manufacturing, which in this case saw the tubes initially developed for camera tripods.

Placement and rigidity of the petals.

The thin, high-strength columns used in the final pavilion were 45mm in diameter with amm wall thicknesses. Like the petals, they are the product of a process of research and development undertaken during their industrial manufacturing, which in this case saw the tubes initially developed for camera tripods.

In order to amplify the perceived movement, clusters of one, three, five and small petals were created. This combination of the number of columns and petals created a different mass per column ratio, allowing them to sway gently in the breeze.

The ambition to dematerialise the structure and blur the threshold between pavilion and park was achieved by material innovation working in parallel with the overall design. Once the 3D computer model was complete, a new fabrication process was developed for camera tripods.

Each petal was mounted on slender carbon fibre columns that were designed to conceal the LED lights as well as allow a wider column-free space for events.

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An eye-catching architectural attraction

The commission and associated programme is quickly becoming one of Australia’s leading design and architecture events and has become one of Melbourne’s leading summer attractions.

By February 2016, AL_A’s MPavilion had attracted more than 64,000 visitors over 126 days to 419 free events through collaborating with more than 260 cultural institutions, architects, artists, musicians, dancers, choreographers, scientists and designers.


One of the unique features of the MPavilion project is that it is gifted to the city and the people of Melbourne. After its four-month programme, the pavilion was disassembled and moved to its new permanent site in Melbourne’s parklands. This creates a permanent legacy that will become part of the cultural heritage and public amenities of Melbourne, attracting tourism, industry development and civic pride.

The 2015 pavilion opened to the public in its new permanent location in the Docklands public park in August 2016.

The pavilion’s lasting legacy is a tribute to the ambition and collaboration that commissioned, conceived, developed and fabricated it. The willingness of the team to extend the boundaries of the possible in taking ordinary materials to new levels is testament to this spirit of innovation shared by all and a mutual confidence in each member’s expertise. MPavilion is a beautiful example of how taking materials and technology beyond their everyday applications can deliver extraordinary and unique results.

Project credits

Architect: AL_A
Project directors: Amanda Levete, Maximiliano Arrocet, Ho-Ying
Project architect: Alex Bulygin
Team: Alice Dietrich, Song Jie Lim, Filippo Pecinat, Giulio Pellizzon
Engineer: Arup
Fabricator: mouldCAM (now ShapeShift)
Main contractor: Kane Constructions
Lighting and sound design: Blandworth and Sam Redston.
In recent years, technology and digital innovation have provided a series of new design tools for the architectural world, which have dramatically morphed the massing of modern buildings. The envelopes which were traditionally constrained to a relatively planar or curved setting-out became complex forms, moulded in the digital environment - shapes that push the traditional boundaries of engineering, fabrication and performance.

This shift has generated a dichotomy, in which two solutions have become apparent: one where the envelope has its own supporting system, often quite complex, which is then dropped onto the main structural skeleton, and one where the skin is both the supporting system and the envelope at the same time.

In both cases, the challenges posed by these complex geometries required a series of digital tools and workflows to be developed, tools that interweave geometrical form-finding, structural optimisation and fabrication output. At AKT II, the work developed on new digital design-to-fabrication techniques has allowed the use of a building technology that integrates architectural form, structural armature and environmental enclosure in single multi-performative skins. This technology, which has been successfully tested on a number of built projects, has produced great savings in cost, use of material, energy and labour, by offering multiple functionalities within fewer building components.

An extension of monocoque construction, commonly used in aeronautical application, this technology is based on the prefabrication of large components in the factory, simplifying assembly in the field. Components are designed to be bolted as a kit of parts and then welded to form a smooth, waterproof enclosure.

**Interrogatives**

This applied research was propelled by two fundamental questions:

One: can the envelope, with its aesthetic and environmental functions, also provide a main structural function?
Structure
The structural system envisaged in this case consisted of a skin manufactured using simple flat metal sheets which were laser-cut and formed into the final curvature, and welded together in the workshop using flat ribs welded orthogonally to the main plate to prevent buckling and provide stiffness. The waterproofing of the enclosure was guaranteed by the welding of the contiguous metal parts, and corrosion was prevented by paint.

An early stage detailed investigation was carried out to determine the factors influencing the construction and build-up of the steel semi-monocoque. The semi-monocoque is made up of a continuous top structural skin and ribs with and without a bottom flange.

The aim of the analysis was to minimise the plate thickness and maximise the rib spacing. The minimisation of the plate thickness was intended to reduce the overall weight of the structure and to reduce the amount of resources used in the construction. However, a lower limit of 8mm was taken to ensure weldability, because challenges can be encountered when welding thicknesses lower than this, due to excessive plate distortion. From the analysis, it was found that the thickness of the top sheet of steel is controlled by plate buckling, due to the compression force that arises from the bending action. This was also affected by the spacing of the ribs, but to a lesser degree. Where large rib spacing was used, the stress at which the plate buckled reduced, making the section less structurally efficient.

The overall structural depth is controlled by the deflection criteria. The semi-monocoque structure allows much smaller depths to be used than could be achieved through the use of traditional steel beams.

Workflow, optimisation, Re.AKT
The project used a complete workflow, from the modelling of the smooth external form of the building, achieved through bespoke smoothing algorithms, to the automated analysis of the structure, enabled by real-time interoperable models which interface with analysis and optimisation tools.

This workflow extends all the way through to patterning tools which set out plates and stiffeners, interfacing with automated fabrication methods designed to achieve high levels of precision in the final fabricated form. The three fundamental steps followed were:
1. Rationalisation of the provided surface to remove imperfections in terms of curvature tangencies and incomplete boundaries.
2. Definition of the optimal pattern for the internal stiffening plates.
3. Definition of the subsequent patches of structural elements for fabrication.

The rationalisation of the surface was an essential step to ensure the elimination of folds which would have defined a clear interruption of the metal sheets. This process was implemented using a smoothing algorithm that was initially created for the movie animation industry. The Catmull-Clark algorithm takes an initial crude mesh and recursively subdivides it, averaging the beast ‘vertices’. This algorithm was embedded in AKT II’s internal toolkit (Re.AKT) and enhanced, introducing between other functionalities the option to assign constraint points, curves and surfaces. This allows the user to script an interpolated smooth surface while still maintaining the original constraints. The differences between the original surface and the rationalised one were assessed by mapping the distortions as a coloured gradient on the surface.
An initial proposal was to use the principal stress limit the self-weight of the structure. To comply with the loading conditions with the need to balance the need for strength and stiffness, the need was for a high-performance and the lightest configuration (Fig. 2).

Fabrication

The fabricator (CGI International) was able to use AKT II’s optimised surface model to inform the subdivision of patches that could be cut from single metal sheets. This process was necessary to obtain strips that could be easily fabricated and transported to the site. The splices were coordinated with the stiffeners’ locations in order to create a simple connection detail for the section inside. Once this information was added to the digital model, the fabricator started production and pre-assembly in its warehouse. The stiffeners were laser-cut and prepped in place, then welded to form a skeletal network which would provide both a base support and a reference for the setting-out of the structure.

The flat metal sheets defining the skin were then welded into the skeleton of ribs and locally adjusted to remove any distortion generated by welding and the imperfections generated in the fabrication process, to maintain tangency and environmental challenges our industry faces.

Installation

Once the building was fully pre-assembled, the parts were carefully dismounted and loaded onto trucks to be delivered to their final location. The vertical side walls were the first to be craned in and welded together, forming the boundary perimeter where the horizontal enclosures could then be supported and welded on. To make sure the structure was not going to distort in its temporary unconnected condition, props were used while the patches were craned into place. After every patch was placed and the local adjustments were made, an onsite welding process took place to seal all the edges and create a skin which could act as a singular structural element, at the same time providing waterproofing to the building. To complete the installation, several layers of paint were laid onto the structure to preserve the metal from corrosion and to give its final look (Figs. 1 and 3).

The Library Walk Cloud pavilion is a link between the Manchester Town Hall and the adjacent Central Library and environmental challenges our industry faces.

In a world where craft and science are merging, fusing different expertise, there is a need for a deep and interactive collaborative process between disciplines. This union has ignited the development of bespoke digital tools for design, optimisation and fabrication that are pushing designers to think deeply about integration of purpose and systems. Multi-performative skins are one example that, with their integrated technology, can address many of the economic and environmental challenges our industry faces.

1. The façade, which is a frameless set of 7.4m high structural glass panels supporting the roof and providing lateral stability.
2. The roof, which consists of a polished stainless steel monocoque construction, allowing it to span 12m across a free-floor space (Fig. 8). These external, exposed surfaces are welded to an internal armature of stiffeners, creating a rigid structure.

The simplicity and purity of this building is achieved by the simple combination of the two structural elements of the roof and the vertical glass façade, which are rigid in virtue of their form.

Another interesting difference of this installation when compared with the previous project is that the internal stiffening ribs follow a simple planar grid, and their distribution is regular due to the smaller number of patches required for the installation. The stainless steel is also welded on top of the stiffeners, following a similar procedure to the Drawing Studio (Fig. 4). The main difference in this case is in the external finish. The library entrance was envisaged to be a reflective surface from the beginning. To achieve this, the fabricator first ground the welding line until it disappeared, and the surfaces were then sand-blasted to further reduce the imperfections generated by the welds. The entire surface was then polished to create the mirror finish and protected with a robust film for transportation. Finally, the prefabricated sections of the upper Cloud were transported to the site and erected onto the pre-installed glass perimeter.
This paper describes the development and fabrication of the Armadillo Vault, an unreinforced, freeform, cut-stone vault, which embodies the beauty of compression made possible through geometry. Specifically, the paper provides insights on how a highly interdisciplinary team managed to bridge the difficult gap between digital modelling and realisation by learning from historic precedent and by extending traditional craft with computation.

The vault is the centrepiece of Beyond Bending, a contribution to the 15th International Architecture Exhibition – La Biennale di Venezia 2016, curated by Alejandro Aravena (Fig. 2). Wrapping around the columns of the Corderie dell’Arsenale, the shell’s shape comes from the same structural and constructional principles as stone cathedrals of the past, but is enhanced by computation and digital fabrication. Comprising 399 individually cut limestone voussoirs with a total weight of approximately 24 tonnes, the vault stands in pure compression, unreinforced and without mortar between the blocks. It spans more than 15m in multiple directions, covers an area of 75m² and has a minimum thickness of...
and efficient structures. Possibilities, but can be the starting point for expressive constraints are not equivalent to limited design planning and constructing freeform architecture. It is rather a direct critique of the current practice of work is not a romantic attempt to revive the Gothic. Of master builders in Gothic times that contrasts with reflect the holistic approach to design and construction with traditional craft enhanced by digital computation, allowed a collaborative team of engineers, designers and by tight limitations on time, budget and construction.

The lessons learned from historical precedent, combined with traditional craft enhanced by digital computation, was developed to realise a structurally optimised material system without obvious mechanisms to compensate for tolerances.

For this project, a smooth digital pipeline/workflow was introduced into a ‘real world’ fabrication and construction process in setting of stones had to be developed. Furthermore, only five months were available for the entire project. This includes time needed for the design, engineering, fabrication and construction of the vault. The challenge was effectively to convert a ‘perfect world’ digital design into a ‘real world’ fabrication and construction process in an extremely short period of time for a constructional/material system without obvious mechanisms to compensate for tolerances.

Digital process

For this project, a smooth digital pipeline/workflow was developed to realise a structurally optimised and fabrication-driven generation of geometry.

Structural design and analysis

The vault’s histmural geometry, which allows it to stand like an intricate, three-dimensional puzzle in pure compression, results from a form-finding and optimisation process based on thrust network analysis (Block & Schimpf, 2000; van Mele et al., 2014). These novel computational methods offer a more controlled, force-driven exploration of (covered) hanging models.

The dominant self-weight of the vault was taken as a design load to define the middle surface of the structure, which was then offset according to assigned local thicknesses based on experience and weight constraints (van Mele et al., 2014). The resulting intrados and extrados define a local shell thickness ranging from 5cm at the midpanes and only 1cm along the line supports to 12cm at the internal touch-down and point springing (Fig. 3).

Based on the designed force flow, the stone envelope was discretised into courses and the courses into voussoirs. Staggering of the voussoirs, and alignment of the courses to the force flow and the boundary, guaranteed proper interlocking of all stones in the surface of the discrete shell (Fig. 4). To speed up the fabrication process, the voussoirs were made as large as possible with an approximate range of 50cm to 80cm, so that they could still be handled by hand or with a lightweight jib crane. The stability of the unreinforced, dry-set assembly under various load conditions, including concentrated loads, settlements of the supports and earthquake loads, was confirmed using discrete-element analysis (Van Mele et al., 2018).

Architectural geometry and fabrication

Due to the limited timeframe and large number of voussoirs, the main goal for the fabrication process was to reduce the average cutting time for each stone. Additionally, since there is no mortar between the voussoirs, which could have compensated for tolerances, the interfaces between stones had to be flush and therefore precisely cut and set.

To optimise the fabrication process, the voussoirs were designed to have a convex curving geometry along the interfaces, such that they could be cut efficiently with a circular saw (Rippmann et al., 2014). However, the vault has several areas with negative Gaussian curvature. Since it is geometrically impossible to discretise such a surface with a convex, planar mesh (Li, Lau & Wong, 2012), the faces of the extrados were allowed to disconnect and create a stepped, scale-like exterior. This visually emphasised the discrete nature of the shell and allowed the flat extrados faces of the voussoirs to be used as a base for the machining process. As a result, the cubic blocks no longer needed to be flipped and re-referenced, reducing fabrication time of the voussoirs significantly. The curved intrados faces were formed by xyle-by-xyle
The different articulation of the intrados and extrados of the stone shell results from a combination of fabrication constraints, machining efficiency and aesthetic considerations.

Cuts with a circular blade, spaced such that thin stone fins remained. Rather than milling these away, the fins were hammered off manually to create a rough but precisely curved surface. The side surfaces perpendicular to the force flow were processed with custom profiling tools that create ruled surfaces with male/female registration grooves. These grooves are primarily used as reference geometry to assist assembly, but also prevent local sliding failure. The other side surfaces of each voussoir were created with simple planar cuts.

From digital to realisation

The vault was test-assembled offsite to allow a team of expert stonemasons to become familiar with the process. During the test assembly (and also during onsite assembly), each voussoir was fully supported by a falswork consisting of a standard scaffolding system with a custom-made wooden grid on top (Fig. 5). The voussoirs were placed manually, starting from the courses at the supports and converging towards the ‘keystone’ courses at the top. To gradually decompose the vault as evenly as possible, a specific sequence for lowering the falswork was determined, cycling through the independent scaffolding towers in several rounds.

Using imprecise formwork

In traditional cut-stone or stereotomic stone vaulting, voussoirs are never placed directly on falswork. Instead they are positioned using shims. This insight was used as a pragmatic formwork strategy that provided a way to deal with the rough interior surfaces of the stones. The wooden falswork was offset inward/downward by 3cm. As a result, large wooden shims could be placed in between the rough, knocked-off fins to support the stones on the falswork and precisely control their position. Additionally, this meant that precise positioning of the falswork sections was less critical. This resulted in significant time-saving and reduced logistical challenges. As an added bonus, the shims served as visual guides during decentring. Once they started falling on the ground, the shell was standing by itself.

Not building the designed geometry

Due to unavoidable machining tolerances, each of the voussoirs could only be within +/-0.4mm of the designed digital geometry. Since the vault was designed to have a high degree of structural redundancy and indeterminacy by introducing locally high degrees of double curvature, these small imprecisions had little or no effect on the structural integrity and behaviour of the overall structure.
Since slight deviations of a fraction of a degree in placement angle at the base (or in fact anywhere along any row) cause significant deviations higher up, several strategies had to be developed. The masons would build a few rows, finish some of the edge arches and check that everything closed. If not, they would take down the rows, adjust, reposition and realign, repeating the entire process as needed (Fig. 6).

For structural reasons, it was much more important to have contacts that were as tight as possible between stones so that, after decentring, no uncontrollable and unpredictable settling of the assembly would occur. Using the above-mentioned shimming, the masons ‘jiggled’ every stone until all interfaces were tight. Where necessary, the interfaces were sanded off to improve the fit. The level of precision reached through manually trimming a stone depends on its initial geometry. Flat surfaces can easily be processed with simple templates and tools. Therefore the geometry of all interfaces was constrained to planar and ruled surfaces depending on their local alignment to the intrinsic geometry. For structural reasons, the expressively flowing stone surface had to be hand-finished to its neighbours was marked on the interfaces.

A successful marriage of precision engineering and craft experience

The Armadillo Vault represents the close collaboration of engineers, designers and skilled stonemasons and builders. It is the culmination of over 10 years of joint research in stone construction, demonstrating that, with advanced, non-standard engineering approaches and novel equilibrium design methods, expressive geometries can be safely developed and – through combining optimised digital fabrication processes and experienced craft – successfully constructed. Proportionally only half as thick as an eggshell and standing without steel reinforcement, the expressively flowing stone surface challenges the conception that complex geometry needs hand-in-hand with inefficient use of material (Figs. 7-10). While the vault’s architectural geometry was optimised in order to achieve all structural and fabrication constraints, and although a smooth digital pipeline with advanced data structures was developed to eliminate any possibility of human error in the handling and logistics, in the end it was the experienced human hand that locally controlled precision.
Achim Menges

Achim Menges born in 1975, is a registered architect and Professor at the University of Stuttgart, where he has been the Founding Director of the Institute for Computational Design since 2008. He has also been Visiting Professor in Architectures at Harvard University’s School of Design since 2009. He graduated with honours from the AA School of Architecture in London, where he subsequently taught as Studio Master of the Emergent Technologies and Design Graduate Programme from 2002-08 as an Honorary Professor from 2009-12 and as the Master of the Studio 4 from 2003-06. He is the author of ‘Towards Generative and Materialization of the Morphologies’ at the HfG Offenbach University for Art and Design in Germany, in addition he has held visiting professorships in Europe and the United States.

His 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, computer scientists, material scientists and biologists. He has published several books on this research and its related fields, and is the co-author of numerous articles and scientific papers. His projects and design research have received many international awards, have been published and exhibited worldwide and are exhibited in several renowned museum collections, including the permanent collection of the Centre Pompidou in Paris.

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Bob Sheil is co-founder and co-Chair of the FABRICATE Conference Series. He is Professor of Design through Production and Director of The Bartlett School of Architecture, UCL. Among numerous articles and papers, he is the editor of Manufacturing the Bespoke (Wiley, 2012) and has edited three issues of AD: High Definition: Zero Tolerance in Design and Production (Wiley, 2014), Protoarchitecture: Analogue and Digital Hybrids (Wiley, 2008) and Design through Making (Wiley, 2006). His built work includes the award-winning 55/02 Shelter at Kielder Water and Forest Park, Northumberland, UK (2008), designed and fabricated in collaboration with Stahlbau GmbH.

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Marilena Skavara has been an integral part of FABRICATE since its inaugural event in 2011. She holds a degree from the National Technical School of Architecture in Athens and completed the MSc in Adaptive Architecture and Computation at The Bartlett School of Architecture, both with distinctions. She mentored the MSc thesis project AptiveB(AC) developed and exhibited during London Design Week in 2018 and has since been published in several publications and exhibitions. Marilena has been a member of the judging committee of leading peer-reviewed international journal and conference.

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In addition to his research, Schoen is also involved in various projects and collaborations, and has been a regular contributor to the digital fabrication community. His work has been featured in numerous exhibitions and publications, and he has received several awards for his contributions to the field of digital fabrication and computational design.
We are pleased to announce that we have secured the domain name fabricate.org and are looking for partners to support us in building this space as a world-leading resource for design and making.

Our existing domains (fabricate2011.org, fabricate2014.org and fabricate2017.org) will migrate to the new timeless address soon.

If you are interested in finding out more about fabricate.org and future FABRICATE events, please email partners@fabricate.org.
FABRICATE 2017: ‘RETHINKING DESIGN AND CONSTRUCTION’ IS THE THIRD VOLUME IN A TRIENNIAL SERIES OF CONFERENCE PUBLICATIONS THAT BEGAN WITH ‘MAKING DIGITAL ARCHITECTURE’ IN 2011 AT THE BARTLETT SCHOOL OF ARCHITECTURE, UNIVERSITY COLLEGE LONDON. THE FIRST CONFERENCE EMERGED FROM A NEED TO EXPLORE THE WAYS IN WHICH TECHNOLOGY, DESIGN AND INDUSTRY ARE SHAPING THE WORLD AROUND US. IN 2017, THE CONFERENCE TAKES PLACE IN STUTTGART, WITH A FOCUS ON HOW NEW PARADIGMS ARE EVOLVING AND TAKING US IN NEW DIRECTIONS. THIS BOOK FEATURES THE WORK OF DESIGNERS, ENGINEERS AND MAKERS WITHIN ARCHITECTURE, CONSTRUCTION, ENGINEERING, COMPUTATION AND MANUFACTURING, ALL OF WHOM ARE WORKING TOWARDS EXCITING GOALS WITHIN FABRICATION. EXPLORING CASE STUDIES OF COMPLETED BUILDINGS, ANALYSES OF WORKS-IN-PROGRESS, THE LATEST RESEARCH IN DESIGN AND DIGITAL MANUFACTURING AND INTERVIEWS WITH LEADING THINKERS, FABRICATE ENGAGES WITH THE KEY CHALLENGES WE FACE DURING AN EXTRAORDINARY MOMENT FOR THE BUILT ENVIRONMENT.

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