Redefining structural art: strategies, necessities and opportunities

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SYNOPSIS

The UN Department of Economic and Social Affairs estimates that by 2050 the world's population will have increased by over 2.1bn people[1]. Providing housing and infrastructure for these people would essentially require building an amount equivalent to what currently exists.

It is simply not possible to build in the future the way we do today if we want to reduce greenhouse gas emissions, slow the depletion of natural resources and minimise waste production. These challenges can only be addressed if engineers and architects actively include them at the source of their designs.

Through full-scale, built research demonstrators by the Block Research Group at ETH Zurich, this paper presents strategies, based on advances in computational structural design and digital fabrication, to take on these challenges, offering opportunities for a necessary disruptive change. It furthermore calls for a rethinking of how we collaborate, teach engineering and develop building codes to allow for greater flexibility and innovation.

FIGURE 1: Armadillo Vault, Venice, Italy, 2016

IWAN BAAN

Redefining structural art

Previous generations of master builders, structural artists like Félix Candela, Eladio Dieste and Heinz Isler, pushed the boundaries of structural engineering. They were motivated by what David Billington came to define as the three 'disciplines': *Efficiency*, *Economy* and *Elegance*[2]. Often designing from limitations of budget, available materials and labour, such constraints also yielded ground-breaking innovations and new structural systems. A classic example is the *'sistema Nervi'* of Pier Luigi Nervi, an innovative group of solutions that grew out of material shortages and government restrictions, particularly related to steel-reinforced concrete, in Italy during and after World War II[3]. In this case, scarcity resulted in dramatic improvements in structural and material efficiency.

With the notable exceptions of Frei Otto and Buckminster Fuller, most of the visionary architects and engineers of the 20th century were not particularly attuned to ecological considerations; however, given the dire environmental crisis and the building industry's contribution to it, more recent scholarship has added *Ecological* and *Ethical* imperatives to Billington's three E's[4]. Though these latter two categories have too often been side-lined by the field as well as the broader public, the tide is changing. The expansion of the built environment due to the rapid growth of the urban population[5] poses a great challenge for sustainable development. Bill and Melinda Gates emphasised the problem succinctly in their Foundation's 2019 Annual Letter: '…the world's building stock is expected to double by 2060 – the equivalent of adding another New York City monthly between now and then. That's a lot of cement and steel'[6].

To appropriately confront the urgency of the environmental crisis, and to address the fourth E, *Ecology*, the building industry faces three immediate challenges:

- reducing pollution, specifically greenhouse gas emissions
- slowing the depletion of natural resources
- minimising waste production.

The challenge of pollution refers first and foremost to embodied emissions, since efforts to reduce this category lag behind what has already been achieved to reduce operational emissions[7–10]. The second challenge of resource depletion asks for a reduction in the demand of material used by the building sector, which is currently responsible for 40% of global resource consumption, resulting in the disappearance of essential virgin materials[11]. The third challenge of material waste centres on what is wasted during and after construction. In the EU, 25–30% of all waste produced by humans, or approx. 800M tonnes per year, comes from construction and demolition[12,13].

Finally, engineers also have an imperative to engage with *ethics* in construction, the fifth E of integrated structural art. The environmental challenges are imminent and our industry can no longer avoid its responsibilities. About 50% of the total floor area expected to be added by 2060 will be built in the next 15 years[14]: we need to take responsibility now to avoid locking in carbon-intensive building investments, especially in developing regions that lack stringent environmental regulations. Rather than signing off on absurd, wasteful or negligent projects, we must question when necessary and remain open to better, more appropriate methods in keeping with the specifics of each location and the availability of local resources and labour. As ethical engineers, we must remain proactively engaged throughout the design-to-construction process, in particular to ensure that these ecological imperatives are enacted. We cannot assume that someone else will take responsibility for them.

Strategies and necessities for change

Based on the arguments above, it should be abundantly clear that we need to change the way we design and build structures, but also that a collective effort is required to present solutions able to reduce pollution, resource depletion and waste.

One sensible approach is to design structures with much longer lifespans, which can resist a wider range of loads and be used for multiple functions. The philosophy here is to avoid demolition and the associated end-of-life waste. For buildings to retain their value, they should be designed to be more flexible and adaptable to avoid obsolescence[15].

An alternative approach is to achieve improvements in the impact of construction by designing structures that use fewer materials, allow more sustainable materials and are easier to recycle[7]. Such structures are lighter and can be more easily disassembled when obsolete. This approach, however, challenges engineers to rethink the way structures are designed and to strive for more efficient, less wasteful construction methods.

This section presents a) the principles that allow the realisation of the latter approach, as well as b) the tools that the Block Research Group (BRG) has developed in pursuit of feasible solutions for practice.

Strength through geometry and material effectiveness

'Strength through geometry' means achieving structural performance not by increasing material mass or strength, but by harnessing the power of well-thought-out structural design. Efficient structural forms, such as shells or vaults, can significantly reduce the required structural volume by placing material only where needed, i.e. by following the flow of forces for all loading cases. In particular, the use of funicular (i.e. compression-only) forms can, even with reduced structural sections, significantly reduce stress concentrations thanks to their ability to uniformly distribute the load across their section, thereby enabling the use of weaker and thus more sustainable materials[16,17].

Structural geometry also usually means the designer will have a clearer understanding of the force flow, and can thus separate compression and tension or strategically discretise the structure to control its structural behaviour. This separation increases longevity and improves recyclability: easier access to components that require protection (from corrosion, fire, etc.) better facilitates their inspection and replacement, and single-material systems allow us to easily discern material for recycling at the end of a structure's life.

However, the geometry of a structure cannot be separated from its materialisation: specific structural forms are more congenial to, or even require, specific materials; i.e. certain materials should be used with certain geometries. Usually, engineers focus on material efficiency; in doing so, they often forget 'material effectiveness'. In other words, structural design is often centred on the idea of optimising the amount of material (efficiency), sometimes without questioning if that material is the right one for that application (effectiveness). We need to use a material for what it is good for.

Concrete is a good example of this. Depending on loading and boundary conditions, large parts of reinforced concrete elements do not contribute to the performance of the structure and are just additional dead load. One could question whether, for spanning elements working in bending, reinforced concrete is indeed the right material, or if other materials or structural systems should be adopted. Tied, spandrel-wall-stiffened funicular vaults, for example, can best use concrete's compressive strength properties in an effective way (see section on *Making the change*).

When applied to building structures and combined with each other, these principles result in dramatic reductions of material quantities and overall weight of the main structural components, enabling a chain reaction of improvements that directly influences the foundation design, transport (cost and emissions) of materials to site, logistics and efforts of construction, etc.

Computational design and digital fabrication

Achieving strength through geometry requires the structural engineer to regain control of the geometry during the design process. Geometry is the universal language that connects the different fields of our industry, but in order to control it, traditional design tools are no longer sufficient, and new solutions are needed for both the design and analysis of structures. More importantly, the design process needs to radically change and encapsulate structural constraints (and ideally also many others, such as mechanical, fabrication or construction constraints) from the outset.

The efforts implemented on the planning, coordination and fabrication side with the introduction of building information modelling need to be matched on the design side with tools that allow all involved actors (architects, engineers, fabricators and contractors) to seamlessly provide input and set constraints for the generation of geometries that are both efficient and complex and integrate all performance criteria. The typical linear and iterative

←**FIGURE 2:** Sustainable Urban Dwelling Unit, Addis Ababa, Ethiopia, 2010

> **“IT IS POSSIBLE TO APPLY THESE INNOVATIONS IN REAL DESIGNS**

ESTO/ALBERT VECERKA

↑**FIGURE 3:** Ideas City Pavilion, New York, USA, 2015

approach is no longer possible or even feasible!

Advanced analysis, design and drafting software solutions are already available and in continuous development (e.g. Grasshopper or Dynamo and their numerous plug-ins). However, in research as well as in practice, time and resources are wasted connecting these software programs and setting up digital pipelines that often need to be completely reconstructed for each new project.

The challenges for our industry to dramatically improve its impact are too big to be continuously ‘reinventing the wheel’. Instead, we need to join forces and work together to achieve a new status quo, sharing best-practice experiences in computational strategies. BRG’s response to this is COMPAS, an open-source computational framework for collaboration and research in architecture, engineering, fabrication and construction (AEFC)[18].

To facilitate interaction and exchange between researchers and practitioners from various fields in the AEFC industry, and the adoption and integration of the tools, expertise and methods of their respective academic or professional communities, the computational core of COMPAS is designed to be entirely independent of computer-aided design software and finite-element analysis tools. It provides flexible and robust data structures, numerical solvers, geometry processing tools, topology algorithms, robotics fundamentals, extensive file format support and transparent wrapping mechanisms for state-of-the-art external libraries that can be used to tackle a wide variety of problems related to virtually every aspect of the modern AEFC development process.

Furthermore, through a unified scripting application programming interface (API) and flexible serialisation and data persistence mechanisms, the core functionality of COMPAS can be easily and consistently implemented cross-platform not only in tools such as Rhino, Grasshopper and Blender, but also in distributable standalone applications and even cloud-based web apps.

With these components and design principles, COMPAS addresses one of the fundamental problems of multidisciplinary collaboration in our industry: the lack of a common language between the different actors and their extremely heterogeneous style, know-how and skill level.

Architecture lags behind other industries not only on the computational side[19], but also on the fabrication side. The means and methods of today’s construction industry are substantially similar to those applied over a hundred years ago. This affects productivity, quality and waste production, especially for non-standard structures, such as structurally optimised geometries that need more efficient shaping strategies for their realisation.

Typically, the production of complex building components is slow and wasteful, but opportunities exist in digital fabrication technology, including full-scale 3D printing, robotic assembly or 3D knitting, which offer fast, versatile and less wasteful means of automated architectural production[20–22].

Digital fabrication not only improves precision and quality, but can also enhance productivity and engagement of labour[23]: the smart input of digital fabrication strategies simplifies logistics and makes building sites more efficient; it may also enhance work options and opportunities for workers, giving them more interesting, engaging or challenging tasks.

Thanks to new computational and digital fabrication techniques, geometry can now contain information and requirements from multiple disciplines. This makes collaboration more meaningful than the current sequential, compartmentalised state of the profession, in which the separation of architect, engineer, fabricator and contractor hinders innovation. It may require the reassessment of current norms and building codes, which remain generally risk-averse and rigid in their resistance to the changing situation.

Opportunities for change

Over the past 10 years, BRG’s projects have increasingly employed the strategies and necessary tools mentioned above to address ecological challenges. These projects can be seen as opportunities to change the way we design and construct building structures, showing that it is possible to apply these innovations in real designs. This section analyses case studies in relation to their varying approaches, and ways in which the different strategies and tools have played a role in the final design:

- Learning from the past: Armadillo Vault.
- Achieving more with less: SUDU, Ideas City Festival Vault, and MycoTree.
- Rethinking formwork: NEST HiLo shell roof and KnitCandela.

FIGURE 4: MycoTree, Seoul, South Korea, 2017

CARLINA TETERIS

Learning from the past

Built for the Venice Architecture Biennale 2016, the Armadillo Vault stood as a statement of strength through geometry rather than through 'an awkward accumulation of matter'[4]. Comprising 399 CNC-cut limestone voussoirs and held together in compression without mortar, glue or reinforcement, the vault spanned 15m with a minimum thickness of just 5cm **(Figure 1)**.

Inspired by Gothic stone vaults, some of which are proportionally as thin as an eggshell, the Armadillo Vault demonstrated the elegance of achieving strength through structural geometry and of effective use of material, made possible by the latest advances in computational design, optimisation and digital fabrication methods[24,25].

Because most modern engineers are stuck in 'Navier's straightjacket', as Heyman rightly puts it[26], such equilibrium structures can no longer be designed today, be it due to inappropriate analysis methods or the constraints of building codes[10]. These exceptional funicular structures are not driven by stress considerations, but demand a good structural form. We need to (re-)educate structural designers on how to discover these structural geometries, e.g. through graphic statics approaches[27], and develop norms that allow them to be reintroduced.

Achieving more with less

A series of structures, designed in collaboration with Prof. Dirk Hebel (Karlsruhe Institute of Technology) and his team and built in diverse locations around the world, addressed the challenge of achieving more with less, i.e. less cost, less waste, less pollution and less dependence on importing engineered materials, such as concrete or steel. These structures demonstrated that, when used effectively, weak materials with low embodied carbon can be activated as structural materials.

For the Sustainable Urban Dwelling Unit (SUDU) built in Addis Ababa, Ethiopia in 2010 **(Figure 2)**, tile and pitched-brick vaulting techniques were employed for the floor and roof respectively[28]. As a result, formwork was not needed, only strings to describe the geometry. More importantly, the tiles had no bending capacity, but because they were placed to follow a tied arch, and stiffened using spandrel walls, their compression strength of only 2MPa was sufficient to guarantee structural safety under all loading cases. Using soil from the site reduced pollution due to transportation of materials, and only a minimal amount of cement (7%) was required to stabilise the hand-pressed, air-dried tiles.

For the ETH Zurich Pavilion built for the New York Ideas City Festival in 2015, local waste products, specifically Tetra Pak from beverage containers, were compressed to form the 9mm thin sheet material from which the lightweight voussoirs that made up the arches were assembled. Thanks to post-tensioning with truck belts and triangular arch-sections, which gave the structure a higher depth for the same thickness and weight, the array of arches, connected at their top chord, was stable and safe for all loading combinations **(Figure 3)**.

Discrete masonry logic allowed for the vault's assembly without glue or mechanical connections, while the forces could be controlled to remain in compression, the key to being able to employ this weak material. Industrial pallets were used as temporary supports, so that the entire structure could be recycled and/or reused following the end of the event.

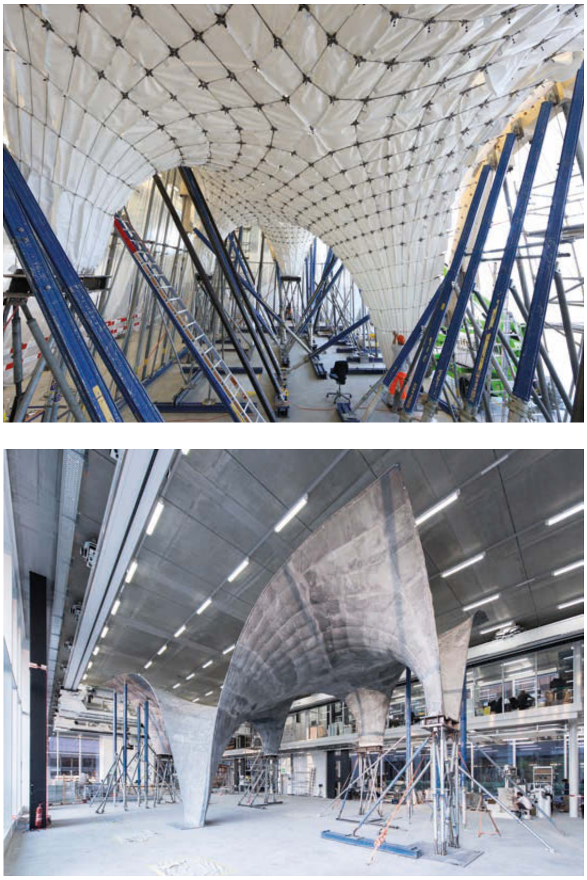
Finally, for BRG's most recent collaboration with Dirk Hebel, the team turned to a renewable resource – mycelium (the root networks of fungi). Built for the Seoul Biennale of Architecture and Urbanism in 2017, this structure embodied the concept of strength through geometry; the MycoTree's compression-only geometry was designed using 3D graphic statics and achieved through post-tensioning **(Figure 4)**. Thus, even something as weak as mycelium (with a compressive strength of less than 0.2MPa) could be used as a loadbearing material. Furthermore, as an organic material, the mycelium could be composted after MycoTree was dismantled[29].

Rethinking formwork

The strategies and tools used for the design of these structures can be applied to other parts of the construction process. While extending the lessons learned about building within hard constraints, achieving extreme thinness and efficiency of materials, and harnessing strength through structural geometry, recent projects have focused on the reduction of materials needed for, and waste produced by, formwork in concrete construction.

A lightweight, reusable cable-net and fabric formwork system was tested as a proof-of-concept construction prototype in the NEST HiLo shell roof, built on the campus of ETH Zurich in 2017 **(Figure 5)**. HiLo is a research and

FIGURE 5: One-to-one prototype for NEST HiLo concrete roof, Zurich, Switzerland, 2017



NAIDA ILJAZOVIC

MICHAEL LYRENMANN

> **“AS STAY-IN-PLACE FORMWORK, IT GENERATED PRACTICALLY NO WASTE DURING CONSTRUCTION**

MARIA VERHULST

ANGÉLICA IBARRA

innovation unit under construction on the NEST building in Dübendorf, Switzerland[30].

Rather than the typical milled foam or custom timber formwork used in the construction of complex shell structures, which also need extensive scaffolding and foundations to be held up, the flexible formwork system, developed as a kit-of-parts of mostly reusable components, marks a dramatic improvement in optimised construction and material efficiency.

Tensioned between boundary beams supported by a small amount of standard scaffolding props, the prestressed cable net was designed to deform into a predetermined shape under the weight of the wet concrete. An optimisation process found the specific, non-uniform distribution of forces needed to achieve this shape and was applied in stages to the cable net with an on-site control system[31,32]. Replacing the mass and waste associated with a traditional (brute-force) approach by intelligence and control was made possible because of computation.

↑FIGURE 6: KnitCandela, Mexico City, Mexico, 2019

KnitCandela, constructed in 2018 at the Museo Universitario Arte Contemporáneo in Mexico City, in collaboration with the Computational Design Group (ZHCODE) of Zaha Hadid Architects and Architecture Extrapolated (R-Ex), utilises a stay-in-place knitted formwork to realise its complex architectural and structural geometry, while minimising cost, weight, time and environmental footprint **(Figure 6)**[33,34].

Its non-standard geometry (a doubly curved, 3cm thick shell with stiffening ribs of a depth of 4cm running in both directions) would have required complex, costly, and time- and labour-intensive formwork if built with conventional methods, thus nullifying the efficiency and economic benefits of such a shape.

Instead, the cement-coated textile shuttering for the formwork of this 50m^2 shell structure provided the required strength and stiffness for the casting of the concrete using only minimal external formwork. As stay-in-place formwork, it generated practically no waste during construction.

The knitting took only 36 hours on an industrial knitting machine, which is much faster than the estimated 750 hours of milling it would have taken to realise a comparable mould surface in foam[35]. It also significantly reduced the carbon emissions from transport, as complex formwork parts did not need to be shipped to site. (In the future, only the data will travel, since local knitting machines could be utilised.) The lightweight 25kg knit was transported to Mexico City inside two suitcases as regular checked luggage.

In addition to benefits of speed of fabrication and ease of construction, the material cost for the cable net, knit and stiffening cement was less than £2000.

Making the change: funicular floor system

A highly efficient, funicular floor system developed by the BRG will be implemented in 2020 as a full-scale, code-compliant structural slab for the HiLo unit. The system shows that much-needed improvements to the status quo can be achieved through structural design. Its optimised, stiffened shell geometry significantly reduces the structural volume required by placing material only where needed **(Figure 7)**.

All common structural slab solutions (flat slabs, ribbed slabs, hollow-core slabs, etc.) use bending action to resist applied loads and need embedded reinforcement. Because of these two characteristics, they all:

- waste material to varying extents, due to section partialisation and reinforcement cover
- need more polluting, high-strength materials to accommodate inherent stress concentrations
- have a reduced lifespan, because of corrosion of the reinforcement
- are difficult to recycle, since the reinforcement is embedded in the concrete.

For these reasons, standard floor slabs usually make up half of a multistorey building’s structural mass.

Inspired by historic, vaulted floor structures in masonry, the funicular floor is designed to be in a uniformly compressed state under distributed loads and stiffened by thin ribs that help to accommodate concentrated loads and to avoid buckling of the vault. The compression thrust is then resolved with tying elements on the edges, keeping the tension and compression forces on distinct paths **(Figures 8 and 9)**. This allows for:

- the use of less material, because it is placed only where needed and does not require reinforcement cover
- the use of weaker and thus more sustainable materials, since the resisting section is fully utilised and stress concentrations are minimised
- an increase in the lifespan of the element, because the steel reinforcement is not embedded in the concrete.

The fact that the steel reinforcement is not embedded in the concrete also makes it easier to inspect, replace and recycle the entire element at the end of its use life.

Compared to a typical, solid floor of reinforced concrete, the funicular floor saves up to 70% of the material, which is analogous to removing more than one-third of the entire structural mass of a multistorey building, even without considering the consequent savings in the other structural elements, such as columns, cores or foundations.

The prefabrication strategies applied to the production of these elements can efficiently use digital fabrication through bespoke, 3D printed formwork constructed from fully recyclable materials. The discretised geometry resulting from the assembly of the prefabricated elements strategically keeps the force flow in compression under all loading cases by releasing bending in specific locations. In addition to controlling force flow, large settlements of the supports will not result in internal stresses. When detailing is done carefully, e.g. without using adhesives, a straightforward disassembly can be imagined, potentially contributing to a more circular economy[36].

Ongoing research by the group is investigating structural behaviour **(Figure 10)**[37], vibration and vibro-acoustic behaviour[38,39], functional integration, real-scale implementation and design for manufacture and assembly strategies. Future research will more specifically study the performance of the slab under non-gravity load cases (seismic excitation, diaphragm action, fire behaviour, etc.) and its use in multistorey building structures.

Thanks to these efforts, the funicular floor system will soon be available for large-scale construction as an alternative to common structural slab solutions, marking an important step in the disruptive change that our industry needs.

Conclusion

As the gravity of warnings concerning global warming and the health of our planet increases, we can no longer ignore the building industry's contribution to the crisis, nor can we continue to build in the same way we have for the last 100+ years, wilfully ignoring the pollution and wastefulness caused by this model.

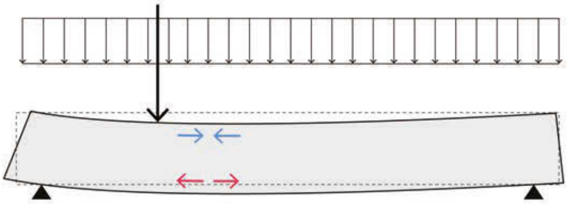
This paper is meant as a 'call to action' for a better way of designing and building structures: we need to collectively work on new solutions to meet the environmental goals. Redefining structural art requires diligent promotion of the ecological and ethical disciplines, which does not require a sacrifice of elegance, efficiency or economy, and questioning whether structural design and engineering are really at the pinnacle of knowledge, or if we may have forgotten important lessons.

Our architecture and structural engineering courses need to be revised to teach those historic, often forgotten principles that value design acumen over material strength and to include more computational and digital fabrication skills. Our building codes need to change and equip engineers with tools to design more innovative structures.

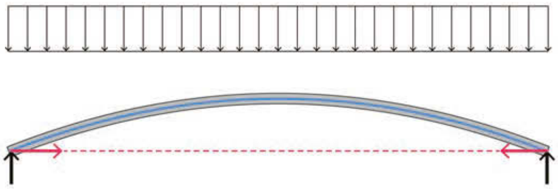
The BRG's research has shown that, when combined with the necessary computational and digital fabrication tools, principles like 'strength through geometry' and 'material effectiveness' can offer new opportunities to change our industry. But many more strategies are needed for different contexts.

Finally, no change is possible if it is confined within the walls of a research institute and is not embraced

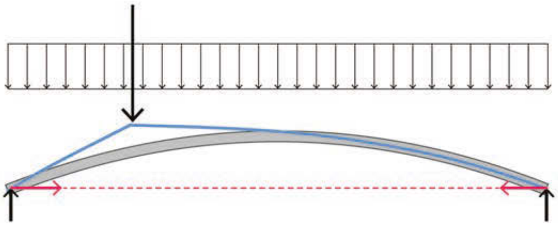
↓FIGURE 8: Funicular floor concept



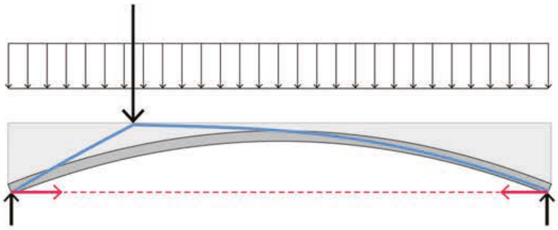
i) Standard concrete element resisting applied loads through bending action



ii) Same load is resisted through funicular (i.e. compression-only) action with dramatic material savings



iii) Concentrated loads modify thrust line, which is now outside section of funicular element



iv) Material is reintroduced (in stiffening rib) to enclose thrust line

↓FIGURE 9: Funicular slab's 3D force flow. Concentrated load is transferred to corner supports through compression in ribs; horizontal component is then equilibrated by tension ties along edges

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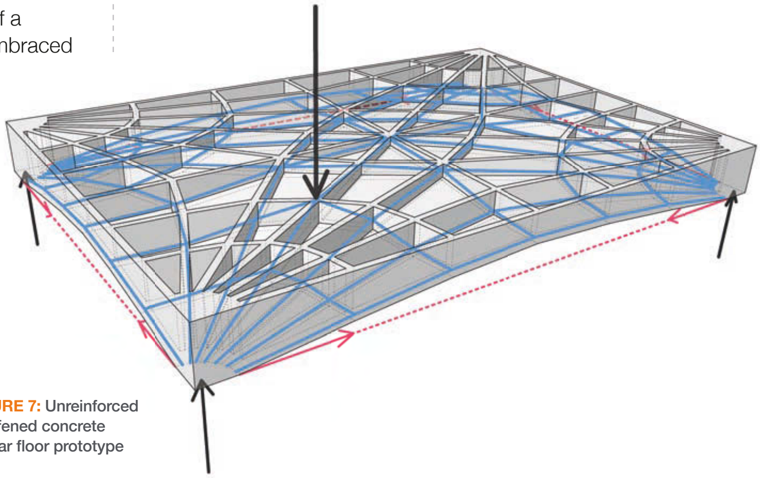
↖FIGURE 7: Unreinforced rib-stiffened concrete funicular floor prototype



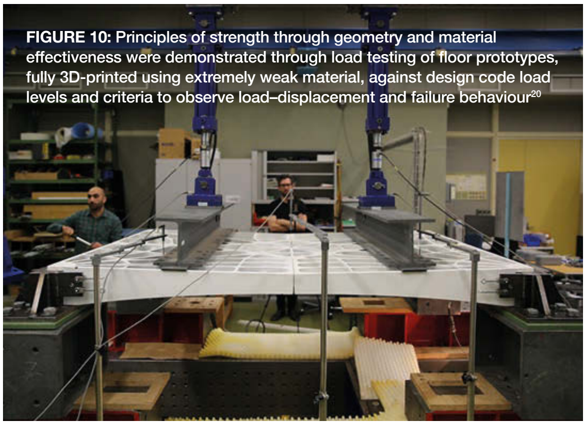


FIGURE 10: Principles of strength through geometry and material effectiveness were demonstrated through load testing of floor prototypes, fully 3D-printed using extremely weak material, against design code load levels and criteria to observe load–displacement and failure behaviour[20]

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by practitioners, contractors and developers. Whether it is for an iconic structure (such as a doubly curved, continuous shell roof) or one of the most common structural elements (such as a structural slab), architects, engineers, contractors, clients and developers must investigate, adopt and promote more sustainable design choices.

We have just about a decade to make a significant change[40]!

Dedication

The authors would like to dedicate this paper to their late co-author, colleague and friend, Dr Matthias Rippmann (1981–2019), whose contributions were essential to numerous research studies, innovations and projects from the Block Research Group at ETH Zurich.

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