E4: Efficiency, Economy, Elegance, and Ecology

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Design begins and ends with constraints. Yet, paradoxically, designing for and within constraints need not be constraining, since it is directly from constraints that innovations arise. Within the next three decades, the building industry will be forced to confront an extremely significant constraint, one that will require a paradigm shift. If current rates of construction are sustained and enough housing and infrastructure are to be built to accommodate earth's ever-growing population, an essential component of concrete – the planet's leading building material – will disappear by the middle of the twenty-first century. The sand that is needed to make concrete is a finite natural resource. We simply cannot continue to build 80% of the world's new construction in reinforced concrete, as we currently do. We cannot continue to ignore the indisputable fact of climate change, or avoid confronting the building industry's massive role in contributing to carbon emissions. The status quo is no longer acceptable. We have an imperative to do better, to design better.

The grand challenge presented by a rapidly disappearing natural resource and the necessity of reducing greenhouse gas emissions is also a grand opportunity for innovation, a chance for disruptive technologies and methods to emerge. We have not yet reached the point of no return, but we must find ways to design with fewer materials, to reduce structural volumes, to slow the rate at which we deplete natural resources, and to reduce or even eliminate the waste associated with construction. Good structural geometry, i.e. doubly-curved, compression-only, shell forms can address the problem of embodied carbon by significantly reducing the amount of material required, thus also reducing a structure's weight and its stresses. Unfortunately, these efficient geometries are often complex and complicated to build. They may require bespoke formworks that cannot be reused and are discarded after construction. If we are committed to exploring the use of such geometries and to exploiting their full potentials, we must also find ways to realise them without producing excessive amounts of waste. Here, innovations in digital fabrication can offer solutions at full construction scale, for example through large-scale 3D-printing, 3D-knitted formworks, etc.

The Master Builders of the previous two centuries, designers and structural engineers like Robert Maillart or Pier Luigi Nervi, believed in the "Three E's": Efficiency, Economy, and Elegance. Their works demonstrate the interconnectedness of these values, as well as the possibility of their equilibrium. Indeed, Maillart, who graduated from ETH Zürich with a degree in civil engineering in 1894, noted the integration of the Three E's when he wrote in 1931, "lighter, less costly, and thereby more durable construction [means] in other words … high quality work" and predicted that "light, slender structures will one day be praised … for being as beautiful or even more beautiful than massive ones."

Maillart came of age as a designer and structural engineer at a time when the status quo of building was also no longer viable, during the era when modern, reinforced concrete was slowly coming into wider use. The initial constructions in this material essentially sought to mimic stone's weight and bulk to imply strength. Hi first construction in reinforced concrete, the Stauffacher Bridge in Zürich (1899), was clad in a stone facade to disguise the shape of the bridge, which itself was technically advanced, but geometrically too far ahead of its time. Maillart's designs, epitomised in the iconic Salginatobel Bridge near Schiers, Switzerland (1929-30), which was named an International Historic Civil Engineering Landmark by the American Society of Civil Engineers in 1991, evolved to take advantage of – and proudly display - concrete's material and aesthetic properties. As Maillart later wrote, he believed "the engineer should free himself from forms handed down by the tradition of older materials in order to reach the goal of fully using the materials in complete freedom and with a view of the whole. Perhaps then we can arrive, as with modern airplanes and automobiles, at a similar beauty with a new style derived from the properties of the material." A newly developed material was thus at once a constraint upon and an opportunity for groundbreaking design.

To the list of the Three E's, our current situation now compels us to add a fourth: Ecology. While significant research and experiments are already being done to produce "greener", cleaner concrete, if we still follow our old ways of constructing, the amount of concrete used is already so large that the impact of the smarter materials is negligible. Additionally, a significant amount of embodied carbon is in the reinforcement steel needed in the bending structures. Only through designing differently to consider structural efficiency and by taking advantage of the opportunities offered through compression-only geometry can we instigate the necessary paradigm shift.

Furthermore, our current systems and practices may be impeding our progress. Design has become compartmentalised; the Four E's are not yet integrated. The architect is responsible for aesthetics; the structural engineer is responsible for safety; the building systems' team fits their cables and pipes into the designs handed to them; and the contractor tries to build the plans he or she receives from the design team as cheaply as possible. The challenge is how to better collaborate; the opportunity is found in computational and digital approaches, in design as well as in fabrication. We must become Digital Master Builders. Design must become more collaborative, with computation serving as the glue of the collaborative apparatus.

This also requires a change in our current pedagogical practices. Architects, civil engineers, and mechanical engineers rarely interact during their studies. They are educated in separate departments and follow mostly separate tracks during their coursework, but from Day One of their professional lives, they are expected to work together, to be able to communicate without having much of a shared language. The next generation of designers must be educated in a new way to facilitate a return to engineers as structural designers – in the manner of Maillart as the supreme example – not just engineers who sign off on architects' plans.

Further impediments may also come in the form of our established building codes. Like the engineers who write them, the codes are risk-averse, making it possible for engineers to hide behind the codes and norms for specific types of construction – the types that are rapidly injuring if not killing our planet. The codes were developed based on decades of empirical research and testing, leading of course to inflexibility and a deep-rooted fear that by changing the system, all that work must be redone for new ways of designing. However, when the "new" ways are also in fact the old, methods that have withstood the test of time, like the eggshell-thin vaults of the King's College Chapel at Cambridge University, the solutions that allow us to do better are actually the "smart" systems of the past: arches, vaults, and shell geometries.

The rib-stiffened funicular floor system developed by the Block Research Group (BRG) at ETH Zürich represents this connection of past, present, and future, as well as an effort to integrate the Four E's. The structural elements of a building account for up to 50% of its embodied energy. In buildings with ten or more storeys, at least 80% of the weight of that structure is contained in the floors, which are most commonly built as thick slabs of reinforced concrete. Rib-stiffened funicular floors are doubly-curved shells that carry loads efficiently in compression. Tension is absorbed externally in tension ties rather than by embedded steel reinforcement. By externalising the steel components, these can be more easily accessed, making fire-proofing, corrosion protection, and maintenance much easier. Most importantly, this leads to a dramatic reduction of structurally unnecessary concrete, which is typically required by building codes to protect the steel parts and is a result of a simplified casting on standard, flat formwork elements on site. This carving out of the floor slab, leaving only what is needed for efficient force transfer in compression for all load cases, results in a reduction of the amount of material used by 70% or more depending on the floor span. Parts that would have been filled with material in typical beam or plate structures instead become cavities. The stiffeners between those cavities can be perforated without reducing the floor's structural performance. This means that pipes, wires, mechanical systems and so on can be inserted and routed through volumes of the floor system that were previously inaccessible. Since building systems no longer need to be placed in a separate layer, storey height can be reduced and much more real estate becomes available for the same overall building height; depending on the context this can be as dramatic as three floors instead of two. Such a project, which is currently being researched at ETH by the BRG together with the Chair of Architecture and Building Systems (A/S), lead by Prof. Dr. Arno Schlüter, demonstrates how computational and digital tools become the glue that binds true collaboration in a design team.

By taking the dramatic reduction of required materials as its guiding principle, the floor system is an example of how the fourth E – Ecology – may be added to the Three E's of Efficiency, Economy and Elegance. The next iterations of the system will be fabricated using two distinct but related methods that both strive to reduce or eliminate construction waste and unnecessary structural weight. The first floor will be cast on a knitted formwork consisting of a custom-knit fabric with integrated channels for the insertion of a capillary tube network that forms a low-temperature, highly efficient, water-based heating and cooling system. The extremely lightweight, flexible fabric is tensioned on site to create the correct geometry. It is then coated with a custom-developed cement paste to create a rigid, self-supporting mould for casting the concrete ribbed floor. The second floor uses a fabrication process based on 3D-printing technology. A thin-walled mould for casting the concrete shell and ribs will be printed in a recyclable material in a small number of discrete parts and assembled on site to form a self-supporting, stay-in-place formwork. The flexibility of the fabrication process enables the integration of ducts and cavities for an air-based heating and cooling system directly into the mould. In both systems, force/deflection and temperature sensors will be cast into the floors to monitor the long-term behaviour of the optimised systems, allowing for the improvement of the structural and thermal analysis and simulation models. These demonstrations of long-term performance also represent important efforts to demonstrate the safety and feasibility of the system and to reduce further the risks for adoption by industry of this disruptive technology.

The following outlook is even more ambitious: even though they are so thin and lightweight, because of their compression-only forms, the floors have low stresses - more than ten times less than those of standard concrete. This means the typical materials can be replaced by weaker ones. Since the strength of a material is directly proportional to its carbon footprint, by using weak materials, we can significantly lower the environmental impact. We can seek extremely low or even no-impact alternatives to the Ordinary Portland Cement (OPC) concretes currently in use; we can replace those with novel “concretes” produced entirely from recycled and/or waste products or even with naturally grown and therefore renewable materials.

Thus, we remain vigilant in our efforts to challenge the status quo. We seek to achieve this by implementing good structural geometry as exemplified in doubly-curved, compression-only forms, by addressing rather than ignoring the imminent depletion of natural resources, and by constantly seeking new ways to reduce or eliminate construction waste. The constraint of the eventual scarcity of concrete offers us the chance to instigate the necessary paradigm shift. Rather than an impediment, this challenge grants us the opportunity to design better.

Appeared in:
Folkers, G. and Schmid, M. (Eds.) *Design - Tales of Science and Innovation*, Chronos Verlag / Collegium Helveticum / ETH Zurich, Zurich, 2019.