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The Future of Lightweight Structures in Research and Practice The Stuttgart Model

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Abstract

Lightweight structures are quintessential for mastering the upcoming (and interrelated) challenges of climate change and resource scarcity. They can best be advanced by an integrated use of digital technologies in the design, construction, and operational phases up to disassembly: this approach requires a tight cooperation of all disciplines involved. At the University of Stuttgart, there is a strong tradition of interdisciplinary collaboration on lightweight structures, made famous by Fritz Leonhardt, Frei Otto, Jörg Schlaich, and Werner Sobek. Based on these forebears, the ILEK in partnership with other institutes currently focuses its research on two main structural areas: sustainable lightweight structures made of concrete, and adaptive structures. In the first field different digital design and fabrication methods are used to develop and build innovative filigree structures, reducing the amount of generated greenhouse gases (GHG) and waste. In the field of adaptive structures, the use of sensor, actuator, and control technologies helps to achieve extremely light systems, as the 36.5 m tall experimental tower D1244 demonstrates.

The design and construction of large-scale demonstrators and the close link with innovative practice is the second key element of the "Stuttgart Model". This is also the case for two innovative lightweight shell structures which have been recently completed: The New Stuttgart Railway Station and Terminal 2 of Kuwait International Airport. Both projects show parallels between research and practice with regard to the use of digital technologies. The experience gained in exploiting the computational power in these two projects are today part of the background the author builds upon in pushing the boundaries of his research. It is the mutual exchange and transfer between research and practice that can help accelerating the transformation of the building sector towards a more sustainable future: For this, improvements in the digital chain from design up to disassembly will play a relevant role.

Keywords: lightweight concrete structure, adaptive structures, shell structures, digital fabrication, parametric engineering, sustainable built environment.

1. Introduction

The research work carried out at ILEK covers a wide range of materials and structural systems. The overall target is to increase resource efficiency, to reduce greenhouse gas (GHG) emissions related to the built environment, and to foster reusage and recycling in the construction field, in order to respond to the interrelated challenges of resource scarcity and climate change [1]. The exploration of innovative fabrication and control technologies as well as the integration of all kinds of digital tools are considered crucial to achieve this goal.

The research focus is set on lightweight structures, as these systems per se optimize the amount of resources. However, the role of emissions and waste is not sufficiently considered in traditional lightweight approaches. Therefore, the author is focusing the research at ILEK on lightweight structures that also have a small ecological footprint, thus also better assessing the role of emissions and waste. This holistic concept is referred to by the author as "*Extended Lightweight Approach*". Concrete structures play a relevant role in this context [2], due to the importance of this material for resource consumption, emissions, and waste generation in the building sector. Each research project, which is selected at the ILEK in this area must address these three aspects: the themes spans from filigree lightweight concrete structures, either produced with complex water-soluble sand formwork [3] or achieved by means of mineral hollow bodies [4], up to the further development of structural materials with a potential CO_2 positive balance as bio-concrete [5].

The second main field of research deals with adaptive structures. Within the Cooperative Research Center CRC 1244 "Adaptive Skins and Structures for the Built Environment of Tomorrow" the ILEK investigates together with 15 other institutes the potential of adaptive technologies for a significant reduction in resource consumption and climate-damaging emissions [6]. Active manipulation of the geometry and the structural behavior makes it possible to optimize for certain structural typologies stress distributions, reduce deformations, and dampen vibrations. To verify the knowledge gained, the world's first adaptive high-rise building D1244 was built on the university campus in Stuttgart-Vaihingen in 2021. The 36.5 m tall adaptive tower serves as an experimental platform for the research: 24 hydraulic actuators are integrated into the steel structure of the tower, in order to dampen vibrations and reduce excessive deformations [7]. This allows for significant material savings compared to conventional passive structures, which are typically over-designed to withstand strong but infrequent loads.

Although these two fields of research appear to be quite distinct from each other, they share a common goal and vision (the pursuit of a light ecological footprint for the structures of the future) and rely on a strong interdisciplinary approach. Structural and mechanical engineers, architects, computer scientists, experts in system dynamics and thermodynamics, as well as biologists, are working closely together to explore new paths towards lightweight and sustainable structures. This builds on the tradition established by Fritz Leonhardt and Frei Otto with the first collaborative research center in the field of construction, the CRC 64 "Long Span Lightweight Structures", founded in Stuttgart in 1970. This special approach, based on a dense network of disciplines, is called the "*Stuttgart Way*". It has become one of the trademarks of the University of Stuttgart.

Figure 1: The main site of the ILEK, designed and built by Frei Otto (© ILEK)

The second pillar of the Stuttgart model for architectural engineering is the close link between research and innovative practice in the building sector. It relies on the fact that leading researchers also have a strong professional background. The author was also deeply involved in professional practice for more than 15 years before returning to the university. He therefore believes that this link is essential to quickly foster innovation in the built environment and to accelerate the transformation of the building sector towards a more sustainable one. He has selected two of the most innovative building projects he has been responsible for so far, and outlines the links (but also the differences) between the innovation carried out in practice and the accents he has set in research since he took over the leadership of the ILEK in 2020.

2. The research work on lightweight concrete structures

The research on filigree lightweight concrete structures follows two complementary directions: either the formwork is complex [3] and the resulting lattice optimized structure is visible; or the formwork is kept simple and the interior space is optimized by means of mineral hollow bodies. The first direction will not be discussed in this paper, since it is the focus of a second specific paper on the Marinaressa Coral Tree, which was exhibited within the frame of the Architecture Biennale in Venice. In the following the recent developments in the field of functionally graded concrete (FGC) are presented; this work is based on the approach developed by Werner Sobek at the ILEK over the last 18 years [8]. An outlook on the current research on bio-concrete complete the overview of the concrete research (see 2.2).

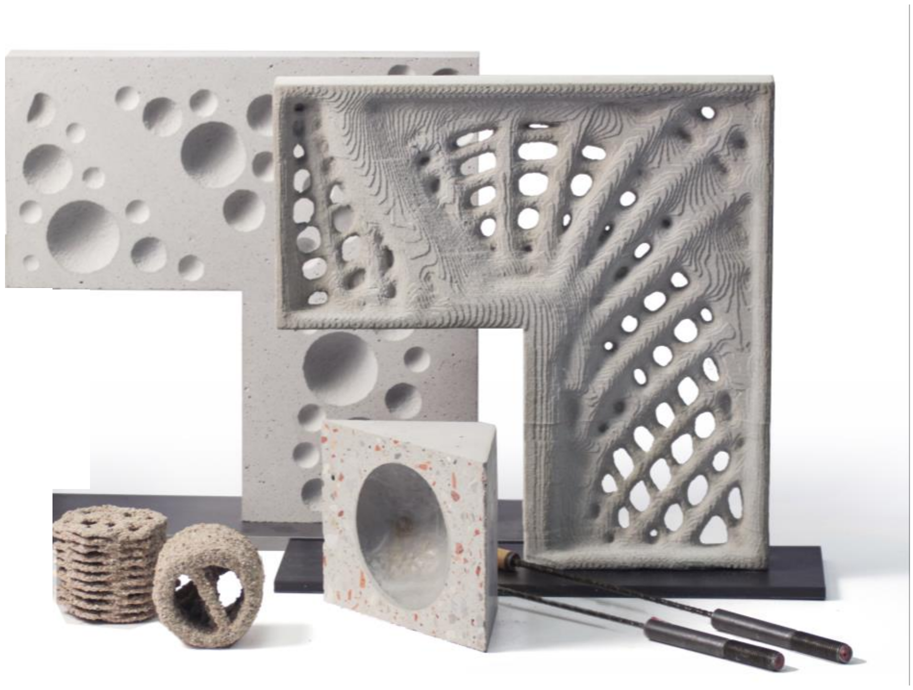
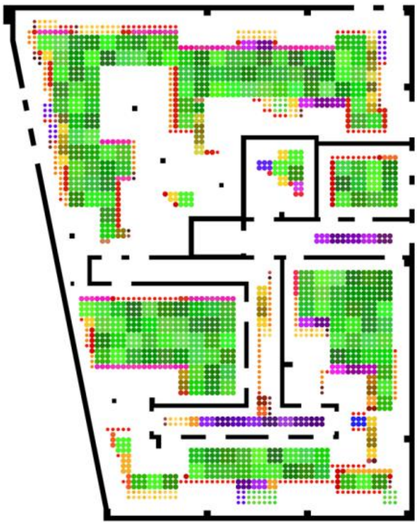


Figure 2: Research prototypes on lightweight concrete structures at ILEK, from left to right: 3D-printed bio-concrete specimens, hollow-sphere cantilever and cut-out from functionally graded component with recycled aggregates, cantilever produced with 3D-printed watersoluble sand formwork, basalt reinforcement (© ILEK)

2.1. Recent developments in the field of functionally graded concrete

Since 2020 the research on functionally graded concrete has been focusing on slab systems, thus addressing biaxial load transfer and the behavior of multi-span systems [9]. The approach is based on Marcus' strip-cross method, which divides a slab with biaxial load transfer into intersecting beams with the same cross-section and boundary conditions. As a demonstration, the world's first full-scale graded concrete slab was designed for the Large-Scale Construction Robotics Laboratory (LCRL) of the IntCDC cluster of excellence at the University of Stuttgart. The slab has a size of about 610 m2 and a height of 45 cm; circa 2.900 mineral hollow spheres (most of them with D=30 cm) are currently being manufactured, so that the foundation slab is expected to be completed within 2024.



	3 × 3	3 × 2	2 × 2	3 × 1	2 × 1	1
d = 30 cm	205	26	62	19	8	116
d = 20 cm	4	5	24	33	17	125

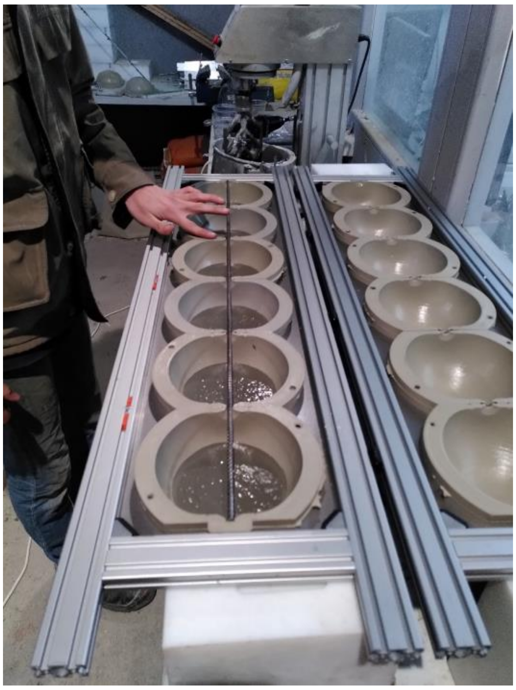


Figure 3: LCRL foundation slab: Left: hollow body layout. Right: preparation of the hollow bodies (© ILEK)

The positioning of bundles of mineral hollow bodies has been defined by means of a developed design algorithm [10], which responds to the given static boundary conditions of the structure. Hierarchical bundles can be defined by the designer in the input interface to account for manufacturing constraints due to transportation, human physical limitations, or robotic gripping. The overall target is to generate a consistent digital chain, which goes beyond design and manufacturing, including in perspective a fully robotic pick-and-place process.

Moreover, the fire performance of these slabs has been evaluated numerically [11] and experimentally, demonstrating that a 90 min fire resistance is achievable without special measures. Current research is also exploring the potential of FGC slabs, prestressed with basalt fiber rebars to increase their stiffness [4], [12]. Given the volcanic origin of basalt, its availability in large quantities and its better ecological footprint compared to other fiber reinforcements (i.e. carbon fibers) [13], this is a promising material to replace standard reinforcement materials, thus also reducing the required concrete cover to a minimum. At the same time, this opens up the possibility of creating a concrete building element consisting almost entirely of mineral components.

2.2. Bio-concrete

The research at ILEK also deals with the material level of the *Extended Lightweight Approach* [12]: In particular, alternative binder materials are investigated that avoid the process-related CO2 emissions caused by the hydration of Portland cement. Through a process of biomineralization the aggregates are bound by calcium carbonate crystals [5]. These crystals are produced by microbially induced calcium carbonate precipitation (MICP). The resulting mineral material is similar in chemical composition to carbonate cemented sandstone and cement-bound concrete, hence the term bio-concrete. High compressive strength values of biomineralized specimens (> 50 MPa) could already be achieved by maximizing the aggregate content and adjusting the cementation parameters [5]. Yet, since one of the challenges is the "cementation depth", one of the outlooks of the research is the combination of lattice systems, produced by means of additive manufacturing technologies, with bio-concrete as a material. This way the maximum depth of each strut is limited and the cementation level could be further improved. The first 3D-printed bio-concrete samples are shown in Fig. 2, bottom left.

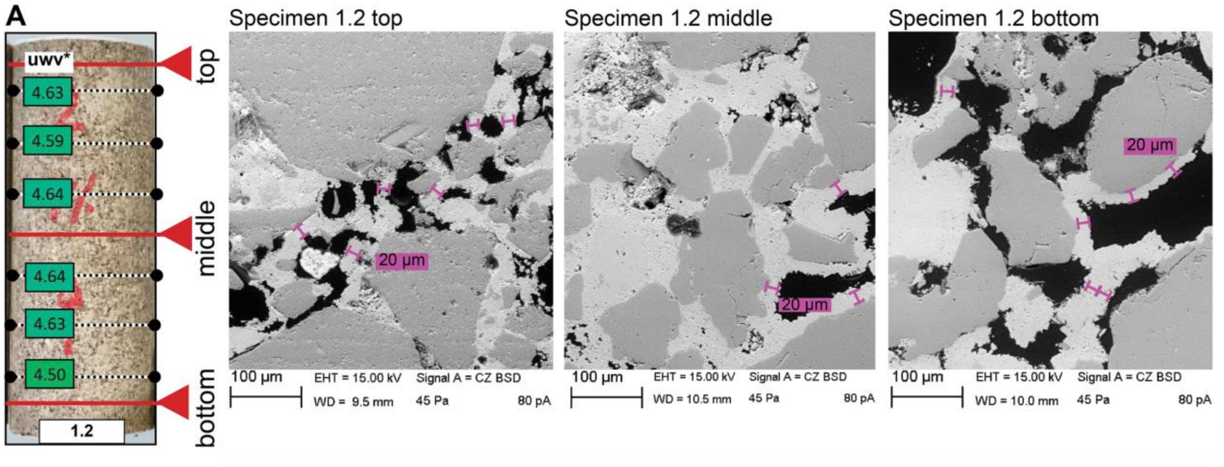


Figure 4: Cross-sections from the top, middle and bottom parts of specimen 1.2. The corresponding images of the specimens with the ultrasonic wave velocity values at the marked points and the positions of the samples taken for the ESEM analysis (indicated by the red arrows) are provided on the left side of the figure [5].

3. The research work on adaptive structures

The target of drastically reducing the ecological footprint of the built environment is also the main compass for the research works carried at the ILEK on adaptive structures with several partners of the University of Stuttgart. The active manipulation of the geometry and the structural behavior through a proper use of sensor, actuator, and control technologies allows for significant material savings in the structures, especially in typologies as high-rise buildings or certain bridges. D1244, an experimental modular 36.5 m tall high-rise building, was built in 2021 on the university campus to show the potential of adaptive structures as well as to verify the developed systems and the related simulations [7]. Due to lateral loading (e.g. wind), material input requirement in high-rise structures increases exponentially with gaining height; therefore, this approach offer a great opportunity to reduce the structural mass.

Figure 5: Demonstrator high-rise building D1244 at the University of Stuttgart (© Rene Müller)

The steel structure is divided into four three-stories modules; the bracing system consists of diagonal cross bracings positioned on all sides. An actuator placement algorithm has been developed, with the target of determining which structural elements should be active (i.e. equipped with actuators) to achieve the best possible compensation of stationary disturbances and increase the damping properties, yet using a reduced number of actuators. As a result, twenty-four hydraulic actuators were installed in the columns and diagonal bracings: 12 of them are placed at the ground floor, eight at the 4th level and the remaining 4 at the 7th level (see Fig. 6). The actuators integrated in the columns are placed in the cavity of the hollow steel section and work in parallel, whereas the actuators integrated in the bracings are placed in series, since they are subjected to smaller forces [7]. This setup allows for approx. 50% steel savings. Strain gauge sensors and an optical tracking system are employed to monitor the state of the structural system. The static and dynamic structural response is predicted through FE calculations.

Figure 6: D1244. Left: Actuator placement in the 3D axis model (the bold line indicates the actuators). Right: Actuators and hydraulic system at one corner of the ground floor (© ISYS)

All elements are dismountable; thus, columns, bracing elements, floor slabs as well as facades elements can be replaced. This provides not only a flexible experimental framework for future research, but also an interesting case study for investigating how building structures can be modified and upgraded over time without generating additional waste. In addition to it, adaptive technologies are being investigated for the design of railway bridge structures [14], since these are characterized by strict displacement and acceleration limits, which typically lead to oversizing. An adaptive under-deck tensioning system with linear actuators (EAT) has been developed, where the adjustment of the length of the linear actuators generates a bending moment that counteracts the effect of the external loads. Numerical results show that the active control by the EAT system allows satisfying the displacement and acceleration limits; a significant reduction of the response is achieved when resonance conditions occur. According to initial analyses, this solution can achieve mass savings of up to 32% compared to an equivalent passive bridge.

4. Lessons learned from the practice

The link between research and innovative practice in the building sector is a relevant key of the Stuttgart Model to accelerate the implementation of innovations in the built environment. Two large scale shell structures are presented and the related use of digital design and fabrication methods as medium to achieve more resource efficiency is critically analyzed.

4.1. New Stuttgart Railway Station "Stuttgart 21"

The new Stuttgart railway station Stuttgart 21 is one of the core projects in the overall effort to modernize the connection between Munich and Paris. The 447 m long and 80 m wide underground hall has been designed by Ingenhoven Architects and engineered by Werner Sobek AG. The roof structure of this hall consists of a shell structure supported by 28 doubly curved columns: the so-called "chalices". The engineering and fabrication of this complex structure has been made possible by the extensive use of customized scripting to generate parametrically the required models [15]. Since the thickness of the concrete shells is not constant, the traditional generation of a FE-model was not possible at the time the design development phase started (2009). Therefore, the middle surface for the structural analysis was generated out of the architectural outer and inner surface in Rhinoceros using custom scripting. The same approach was used also to parametrically generate the mesh , so that a text file with all the necessary information (i.e. node coordinates, element numbering, node thickness, etc.) could be exported to the FE-program SOFiSTiK (see Fig. 7 left).

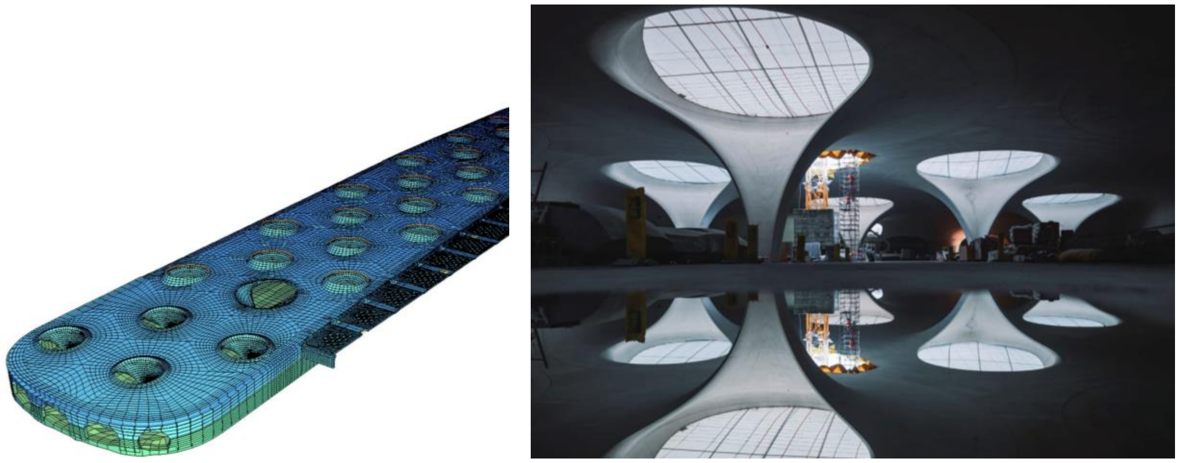


Figure 7: Railway Station "Stuttgart 21". Left: FE-model of the railway station (© Werner Sobek AG)
Right: View of the underground station at the final stage of the construction works in 2023 (© Moritz Metzger)

The design of the reinforcement was also supported by a parametric approach: the axes where generated automatically and then polygonised in Rhinoceros by means of custom scripting. The grouping of rebars within predefined geometric tolerances was also visually highlighted by color coding, (see Fig. 8 left). The same software was also used for a preliminary clash control and to make sure that the minimum cover was assured.

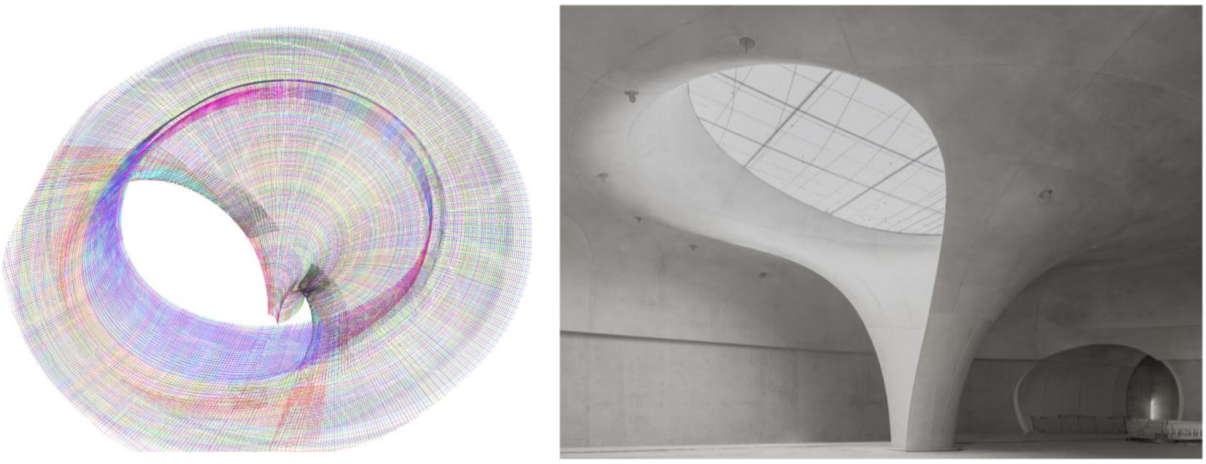


Figure 8: Railway Station "Stuttgart 21". Left: 3D parametric model of the concrete reinforcement (© Werner Sobek AG)
Right: View of one the built 28 concrete "chalices" (© Ingo Rasp)

Later on, the information was transferred into the contractually required construction drawings by means of the program Allplan/Nemetschek and used as the basis for the automatic manufacturing of the rebars. The 3D model was also used by the construction company (Ed. Züblin AG) for the development of the formwork construction (Ed. Züblin AG). Due to the complex approval process for this type of structure, the entire engineering work took more than 10 years. The preparation of the construction works started already in 2014, but the concrete shell structures were not completed until 2023. Fifteen years after the start of the process is a good moment to carry out a review: on the one hand, it is only thanks to the extensive use of digital tools and the parametric approach that engineering and manufacturing were possible. On the other hand, at the time some steps in the overall process could not be fully automated, thus resulting in a huge effort and a lot of construction documents. The timeless elegance of the completed structure (see Fig. 7 right) is worth the effort. Today, however, we could be much more efficient.

4.2. Terminal 2 of Kuwait International Airport

The roof structure of the Terminal 2 of the Kuwait International Airport offered the chance for the next generation of shell structures to be engineered and manufactured based on a parametric approach. The new terminal designed by Foster and Partners is characterized by a continuous shell structure which allows for a naturally shaded entrance areas and a flexible interior space. The schematic engineering work was carried out by ARUP [16], whereas Werner Sobek AG was appointed by the general contractor LIMAK to carry out the design development and to prepare the construction documentation [17].

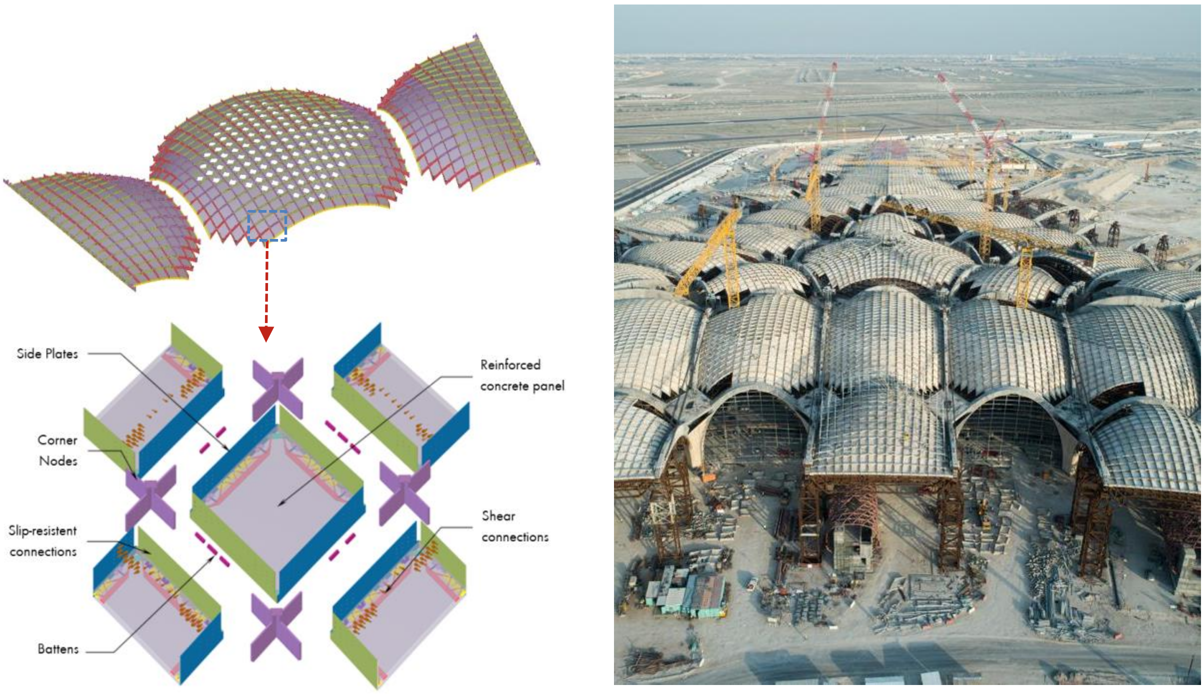


Figure 9: Kuwait International Airport T2. Left: Tekla fabrication model of a shell (© Werner Sobek AG)
Right: Aerial view of the Kuwait International Airport construction site (© Foster + Partners)

The shell structure spans up to 120m between the main bearing post-tensioned reinforced concrete arches (see Fig. 9 right). The process relied on the experience gained from engineering the train station "Stuttgart 21": The preprocessing was scripted parametrically in Rhinoceros, thus allowing for a centralized and flexible generation of the geometrical and structural input data (single source of input). This data was then exported to other software programs (SOFiSTiK for the FEM analysis, Revit for BIM coordination, Tekla and Allplan/Nemetschek for CAD/CAM purposes, etc.). The 320,000 m^2 big shell structure is segmented and prefabricated: It is made out of 37,000 elements called 'cassettes', and out of 41,000 bolted cruciform connection nodes composed of 40mm thick steel plates (see Fig. 9 left).

Each cassette consists of four steel side plates and a 160mm thick double-curved reinforced concrete panel. Based on a specific parametric description, the height of the plates varies between 560mm and 1,300mm. Depending on the structural utilization, the wall thickness of the side plates was optimized by the author and his team within a range from 10 to a maximum of 20mm. The concrete double-curved panels were cast using 85 adaptive molds: this allowed 13,000 different geometries to be produced, mainly with an automatic set-up change driven by the modeled surfaces. No milled foam was required as in other projects of similar geometric complexity and there was no waste generated out of the formwork.

In short, the structure relies on a much higher level of prefabrication and modularization than Stuttgart 21, and thus achieves a very high level of precision, despite the fact that the production facility is right next to the site. It was also possible to convince the client to accept the models as source for fabrication and control. Although the roof is about ten times larger than the Stuttgart 21 roof, the number of drawings required was about1/10 and the overall structure was more sustainable. In addition, the structure in Kuwait was completed one year before Stuttgart 21, although the construction began two years later.

5. Conclusion

The present paper presents a wide range of recent research and practice projects, all of them based on the lightweight tradition following the so-called *Stuttgart Model*. The author is convinced that much more lightweight structures are needed in the built environment, in order to reduce the amount of natural resources used. Furthermore, the search for optimal lightweight solutions should include a proper evaluation of the associated GHG emissions and waste generated: This has been defined as *Extended Lightweight Approach* and is the key to all lightweight research at the ILEK. The objective is to contribute to addressing the interrelated challenges of resource scarcity and climate change.

Digital tools in the design and fabrication phase -if properly used and linked- offer a powerful medium to achieve this goal. However, the potential is much greater if such tools are also integrated into the operational phase, as demonstrated, for example, by the research on adaptive systems. Moreover, this approach could also be used to support disassembly and reassembly (designed for reuse). Such a holistic way, covering the span from design to reassembly has yet to be widely implemented in the practice. The interdisciplinary research carried out together with mechanical engineers, computer scientists and experts in system dynamics and thermodynamics helps to think outside the box and proves that much more is possible. It breaks new ground in order to raise the level of innovation in the building sector. This is the first pillar of the Stuttgart Model.

The second pillar is the close link between research and innovative practice to properly support the necessary transfer. The use of digital tools has proven to increase resource efficiency in long-span roofs for example, by rethinking concrete or hybrid shell structures. This is a first step. However, this approach has worked for the two projects shown because their size and iconic character allow significant development work to be integrated into the engineering phase. The current challenge in the practice is to extend the use of this approach to a wider range of projects. In addition, the target is to raise the attention being paid by architects and engineers to grey emissions and waste production. And so, the looping between research and practice can accelerate the necessary transformation of the built sector, together with all other stakeholders from industry, politics and business.

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