

PHD THESIS

ARCHITECTURAL ENGINEERING **TO** SUPER-LIGHT STRUCTURES

-DESIGN, IMPLEMENTATION AND CONSTRUCTABILITY

ANDREAS CASTBERG

Technical University of Denmark
Department of Civil Engineering
Section for Building Design

Copyright © 2013
by Niels Andreas Castberg

All rights reserved. No part of the material protected by this copyright notice may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, recording or by any information storage and retrieval system, without explicit written permission from the author.

Preface

The intention with this PhD thesis is to engage and contribute to the creation of varied and structurally challenging architecture by investigating the enriched opportunities via the use of Super-Light Structures. The hope is to bring the opportunities of these structures into the architectural idiom.

The thesis focuses on the opportunities of Super-Light Structures and the interplay between architects and engineers during the development of structural concepts. The intention has been to challenge the common perception of this interplay and to examine how architectural engineering may contribute to an improved shared understanding and use of engineer knowledge in the early design phases. It is the hope that the more holistic view represented by architectural engineers, will influence the design process and utilise the advantages of Super-Light Structures by integrating the structures in structural concepts to the benefit of the architecture.

This thesis is submitted as part of the requirements for the Danish PhD degree.

August 2013
Niels Andreas Castberg

Acknowledgements

I would like to express my sincere gratitude to my supervisor Professor Kristian Hertz for the opportunity to become a PhD student and for guidance throughout the study. My thanks are extended to my colleagues in the Section of Building Design at DTU Department of Civil Engineering for encouragement and professional discussions.

A great debt of gratitude is also owed to Bjarke Ingels Group for accepting me as the first PhD student in their office. I wish to thank everyone at Bjarke Ingels Group, especially Finn Nørkjær and David Zahle for taking a genuine interest in my work and being willing to involve me and my research in their projects.

I am very grateful to my parents for always supporting and motivating me for studying despite my dyslexia. Thank you; Filip and Julie for your invaluable help with proof-reading. Finally, I wish to express my deepest gratitude to my family and especially my wife, Julie, for their invaluable support, love and understanding throughout my studies.

Abstract

The increasing global urbanisation creates a great demand for new buildings. In the aim to honour this, a new structural system, offering flexibility and variation at no extra cost appears beneficial. *Super-Light Structures* constitute such a system.

This PhD thesis examines *Super-Light Structures* with *architectural engineering* as a starting point. The thesis is based on a two stringed hypothesis: Architectural engineering gives rise to better architecture and Super-Light Structures support and enables a static, challenging architecture.

The aim of the thesis is to clarify architectural engineering's impact on the work process between architects and engineers in the design development. Using architectural engineering, Super-Light Structures are examined in an architectural context, and it is explained how digital tools can support architectural engineering and design of Super-Light Structures. The experiences of implementing a new structural system are described, as well as cases, demonstrating how concept solutions with Super-Light Structures can support architecture.

The research in this thesis is carried out in cooperation with architect practice Bjarke Ingels Group (BIG), who has allowed the projects to be subjects of examination for this thesis.

The research results show that architectural engineering has a significant impact on a design process. The projects illustrate that simple explanations, underpinned by visualisations of the challenges between shape versus structure, often creates a shared understanding between architects and engineers that has a positive impact on the design process.

In the thesis, digital tools are examined that allow interaction between parametric modelling tools and finite element programmes. They are of great help in designing complex Super-Light Structures. Also, they proved to significantly reduce the engineering response time, permitting the engineers to play a more active role in the design process. However, evidently, the tools were developed for other purposes, why further development for architectural engineering and Super-light Structures is recommended in order to exploit their full potential.

Implementing Super-Light Structures, non-transparent responsibility distribution and low risk-taking proved to be significant barriers for new products in the building industry. The thesis does not answer the question whether it is easier to launch a fully-developed product on the market, or to finalise the development in collaboration with the market players. However, it seems easier to convince market actors to adopt a finalised product.

Super-Light Structures - mainly in the form of the SL-deck - proved very suitable at supporting the architecture in the examined projects. The greatest advantages were the option of making cantilevered structures and use of joints and integrated beams, which, because of their flexibility, seemed easier to integrate into the architectural concepts. The concept of Super-Light Structures has matured during the study period, but the concept still has a considerable unexploited potential.

The thesis contributes with new knowledge on architectural engineering in a Danish context, and how it can positively influence the design process. Furthermore, new knowledge are presented via examples of how Super-Light Structures support structurally challenging architecture.

The research, methods and results are reported in this thesis and in journal papers.

Resumé

Tilflytning til byerne er en global trend og skaber stor efterspørgsel efter nye bygninger. I forsøget på at efterkomme dette, vil et nye fleksibelt konstruktionssystemer med mulighed for variation uden ekstra omkostninger fremstår fordelagtigt. *Super-lette konstruktioner* udgør sådan et system.

I denne afhandling beskrives *Super-lette konstruktioner* med udgangspunkt i *architectural engineering*. Afhandlingen tager afsæt i en tostrengt hypotese; at architectural engineering medfører bedre arkitektur, og at Super-lette konstruktioner understøtter og muliggør konstruktionsmæssigt udfordrende arkitektur.

Afhandlingens formål er at klarlægge architectural engineerings indflydelse på arbejdsprocessen mellem arkitekter og ingeniører i designudviklingen. Vha. architectural engineering testes Super-lette konstruktioner i en arkitektkontekst, og det forklares, hvordan digitale værktøjer kan understøtte architectural engineering og design af Super-lette konstruktioner. Erfaringerne med implementering af et nyt konstruktionssystem beskrives, og en case-gennemgang demonstrerer, hvor Super-lette konstruktioner kan indgå som konceptløsninger, der understøtter arkitekturen.

Forskningen, som præsenteres i afhandlingen, er udført i samarbejde med arkitekttegnestuen Bjarke Ingels Group (BIG), som har stillet projekter til rådighed for afhandlingens undersøgelser.

Forskningsresultaterne viser, at architectural engineering har væsentlig indflydelse på designprocessen. Projekterne illustrerer, at enkle forklaringer – understøttet af visualisering af udfordringerne mellem form og konstruktion – ofte skaber en

fælles forståelse blandt arkitekter og ingeniører, som giver positivt udslag i designprocessen.

I afhandlingen undersøges digitale værktøjer, der muliggør interaktion mellem parametriske modelleringsværktøjer og FEM-programmer og er til stor hjælp i modelleringen af komplekse Super-lette konstruktioner. Endvidere medførte de en kraftig reduktion i ingeniørsvartiden, så ingeniørerne nu kunne spille en mere aktiv rolle i designprocessen. Dog var det også tydeligt, at værktøjerne er udviklet til andre formål, hvorfor de bør videreudvikles til architectural engineering og Super-lette konstruktioner for at udnytte potentialet til fulde.

Implementeringen af Super-lette konstruktioner demonstrerede, at uklar ansvarsfordeling og lav risikovillighed udgør betydelige barrierer for nye produkter i byggebranchen. Afhandlingen besvarer ikke spørgsmålet, hvorvidt det er lettere at lancere et færdigt produkt på et marked fremfor at færdigudvikle produktet i samarbejde med markedsaktørerne. Men det synes lettere at få aktørerne til at tage et færdigt produkt i brug.

Super-lette konstruktioner, primært i form af SL-dækket, viste sig yderst anvendelige til at understøtte arkitekturen i de undersøgte projekter. De største fordele var muligheden for at lave udkragede konstruktioner samt anvendelse af samlinger og integrerede bjælker, der qua deres fleksibilitet var lettere at integrere med de arkitektoniske ideer. Super-lette konstruktioner har gennemgået en vigtig modning i løbet af Ph.d.'en, men konceptet rummer stadig et stort uudnyttet potentiale.

Afhandlingen bidrager med ny viden om architectural engineering i en dansk kontekst, samt hvordan architectural engineering kan have en positiv indvirkning på designprocessen. Endvidere præsenteres ny viden via konkrete eksempler på, hvordan Super-lette konstruktioner understøtter konstruktionsmæssig krævende arkitektur.

Den udførte forskning, dens metode og resultater er rapporteret i denne afhandling og i artikler til videnskabelige tidsskrifter.

Table of contents

1 3/ INTRODUCTION

- 6/ Hypothesis
- 7/ Aim and Objective
- 8/ Project framework
- 10/ Research methodology
- 12/ What are Super-Light Structures?
- 18/ Structure of thesis

2 21/ ARCHITECTURAL ENGINEERING

- 23/ Abstract
- 23/ Introduction
- 26/ Method
- 29/ Analysis
- 34/ Cases
- 40/ Tools
- 41/ Discussion
- 43/ Conclusion

3 45/ DESIGN

- 47/ Abstract
- 47/ Introduction
- 50/ Hypothesis and Methods
- 51/ Analysis
- 54/ Rhino to Robot to Rhino
- 56/ Cases
- 65/ Discussion
- 66/ Conclusion

4 69/ IMPLEMENTATION

- 71/ Introduction
- 76/ Cases
- 86/ Generalisation and Discussion

5 91/ CONSTRUCTABILITY

94/Snippen

- 95/ Summary
- 95/ Introduction
- 98/ Method
- 101/ Results
- 105/ Discussion
- 107/ Conclusion

108/Batteriet

- 109/ Summary
- 109/ Introduction
- 112/ Structural Concepts
- 118/ Cantilevering SL-decks
- 119/ Conclusion

122/BIOVAF

- 122/ Introduction
- 124/ Primary structural concept
- 125/ Use of SL-decks
- 128/ Conclusion

130/Frederiksborgvej

- 131/ Abstract
- 131/ Introduction
- 136/ Method
- 138/ The building geometry and overalls structural system
- 144/ The Balconies
- 148/ Cantilevered gable boxes
- 152/ Conclusion

6 155/ DISCUSSION AND CONCLUSION

- 157/ Architectural Engineering
- 158/ Design
- 159/ Implementation
- 160/ Constructability
- 164/ Bibliography

177/ APPENDICES

- 178/ Journal Paper / SL-deck
- 186/ Conference Paper /1/ Snippen
- 196/ Conference Paper /2/ Batteriet

/01/ INTRODUCTION

Introduction

Buildings designed by architects and engineers create the world we work and live in. Buildings are the frame of the civilized world. A frame that is constantly developed and expanded to keep up with the increasing demands from society. A society that in the western part of the world has a growing demand for more space per person and where the movement from country to city has been going on for decades. In particular, this trend is intensified by people moving from less developed regions to cities in the industrialised countries. Furthermore, the soaring income growth in the less developed parts of the world and the explosive development of cities require many new buildings. In general, the demand for more space and modern buildings is an on-going requirement to be solved; a demand that can be fulfilled by erecting identical mass-produced buildings. However, this should not be the kind of cities that we strive for. Today's buildings should vary in design and shape and be able to meet the requirements of tomorrow in order to create cities worth living and working in – today and in the future.

Architects and engineers are both responsible for overcoming these challenges; a relationship that has led to great buildings and which in many ways is basis for new developments. It is an alliance between professions and mind-sets of different worlds that has been under constant development. It is the meeting between art and technology opposites that are interdependent; yet they do not understand each other. Architects and engineers use different methods to gain results and constantly question each other, hereby expanding the boundaries of what is possible. However, the potential of the interac-

tion of these opposites are in many cases not fully utilised and often leads to waste of time and talent due to limited mutual understanding and communication. Furthermore, the interaction often only starts late in the design process where important decisions have already been taken, another hindrance for potential utilisation.

The structural systems, used to fulfil the on-going demands for new and more geometrically advanced buildings, have also undergone great developments and are still evolving: From stone-based compression structures to introduction of tension via utilisation of steel, to great spans and heights with the intervention of steel trusses, to the release of shape that the reinforced in situ concrete allowed, to the mass-produced element-based buildings. In parallel to this transition, the approach has changed from experience-based to knowledge-based. The structural systems have been through great changes and enormous achievements, with respect to utilising the materials and optimising the production to reduce the construction period and to lower the costs. The optimisation has allowed great and significant unique buildings to be built, but unfortunately, the price of product of optimisations and cost reductions has been less freedom to shape the buildings.

This thesis deals with a small contribution improving the design process of new buildings in mainly two ways. First, the relation between architect and engineer is investigated, where the saying “a good start is half way to success” seems appropriate. Second, the introduction of Super-Light Structures is considered. Hopefully, it will challenge the uniformity tyranny of mass production and re-release the architectural idiom.

These challenges and considerations constitute the basis for the hypothesis.

Hypothesis

The thesis is based on a two stringed hypothesis:

Architectural engineering gives rise to better architecture

Super-Light Structures support and enable a static challenging architecture

The first string of the hypothesis emphasises that architectural engineering positively influences architecture. *Better* can be interpreted in many way, however, in this context, it means that providing an architect with structural engineering knowledge from the beginning of the design process, in a language understood by the architect, gives a *better* chance that the architect's vision of his project is achieved and that *better* architecture is developed.

The second string claims that static challenging architecture is possible with Super-Light Structures. This does not imply that all shapes can be solved, but it opens for a range of possibilities previously considered too expensive to solve, that now can be handled as more common structures. This will *enable* challenging architecture that otherwise would have been abandoned. The architectural engineer is needed when the architect makes an initial design in order to keep the possibilities open.

Aim and Objective

The hypothesis is examined through an interaction between theory and practice within the PhD project framework. The objective is to test the theory - of architectural engineering and Super-Light Structures - in practice and apply the knowledge and experience gained to develop the theories further.

The aim is polynomial:

Architectural Engineering

To clarify the influence on the architect-engineer work process and the design development

Design

To identify how digital tools can support architectural engineering and design of Super-Light Structures

Implementation

To expose experiences from implementing a new structural system

Constructability

To show how Super-Light Structures can support architecture in multiple cases using concept solutions solved with Super-Light Structures

Applying engineering knowledge from the onset of the design process and securing a shared understanding and a constructive dialogue between architects and engineers will not only support architectural visions, but benefit the entire building process.

Knowledge of Super-Light Structures and how they can be utilised in architecture can tune the development and market-orient the product. So far, Super-Light Structures

- in form of the SL-deck - have only been used in one case for a part of a building. This PhD work is the first to test and develop the capability of the Super-Light Structures in an architectural environment.

The PhD focuses on investigating the aims in the early design phases. All the solutions presented are on a conceptual level - no detailed calculations are included. This is a deliberate choice as it reflects the level of details used at these stages of the design, and because it was the aim to follow the design processes. It would make no sense to get stuck on one specific design and make elaborate details for it, while the team may have moved on with further and different design developments.

Project framework

The research project was carried out at the Technical University of Denmark (DTU) in cooperation with the architect firm Bjarke Ingels Group (BIG). This setup constituted the PhD framework. During the three years' research, the work was equally carried out at DTU and BIG.

The setup between DTU and BIG allowed doing research with stated aims, where DTU fostered the basis for the theory and BIG constituted the practical test-bed. In this way the duality between theory and practice could be embraced in the project. This provided unique access to practice research in the core of the design teams, and to apply research results on Super-Light Structures from the beginning of design processes. BIG offered free access to their work, allowing the PhD student to follow multiple projects as an active team member, not just as an observer. This position gave valuable insights to the working process and output to the design of the Super-Light Structures.

Figure 1. *Picture of BIG Copenhagen office space. Photo: BIG*



Research methodology

The general research methodology for the PhD project was case study-based. The objective was to follow a number of projects at BIG in the light of the aim of the PhD project. After following the cases, the accumulated knowledge and experience was reflected upon in relation to the main hypothesis. By applying this methodology, the research was organised in a grid system allowing the cases to follow their individual timeframes and subsequently investigate the aims across the cases, see *Figure 2*.

This system allowed investigating the aims in different cases, leading to a broader perspective with multiple views on the topic. In practice, the cases were not carried out at the same time, why the aim was to reflect on each individual case before the next case study began, building on top of the gained knowledge in-between the cases.

As the PhD student not only observed the team, but actively contributed to the team, naturally, his suggestions also influenced the outcome. The active status made it possible to bring in knowledge to the team and gain a response for future use. It was a rewarding interplay, crucial to the development of the Super-Light Structures, and to the observations how architectural engineering influenced the process of design.

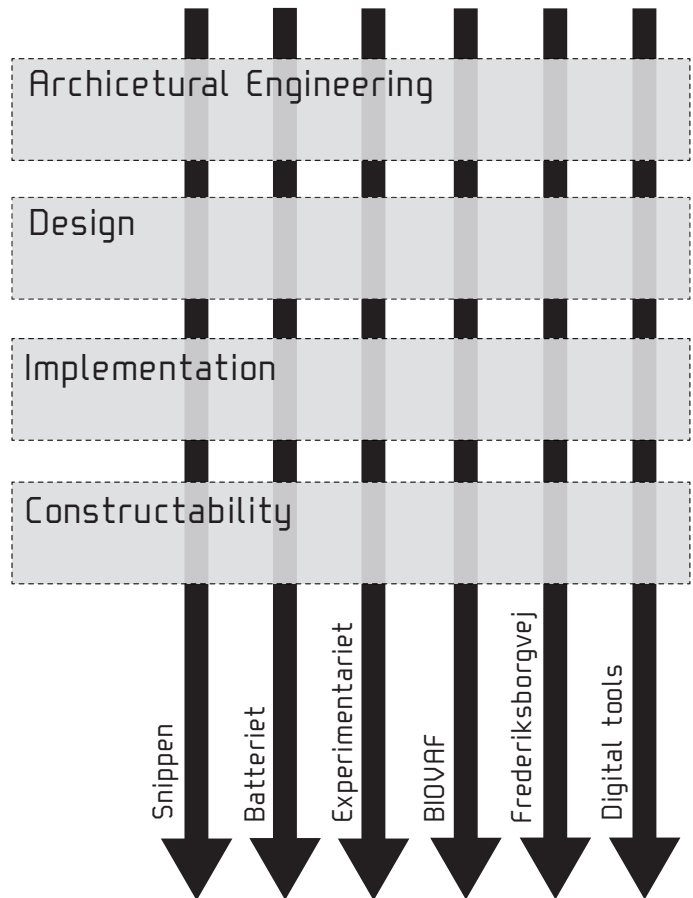


Figure 2. *Research diagram*

What are Super-Light Structures?

Super-Light Structures are invented and patented at DTU by professor Kristian Hertz in 2008. Based on the patent, a spinoff company Abeo has been started, being host for the patents. The company's aim is to further develop the Super-Light Structures in cooperation with DTU and to introduce new structures based on that to the market.

The Super-Light Structures concept is based on a solution to a series of problems for optimising concrete structures.

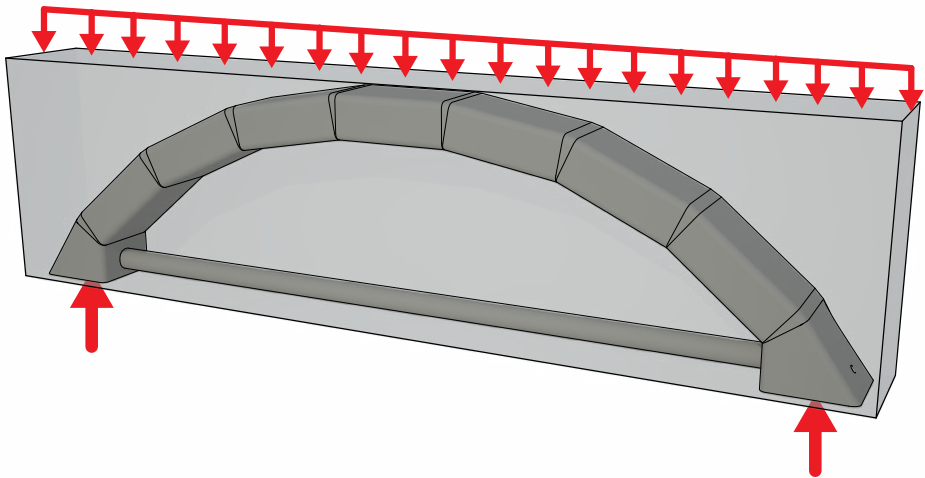
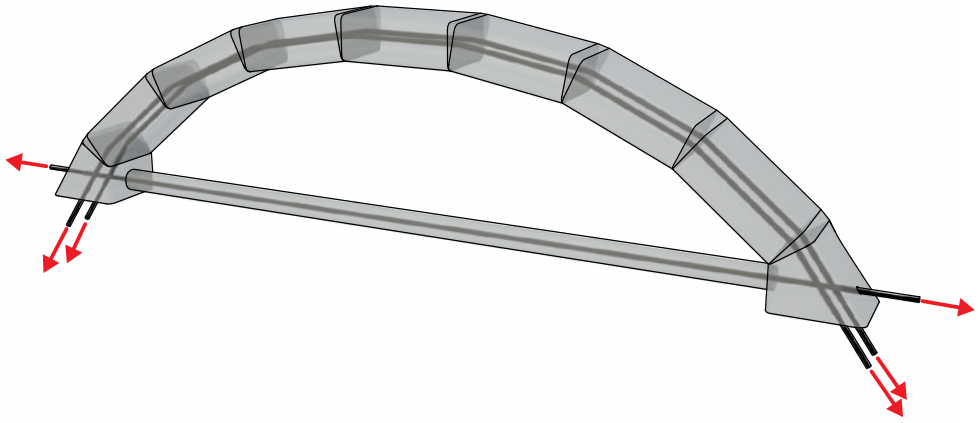
A traditional concrete structure is cast as a massive stone. In a Super-Light Structure, the strong concrete is placed where the forces want to be, and the rest of the shape is filled out with light concrete, reducing the total weight and material consume. Hence, the strong concrete is often placed as arches stabilised by the light concrete that may serve as permanent moulds.

One particular problem is that high strength concrete exposed to fire is likely to explode as the high density does not allow water steam to leave the concrete. This is not a problem to light aggregate concrete as it is very porous in the structure and at the same time has insulation properties. By embedding high strength concrete with light aggregate concrete, the light concrete works as insulation for the strong concrete whereby explosions are avoided.

Another problem is sound insulation. A massive concrete structure can only be improved by adding more mass. In a Super-Light structure, however, different oscillation properties of the light and the strong concrete may cause an improved sound insulation without adding additional mass.

Figure 3. Strong concrete 'pearls' tighten up with wires to form an arch skeleton

Figure 4. 'Pearl-chain' skeleton embedded with light aggregate concrete. The light concrete transfers the load to the skeleton, that transfer the load to the supports.



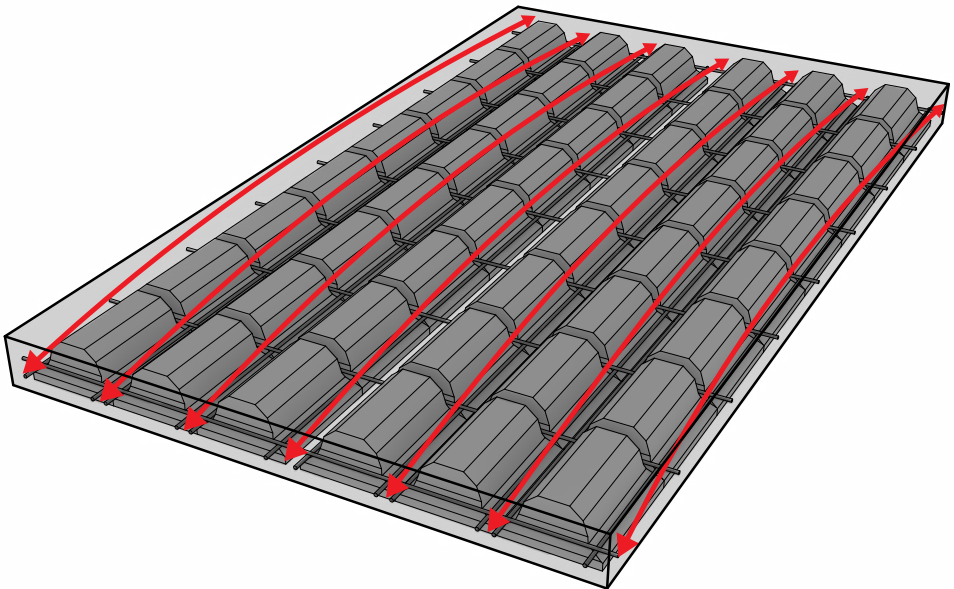
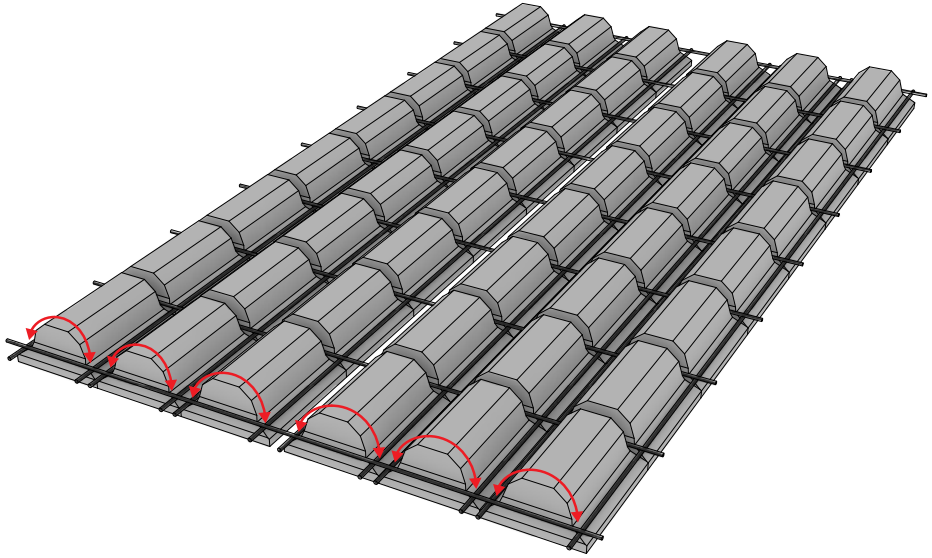
By only placing the strong concrete where needed, using the light concrete as support or filling up a form if required, the total weight of the structure can be reduced by 20-50%; hence the name Super-Light Structures.

To facilitate and control the placement of the strong concrete, the pearl-chain system was invented and patented. The concept of a pearl-chain structure consists of elements of strong concrete as parts with straight and angled ends placed on a cable – as pearls on a string – and tensioned together to the requested shape. (See *Figure 3 and Figure 4*). Furthermore, this system has the advantage of allowing prestressing light aggregate concrete. But first of all, it permits curved shapes to be built at low cost, and thereby it reopens a possibility of applying arches extensively in labour-expensive countries.

The SL-deck is the first Super-Light Structures technology product ready to production. It is intended as an alternative to known solutions for deck structures, offering many advantages due to the Super-Light Structures system. The deck has undergone a number of design changes and is now ready to production. The principle of the deck is to place arch-shaped blocks of light concrete in the bottom, creating arches or vaults in the transversal direction of the element. In the grooves between the arches prestressed wires are placed in the longitudinal direction and slack reinforcement bars in the transversal direction. On top, a plastic strong concrete is casted. Hereby, the arches of the strong concrete transfer the load to the 'beams' created in the grooves, spanning in the longitudinal direction (see *Figure 5 and Figure 6*). The slack reinforcement obtains the transversal reaction created by the arches. Due to how the deck is casted, the advantages in flexibility known from in situ casting are brought to the element. The element can be cantilevered and placed continuously over supports. It can have fixed ends, long span lengths, resist fire for over four hours, and it has a good sound performance.

Figure 5. *The light aggregate blocks form an arch, that work as a permanent mould. The forces will follow the arches and the transversal reinforcement will obtain the outgoing force.*

Figure 6. *In the longitudinal directions will the 'beams' in between the blocks transfer the load to the support at the ends.*



The SL-deck has been tested to secure coherence between calculations methods and practical performance. The tests were executed on test elements with three light aggregate blocks in the transversal direction. Regarding strength, the element was tested for moment-, shear- and pull-out resistance where all tests proved results on the safe side of the calculations. Acoustic performance tests were made in a sound hard room for airborne insulation and for impact noise. These tests showed an airborne insulation in compliance with the Danish requirement for domestic buildings and an impact noise that fulfilling the requirement, when using a damping floor. Finally, the calculation methods were supported by a fire test, proving fire resistance of up to four hours. Based on all these tests, the SL-deck has been slightly adjusted to optimise it for production.

For more details see appendix 1: Super-Light concrete decks (journal paper).

Figure 7. *Production of test elements. Photo: K. Hertz*



Structure of thesis

The thesis is paper-based according to the guidelines of the PhD school at the Department of Civil Engineering at DTU. In this case, a paper-based thesis means, contrary to a monograph, that the papers written during the PhD project are used directly as thesis chapters or sections. The paper layouts are adapted according to the general layout of the thesis, but there are no content changes. This will prompt minor repetitions in the thesis as some of the general descriptions are mentioned in the introductions and method sections of more than one paper. However, the papers are written according to the overall thesis chapter structure, maintaining the overall flow through the thesis while minimising overlaps. The thesis chapters or sections, that are not papers, are written with a paper-like structure to give coherence.

The thesis covers work carried out during the PhD project at DTU and BIG. The thesis is structured according to the aims of the PhD project why it does not present the design cases in chronological order. Consequently, the chapters move across different relevant cases to reflect on the aims (see *Figure 8*). The three first chapters are either papers or written chapters. They are built up around a general theoretical subject description followed by a number of case descriptions. The fourth chapter consists of a number of sections: written sections, conference papers or papers, each describing the use of SLS in a case. With this structure, the thesis seeks to illustrate how the overall aim of the thesis has been investigated and to present the results in an accessible format.

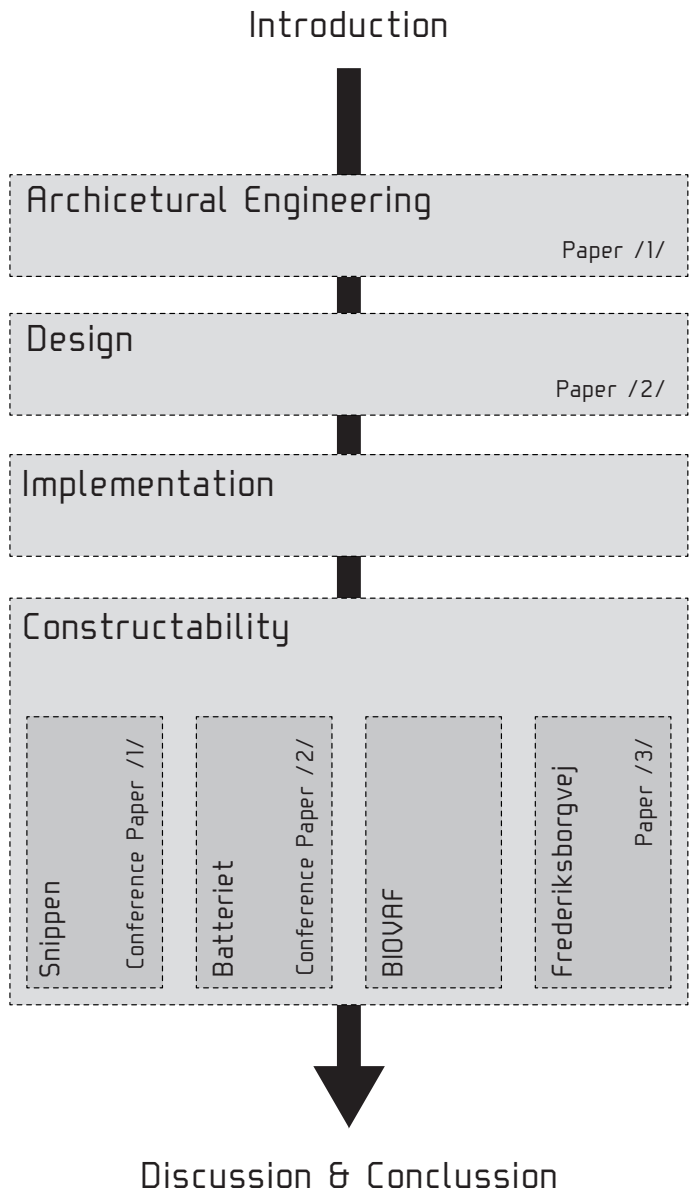


Figure 8. Diagram showing the structure of the thesis and how the papers are placed in the overall structure.

/ 02 /

ARCHITECTURAL ENGINEERING

Paper /1/

How Architectural Engineering can be Beneficial to a Design Process

Submitted to:
Design Studies

Authors:
Niels Andreas Castberg
Kristian Hertz
Christian Rønne

Abstract

Architectural engineering can be beneficial to a building design process as it fills the gap between architects and engineers by facilitating an improved shared understanding in the design process. It is crucial that engineers enter early in the design process to achieve optimal design solutions. The paper examines the role and strength of architectural engineering in the traditional architectural and engineering work process. The main author's observations during his work as an architectural engineer in the architect practice Bjarke Ingels Group (BIG) over a period of three years form the empirical basis of this paper.

Introduction

The two professions not only have different approaches to the same problem, but also have a real problem in communication: they talk different languages and do not understand each other. (Salvadori, 1989)

The relative new profession architectural engineering can help creating a better design in the initial phase of the building design process and reduce later complications (Bjerregaard Jensen, 2007; Kongebro, 2012). Architects are supported with engineering knowledge on the design already in the conceptual stage, using a terminology shared by architects and engineers, hence bridging the gap between architects and engineers. The purpose of architectural engineering is to support the architect in reaching his design visions by suggesting solutions that embrace the architects' idiom. As a natural consequence of the match between design and structure, the civil en-

gineer's task is relieved – which again will cause a better construction process.

Historically, the same individual managed both architectural and engineering building tasks (Larsen and Tyas, 2003). This is also evident from the Greek root to the word architect, *architekton*, meaning master builder. Modern civil engineering started with construction of bridges, highways, railways, harbours and other large-scale structures. From the middle of the 19th century and onwards, the increasing demand for large-scale buildings, such as railway stations, exhibition halls, skyscrapers and stadiums brought the engineer into the traditional field of architecture (Herbert, 1999). As a result, two professions with different educational backgrounds and mind-sets have to co-operate in the design process.

The educational tradition of both professions varies widely between countries, i.e. the degree of architects' technical skills and the engineers' design-orientation. The present study was carried out in Denmark where the architectural education is influenced by the intuitive design method (Bertram, 2009). A strong tradition for an art-based architectural approach has limited the architectural profession's technical knowledge, and correspondingly, engineers only receive sparse training in architecture. As this has widened the gap between the two approaches, the demand for architectural engineering has only grown stronger. Although this paper is written in a Danish context, the cultural clashes between architects and engineers are a worldwide phenomenon (Salvadori, 1989).

Architects and engineers face wicked problems in everyday practice and they apply different world-views to the way they operate (Holzer, 2010). The work process is traditionally divided, so architects make a design, shape and concept in the initial phase of the process, while engineers enter at a later stage to design the technical parts. However, the border between the two professions is blurred,

and the architects are still very active at the time that the engineers enter. In addition, the increasingly complex building shapes and new requirements to complying with many structural and energy codes have forced the two professions to closer collaboration (Herbert, 1999) and emphasised the need for integrating the engineers earlier in the design process (Au, 2012). Holzer highlights the problems of traditional collaboration between architects and engineers *'initial feedback from professional consultants often occurs too late – namely, at the time when many of the basic design drivers are already determined by the architect.'* (Holzer and Downing, 2010)

Multidisciplinary teams often face collaboration and communication challenges and tensions arise when two professions have to work closer together (Bucciarelli, 2002). Lack of shared understanding is an important factor. A questioner may expect a certain type of answer to help him further the work process, and frustration may arise when the answer does not comply with this norm. This is a classical issue in the co-operation between architects and engineers and comparable to the problems described between industrial designers and mechanical engineers (Kleinsmann and Valkenburg, 2008). There are many differences between the industrial and architectural design processes, such as the number of objects produced per design, the scale and time of the design process. Nevertheless, also many similarities can be highlighted. As the literature on the work relationship between architects and engineers is fairly poor, this paper will draw on some of the lessons from the richer industrial design literature.

The author's PhD work has been undertaken in close cooperation with the internationally well-recognised architect practice Bjarke Ingels Group (BIG). The many observations on the cooperation with engineers in practice form the empirical basis of this paper. BIG is a very internationally-oriented architect firm and has a very pragmatic approach to design. The company is good at incorporating and

working with inputs from engineers in a creative manner, which gives it the openness to adopt the architectural engineering function in their processes.

Method

Based on the challenges of uniting engineers' and architects' efforts, this article hypothesises that architectural engineering can be beneficial to building design processes.

The main author's observations during his work as an architectural engineer on multiple projects in the architect practice Bjarke Ingels Group (BIG) over a period of three years form the empirical basis of this paper. The focus has been on the cooperation and workflow between architects and engineers. The analysed actors were BIG's architects and engineers from external consultants assigned to the projects. As the author participated in the projects, it was possible not only to identify the problems, but also to attempt to solve them by 'translating' between professions and by offering engineering advice.

The method is based on Schön's principles on how professional knowledge is created, where experiences are analysed retrospectively (Schön, 1983). Nonaka has introduced the SECI model (Nonaka and Konno, 1998; Nonaka, 1994) that describes how knowledge in organizations is managed and created through knowledge conversations between tacit and explicit states. The model has four stages: socialization, externalization, combination and internalization (*Figure 9*).

First, practical skills (tacit knowledge) are transferred through training (*socialisation*), next the tacit knowledge

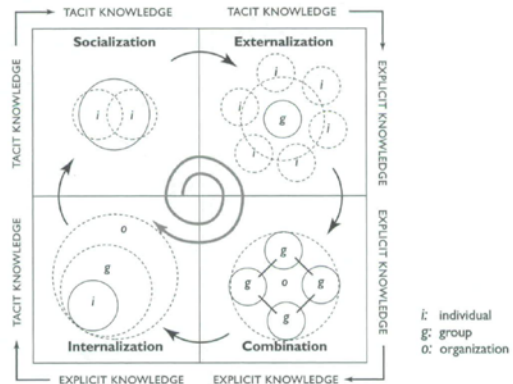


Figure 9. Nonakas' SECI model

is made explicit (*externalization*). Different explicit knowledge is then combined to new knowledge (*combination*), and learned by the individuals in the organisation and has become tacit knowledge for the new task (*internalisation*). The process is an on-going spiral (Sattrup, 2011), and research can be defined as the movement that brings knowledge to next state. The reflection of action takes place in the externalisation: The gained knowledge from the two professions' tacit knowledge is transferred to a joint explicit knowledge (Figure 10). In the design process, the architectural engineer's role is to facilitate the externalisation. Knowledge creation highly depends on sharing a common conceptual and/or physical space that acknowledges differences and allows trust-building (Nonaka and Konno, 1998).

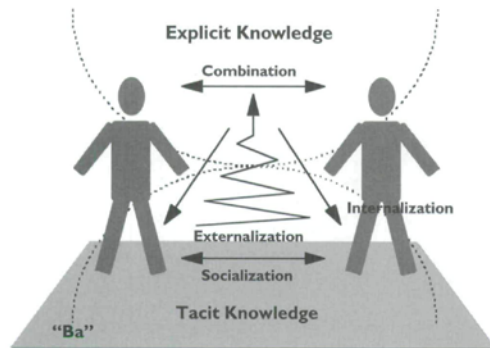


Figure 10. Nonakas' "Ba" model for interaction between people

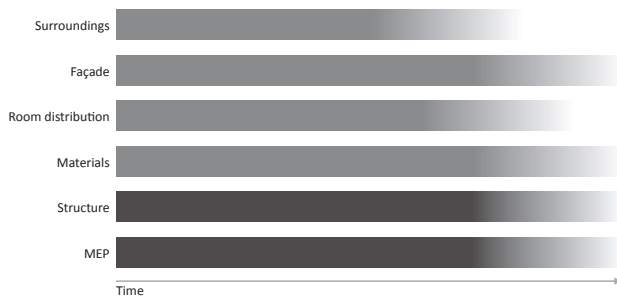


Figure 11. Bar-system of the design process. Bars represent focus areas in relation to the process.

The ability to understand other mind-sets is much related to how communication is executed. For analytical purposes, a distinction between data and information is helpful. While data is the raw input, information can be defined as data organised in sentences that enable the recipient to intelligibly perceive data. Hence, information is only information if the recipient categorises it as such (Davenport and Prusak, 2000).

Architects' and engineers' typical work processes in the building design process can be depicted as curves in a system of bars where each bar represents a focus area in the process, such as relation to surroundings; relations between rooms, daylight, structure, materials etc. to be evaluated. Using this graphic approach, the need for the architectural engineer becomes evident and will subsequently be described in case-based examples. Reflecting on the observations, it has also proved important to examine what is tacit and explicit knowledge for the respective professions, how it has influenced the communication, and secondly identifies new practises for the architectural engineers.

Analysis

Understanding the mind-sets of the two professions is vital. The next sections will describe the respective work processes. This will help to define the role of the architectural engineering, and why and how it can benefit development of a new design process. Defining the role of the architectural engineer points to tools that can support this new process.

Architects

The architectural work process contains in general a number of loops. The typical task starts with a competition for the building. The proposals must comply with a programme consisting of certain predefined criteria. Initially, many ideas to fulfil the programme are put on the table. Then, the number of shape suggestions are merged and narrowed down into one design. This creative process involves many loops with tests different designs and variations for sub parts to both meet the programme's criteria and reach an aesthetically acceptable solution.

The design process is a process of embedding intents in the design object, navigating and calibrating the constraints and opportunities surrounding the project (Satrup, 2012). The architect solves problems by testing many designs and design combinations that comply with the programme until an acceptable solution is found. "For an architect, design is the process of synthesis" (Pfammatter, 2000). The architects often define a set of context-specific design rules to guide the design-making process. These rules may or may not be explicit, and it also varies how strictly they are followed. However, this may result in a tacit knowledge only known to the architect.

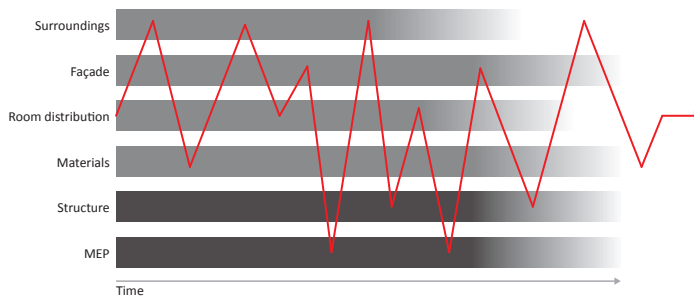


Figure 12. *The architect works with and shifts between all bars during the design process.*

The architect has some or all bars in play at the same time as they are interdependent. The architect switches between designing and adjusting the parameters symbolised in the different bars and in all are in charge of the overall design (Herbert, 1999). As part of the design decision-making, the bars can be prioritised according to the design rules. The prioritisation is an aesthetic assessment that is subjective, influenced by the architect's intuition. Once this overall design is decided, the engineer enters in the process and gives feedback that may result in more loops to make the engineering aspects merge with the aesthetic design. At this stage, the architect faces a great challenge in communicating aesthetic priorities behind the design decisions in a manner that is intelligible to the engineer and enables him to comply with the design priorities.

Engineers

The engineering work process is generally more straightforward. Traditionally, design theory and design processes for engineers have focused on the final stages (Bjerregaard Jensen and Nielsen, 2011). Typically, the engineer's task is to analyse a building design presented by an architect and document the structural system that seeks to accommodate the architect's ideas and identifies potential problems. It is crucial that the engineer presents the results in language understandable to the architect. Subsequently, the architect and engineer will discuss potential changes of the design and structure. This may be a time-consuming process with many examination loops,

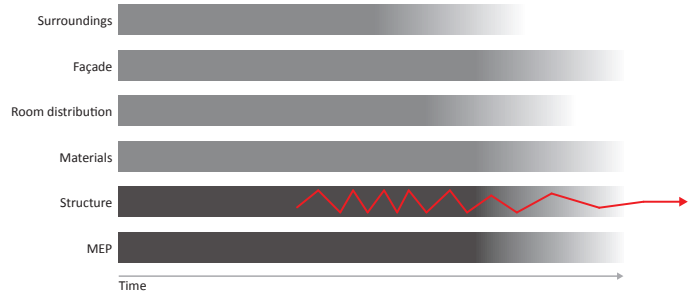


Figure 13. *The structural engineer enters the process late and works only within his own focus area.*

determined by many factors, such as the complexity of the design, the engineer's creativity, when in the process the engineer is involved and the architect's willingness to change the design. When the overall structural concept is solved, the engineer moves to the more detailed calculations. The dimensions are fixed and the joints are designed.

Applying the same system framework in the analysis of the engineering process, it is evident that the engineer - unlike the architect - mainly works within one bar; *he is designing a subsystem of the overall design* (Herbert, 1999). In the building industry, the engineering profession has undergone a specialisation into subfields, such as construction, energy, fire, etc.. Although this development has resulted in highly skilled engineers within narrow areas (symbolised by the bars), the price has been less apprehension of aspects beyond their subfields. Hence, they may be unable to follow the logic behind architects' decision-making, and consequently, may only be able to offer solutions for optimisation within the boundaries of their bar and not interact with areas in other bars.

The engineer solves problems by knowledge-based experience, analysis, calculations and simulations. According to Pfammatter, to an engineer most design effort involves analysis (Pfammatter, 2000). Engineerical solutions are highly factual and precise, directed at a specific problem. The engineering are based on calculations and can be expressed in formulas, i.e. it is explicit knowledge. How-

ever, calculations and formulas may be unintelligible to architects, they are not perceived as *information*, and the knowledge becomes tacit.

Architectural Engineer

Collaboration needs to be encouraged during the conceptualisation stage, rather than relying on structural gymnastics to 'hang' architecture on to, or on bringing in engineers later to make an architect's concept 'work'(Kara, 2010).

In the early phase of the design process, many shapes are suggested and tried and the design changes rapidly. Already at this stage, a number of decisions are taken; some of which may have great negative influence on the design later in the process if they are based on incorrect information. It is essential to choose the right areas to analyse in order to do most effective analysis. An engineering approach is required, capable of giving quick answers to architects earlier in the design process than what is the case today. The engineer's answers are not necessarily based on detailed calculations but can be a mix of rough analyses and knowledge-based assumptions.

The way the architects and the engineers work together today leaves room for a third actor in the cooperation: The architectural engineer. The actors of the design team communicate in different ways so even the same words may be comprehended differently (Kleinsmann et al., 2007). Furthermore, the actors hold different views about which part of the design that is most important (Bucciarelli, 2002). Architectural engineering is a discipline which is engineering based, but has a much greater focus on early stages in the conceptual design, shaping and overall concepts compared to more traditional civil engineering disciplines. An architectural engineer is not only trained in civil engineering but also in architecture. This broaden his horizon, an important asset according to Sobek(Sobek, 2008). Architectural engineering is a natural development

caused by the demand for close collaboration between architects and engineers and their limited ability to inform each other in a constructive way. The architectural engineer interacts in the early design stages to allow engineering aspects to support the architect in his design visions and facilitate that the engineering data is communicated so it is understood as information. Furthermore, the architectural engineers aim to transform the architectural decision process and criteria from tacit to explicit knowledge to the civil engineers. The early entrance and the shared understanding will gain value to the process and limit any greater design changes that sometimes have proved necessary when the engineers traditionally are introduced to a design. In this way the engineer's aspects can be incorporated into the architectural design, not just added to it. Finally, in the field of product design, diversity of input, already at the beginning of the design process, has often lead to innovations (Buijs, 1987). It seems very probable that the same will be the case in architectural design.

Leaving the classic approach, where the engineer is presented to a more or less fixed design, to a much more dynamic approach, open to radical design changes, the engineering work change its focus from exact calculations to the overall structural concept design. The engineer must listen to the architect and must have an educational background to understand even very imprecise formulations from the architect in the early phases (Sobek, 2008). Another very important factor is the capability of communicating engineering results to the architects in a 'language' that the architects can understand. This is important because the shared understanding influences the quality of the final design (Dong, 2005; Kleinsmann and Valkenburg, 2008; Valkenburg and Dorst, 1998). Furthermore, the well-understood results from the engineer can be of use for the further development of the design. The architectural engineers' profile is to have the engineering mind-set and knowledge but at the same time a deep in-

sight and understanding of the architectural mind-set and design approach. He is able to ‘translate’ between the professions, hereby creating shared understanding of the project, essential to avoiding unnecessary iterative loops in the design process (Valkenburg, 1998). The translation is not only from data to information and vice versa, but also from tacit to explicit knowledge in both professions. The architectural engineer’s placement in the system is different to the civil engineering professions. Due to his

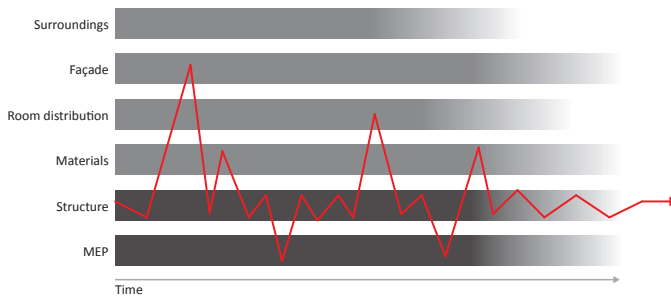


Figure 14. *The (structural) architectural engineer enters at the beginning of the process and works across bars that are influenced by his main focus bar.*

understanding of the design process and decision-making, the architectural engineer can interact with the bars in the system operated by the architect. In this way, the architectural engineer breaks the bar’s limitations for e.g. the structural engineer and may enter a dialogue with the architect on integration of the structure in the design.

Cases

“Batteriet”

The ‘Batteriet’ case started with a number of stages (*Figure 15 and Figure 16*), where only architects were involved in the development. The parameters for the development of the design were the distance to the neighbouring buildings and streets. These two parameters influenced the height, location and entrances to the buildings, as well

Figure 15. Two early concept models and two later stage models. Photo: BIG

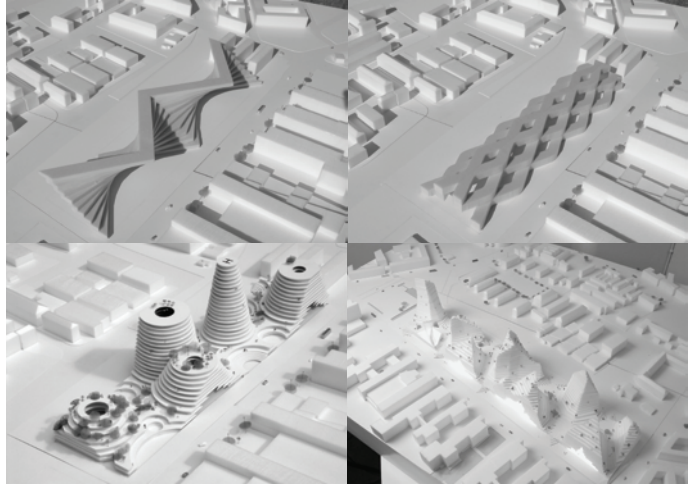
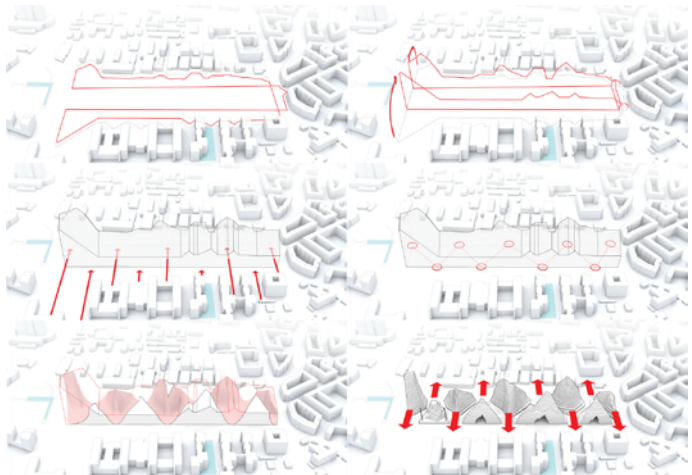


Figure 16. Diagrams explaining the development of the final concept. Illustrations: BIG



as access to the area. Analysed confer the bar-system the bars related to the building's surroundings had a great impact on the design decision-making. The internal parameters were only introduced, once the outer shape had been decided, and only adjustments of the outer shape was then allowed.

After the architect had decided the overall outer shape the architectural engineer (in this case, the main author)

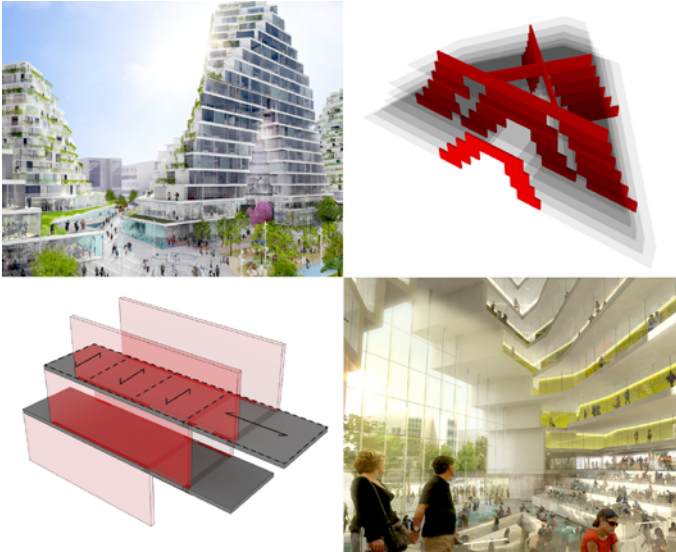


Figure 17. The overall structural concept and a concept solution for the balconies with new structural system. Visualisations top right and bottom left: BIG

was involved in the project. The architectural engineer helped with investigating overall structural concepts that could make the design buildable. He tested the structural system in relation to how they influenced the flexibility of the room distribution and he undertook studies to see how to construct the atrium openings in the building and how they would influence the design. The decisions were based on a quantitative dialogue supported by the architectural engineer's sketches and visualisations. With respect to the internal design, especially the cantilevered corridors towards the atrium proved challenging. The architectural engineer introduced a new technology called Super-Light Structures (Hertz, 2009) for the deck structure, enabling integration of structures and design in a way unfamiliar to the architect (Castberg and Hertz, 2012). Engineering knowledge was hence introduced early in the internal design-making, resulting in solutions much closer to the architectural vision than a traditional solution could offer.

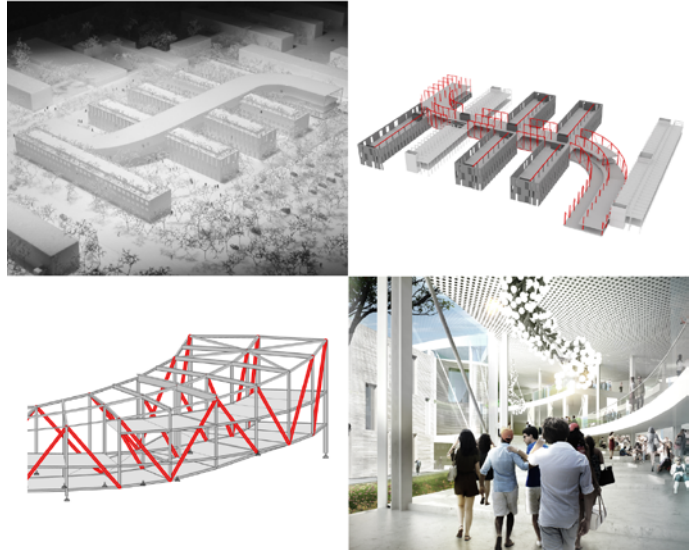


Figure 18. *BIOVAF: the overall structural system and the curved 'snake' part. Visualisations top right and bottom left: BIG*

BIOVAF

As an architectural engineer, the author played a major role in the design phase of the project BIOVAF, a building for three institutes at the Technical University of Denmark. From the very start, structural concepts were suggested and debated in relation to the different concepts of shape that were investigated. When the overall shape was decided, and a structural concept was chosen for the straight parts of the building, three different concepts were investigated and discussed between the architect and the architectural engineer for the curved snake part of the building. Through 3D sketches based on rough dimensions, the architectural engineer investigated a bridge section solution, a truss system and the new structural system, Super-Light Structures. These sketches made it clear that a truss system was most in line with the architectural visions.

The curved part of the 'snake' underwent significant changes through the process why the structural civil engineer had difficulties understanding the shape, the different levels and the different upper and lower double curved surfaces. The architectural engineer was then able

to translate the architect's wishes and changes to the structural engineer - and translate back to the architect how the engineering calculations would influence the architectural model. This way a shared understanding of the geometry grew between the actors as tacit knowledge became explicit.

In this case the architectural engineer made it possible to make a decision for the structural system early in the design process based on engineering knowledge. Furthermore, he facilitated the communication between the architect and the civil engineer in the later more detailed calculation process.

Experimentariet

At a competition for an extension of a large experience centre, BIG made a proposal consisting of boxes added on top of the existing building. A large internal garden was located in one of the boxes. This posed a challenge due to the weight of the soil. To solve this, the engineers suggested to support the garden with enormous beams, spoiling the exhibition space underneath. As an architectural engineer, the main author explained the design team how forces were distributed in a beam and introduced the team to the principle of arches. Applying this knowledge,

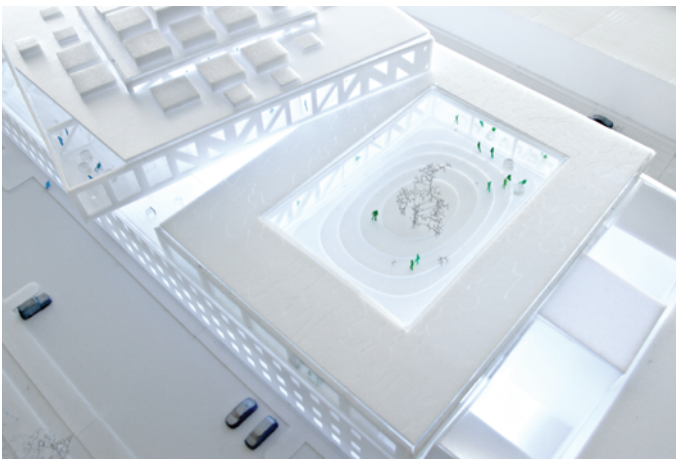


Figure 19. *"Experimentariet": The boxes on top of the existing structure. Photo: BIG*

A different box was meant to be made of concrete. The architectural engineer explained and visualised the structural calculations with a colour plot of a finite element analysis, locating areas of high pressure and areas where material could be removed based on stresses and support. Hereby, the engineering knowledge was transformed from tacit to explicit to the architect. The architect used the new gained knowledge to place the windows in the façade according to stresses in the structure, whereby the design became an expression of the forces.

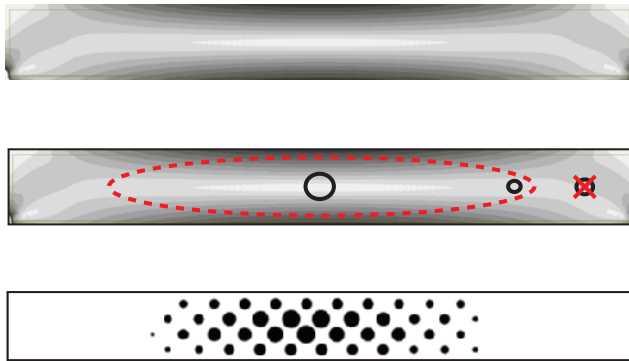


Figure 22. A stress plot transferred in to a hollow pattern reflecting the concentration of stresses.

The case demonstrates how engineering knowledge added and understood early in the design phase can be incorporated directly into the design and help guiding the design in a positive way.

Tools

New work processes require new tools to support new ways of working. In the cases, 3D software was of great help for presentation of engineering results. The digital tools also facilitate better interaction opportunities than traditional paper-based communication (Oxman, 2006) as

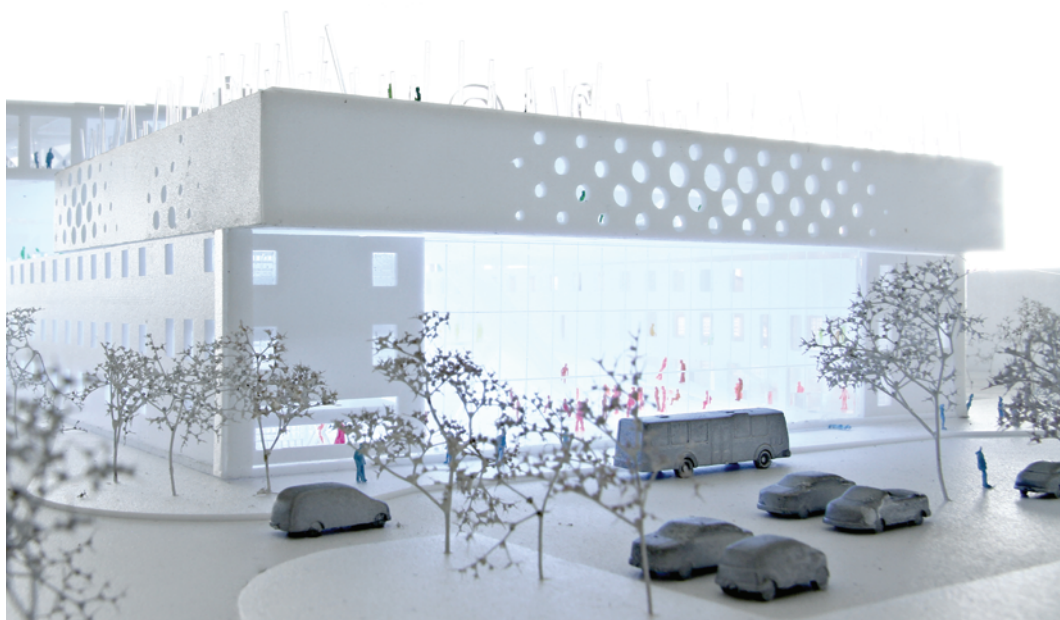


Figure 23. *Model photo of the concrete box with the facade expressing the stresses. Photo: BIG*

it is easier to communicate based on a 3D model or a coloured stress plot compared to numbers in a spreadsheet. This paper will not explain the software in detail, but software facilitating transfer of geometries between architectural and engineering software proved helpful. The software allowed quicker responses to the architect and can support a closer interaction between the engineering results and the architectural design (Castberg, n.d.).

Discussion

In general, it is always difficult to grasp a whole profession in one stereotyped description of the work process. Many parameters influence the work process, such as different educational backgrounds, regional and company culture, and not least different ways of working. Nevertheless, some overall characteristics of architects and engineers can be illustrated in a system of bars symbolising build-

ing design parameters. Architects work with many bars at a time - where an engineer works within one bar only. This may be a bold statement as it is only based on attending projects at one architectural company. However, this has been a premise for the article. Also the tradition in a given country may determine the exact division between architects and engineers. The study was undertaken in Denmark, a country with a strong tradition for an artistic based architectural education and very specialised engineers. However, BIG is an internationally-orientated company and works with engineering companies from many countries, among which countries with a stronger architectural engineering tradition. As a result, some of the studied cases have been based on engineering input early in the design.

It obviously varies from project to project, when the architectural engineer enters the process. Some will argue that there is no place for engineers in the process, before calculation is needed, which can be partially right. However, many decisions are taken in a project's initial phase, and engineering input does not necessarily involve calculations but may just be a discussion guiding the architect. Diversity in the beginning of the design process may be an asset, facilitating better and more innovative design results.

Whether a civil engineer could do the same as an architectural engineer is of course a relevant question. Some can. Typically, it is because they have a long experience and have learned to understand the architectural mindset and communication. Nevertheless, most cannot and do not have the background knowledge needed. They have good engineering skills, but are less able to communicating and creating a shared understanding about the implication for the project of their calculations. In the cases described, it was significant how much a project gained from architectural engineering communication that led to a shared understanding.

Conclusion

The article describes how architectural engineering has a positive influence on the design process. It is described how diversity from the beginning of a design brings innovative results. Through case studies, it is shown that involvement of an architectural engineer has a positive influence on the design. It is described how shared understanding is important to the design process and how different professions speak different languages. The cases demonstrate a need for 'translation', and that the translation offered better solutions.

This need for bridging is acknowledged by The Technical University of Denmark. In 2002, it started its first education in architectural engineering. In other countries, similar educations have existed for a longer period of time. Some engineers can communicate their results to the architects, and some engineers do enter the design process early. However, there is room for a major improvement. Hopefully, the entrance of architectural engineering will contribute to better design solutions.

Paper /2/

How Digital Tools Can Help Optimizing the Workflow and Process of Architectural Engineering

Submitted to:

Automation in Construction

Authors:

Niels Andreas Castberg

Kristian Hertz

Abstract

The increasing complexity of building designs requires an integrated work process involving architects as well as engineers from the very onset of the design process. Architectural engineering facilitates this integration. Tools providing quick analyses and fast response times are needed to support implementation of engineering input in the early design phase. This article argues how exchange of parametric models between architectural and structural engineering software can support and qualify the design process by exploiting opportunities of quick analysis. The parametric exchange program *GeometryGym* is used in two projects at the architect firm Bjarke Ingels Group, BIG. The article describes how the projects can benefit from applying the tool. Furthermore, it is described how the exchange and optimisation option can support design of more complex shapes, such as those made possible by application of the newly patented structural system *Super-Light Structures*.

Introduction

Architects and engineers are required to work more and more closely together because of the increasing complexity in buildings and more strict codes (Herbert, 1999). This new closer relationship requires new work processes that can be assisted and facilitated by an architectural engineer (Castberg et al., n.d.). Architectural engineering is a work process where the engineer joins the design team much earlier than what has been common practice so far. This requires an ability to give quick responses to the architect, because the architect usually makes many major changes of the design in a short time at the beginning of a project. By entering early in the design process, the en-

engineer's perspectives on the design can be incorporated much earlier in the design. Consequently, the number of loops caused by not-buildable solutions is limited and the design process optimised. Tools supportive of good decision-making at this early stage are of great help to the design team (Harding et al., 2012), as the most impactful decisions in the design process are made at the start of any project (Turrin et al., 2011). The architectural engineer is based on the traditional civil engineering disciplines but possesses a better understanding of the design process and the architects' mindset, making him able to act in the early design process and present the engineering results in a way that is understood by the architect.

Digital tools facilitate better interactive opportunities than traditional paper-based communication (Oxman, 2006). E.g., it may often prove easier to communicate based on a 3D model or a coloured stress plot compared to a spreadsheet with numbers. When Passas speaks of development of a common language between the architect and engineer, he highlights geometry as something used by both professions to communicate precisely and effectually (Passas, 2012). Furthermore, graphic representations of complex force distributions via force diagrams promote an intuitive understanding (Lachauer et al., 2011). Interdisciplinary use of a 3D model offers better control of geometrical relationships across disciplines which results in more shared understanding of aims and intentions supporting the collaboration (Moum, 2010). Therefore, it is essential that the architectural engineer has geometrical presentation tools at hand, when he has to 'translate' the engineering results to the architectural way of thinking.

There is no question that digital media have played a role in supporting and unifying such interactions as 'enabling technologies' that enhance the potential for communication and collaboration between architects and engineers. (Kara, 2010)

To establish this more dynamic understanding and workflow across professions, it is highly relevant to look at which tools the professions use and possibilities of data transfer across the different platforms. In the design phase, a common challenge faced by engineers in giving quick responses is the time-consuming process of model building in engineering software. Recent development in software enables models to be used across multiplier software which can reduce problems at early stages of design development (Mirtchin, 2011). The parametric models support a more integrated approach in the team and facilitate better dialogue among the participants (Hudson et al., 2011). The article will look at tools - mainly *Grasshopper3D* ("Grasshopper3d," 2013) and *Geometry-Gym* ("Geometry Gym," 2013; Mirtchin, 2011) - that can facilitate data transfer between the architect 3D modelling program *Rhinoceros* ("Rhinoceros," 2013) (Rhino) and the engineering finite element program *Autodesk Robot Structural Analysis* ("Robot," 2013)(Robot). Geometry-Gym is a plug-in that facilitates the transfer from Rhino via Grasshopper3D to the FEM software. It has a traditional engineering target group and focuses on the optimisation through the parametric scripting in Grasshopper3d. This article will examine how the software can be used as a link between the architectural model and the structural engineering model, thereby adding value to the design process in architectural engineering.

The background for this article is the author's PhD studies carried out in cooperation with the internationally well-recognised architect practice Bjarke Ingels Group (BIG). The PhD has a focus on architectural engineering and development of Super-Light Structures in an architectural engineering context. Through this work, it has been observed how digital tools help the design process and where there is room for improvement.

Hypothesis and Methods

Sketching and making sketch models are essential parts of the design process (Goldschmidt, 1994). It is the hypothesis that digital tools can benefit the architectural engineering processes by facilitating an easier access to calculations related to the sketch models and thereby support the decision-making.

Initially, a quick screening of programmes available and relevant in relation to BIG was performed. Next, software was selected and examined according to its potential to support the architectural engineering process. The selected tools were examined in relation to the projects at BIG, in which the author was involved. It was tested how the tools performed in these design cases in relation to technical performance and limitations and in relation to their facilitation of presenting results to be used in the design process. This article will describe two cases: 1) BIOVAF illustrates problems of not having a quick link between the architectural and the engineering models, and how such a link might have helped. 2) EXPERIMETARIUM describes how exchanges in a simple form were applied, and how an advanced model would have been beneficial. Furthermore, the tools were examined in relation to the modelling of a new structural concept Super-Light Structures (Hertz, 2009). The analysis of Super-Light Structures is used as a case to examine the tools performance in more complex geometries.

The method is based on 'reflection on action' described by Schön in his outline of how professional knowledge is created (Schön, 1983). The method is retrospective analysis of the actions taken. Following Yin's recommendation, the case-study data has been collected from different sources (Yin, 2009). Hands-on knowledge of the subject in question was gathered by observations at design meet-

ings, investigations of project material, experiences from active design participation using the tools, dialogue during the case project periods with architects and engineers and an on-going dialogue with the programme developer.

Analysis

New work processes require new tools. As mentioned, the architectural engineer joins the design process earlier than the traditional building engineer and participates more in the design dialogue with the architect. At this stage, the architectural model is still so rough that it is often sufficient to answer yes or no to a design while the precise structural dimensions are irrelevant. If engineers want to navigate in and to contribute positively to the early design stages, it is essential that they keep up with the speed at which the architects change the design. Therefore it does not add anything positive to the process if it takes the engineer a week to produce a precise model, when the architect has changed the geometry twenty times in the same period. But the option of being able to make a structural model parallel to the architectural model and connect them enhances the communication between architects and engineers in the development of novel buildable and efficient forms (Shea et al., 2005).

It is relevant to look at how creation of the engineering analysis model can be speeded up. The starting point of the geometry in need of analysis is the architectural model, so of course using the geometry already modelled will be the most effective way to undertake the analysis. This can be done in two different ways: A) import the analysis into the modelling program used by the architect or B) transfer the geometry to the engineering software. During the last couple of years, solutions have developed for both ways - as part of the generally increasing use and de-

velopment of software to the building industry all covered by the description of BIM. Many tools are intended for the final detailed design phases where traditional engineers commonly work. Here, BIM becomes very powerful as these later design stages are focused on the coordinated assembly of building components and clash detection. (Holzer, 2010) But there is also an increasing amount of software developed for the conceptual design phase. The relevant tools in the researched model for this article are related to the 3D modelling program Rhino, since this was the main programme used in the early design stages at BIG. For Rhino, a plug-in called Grasshopper3D exists that allows the user to make scripts for parametric modelling in Rhinoceros. *Parametric modelling tools helped the research team produce a quick turnaround of design options by allowing the generation of multiple alternatives to keep a design in a flexible yet controlled state.* (Holzer and Downing, 2010; Parthenios, 2005) Furthermore, Grasshopper3d is free to use and has an open API (Application Programming Interface) that allows adding plug-ins. By now, plug-ins have been developed that allow FEM analysis within the Rhinoceros/Grasshopper3d environment such as Karamba ("Karamba3d," 2013) and ScanandSolve("Scan-and-Solve," 2013) (A), while other plug-ins permit export to FEM programmes such as Autodesk Robot Structural Analysis, SoFiStik, Oasys etc. via GeometryGym (B). Finally, there is an option of saving the geometry as .SAT format and then open it directly in the FEM programme. However, this can only be used for the geometry and does not contain any information on other properties which limits its usefulness. Whether method A) or B) is best is a question of need, however, the solution within Rhinoceros might be a bit more dynamic to the design process as it is all contained within one programme. On the other hand, by transferring the geometry to a FEM program, the analysis is made in a well-known and recognised environment to the engineer, why only a lower level of verification of the calculated results are required. Hence, the work is done with a recognised FEM

tool. The transfer option is also useful if more complex calculations are needed. This allows the architectural engineer to start building a model and later pass it on to the structural engineer for more complex and exact analyses. Despite the advantages, B) is not as intuitive and fluid as A) in the bilateral exchange process between the programmes. Furthermore, it adds an extra step to the process, and sometimes the FEM programmes can be too complicated and heavy for the quick analysis wanted in the conceptual design phase. Nevertheless, in both cases there is a great advantage in making the structural model parameter controlled and let it follow the architectural changes. At BIG, the transfer solution was preferred because of the well-known performance abilities of the FEM programme Autodesk Robot Structural Analysis.

Harding raises an issue with parametric analysis in the early design stages (Harding et al., 2012) where it may prove challenging to make a model that can adopt the architect's variations in geometry. Zofchak points out that the parametric script can only give results within the limits of the script (Zofchak, 2012), leading back to the fact that it is the tool user that limits the solution frame. These limitations often restrict the parametric model to only being able to adopt geometric changes within one typology and often the architect can work within several ones. The consequence can be that a new parametric data exchange model has to be made for each geometrical typology. Despite this relevant objection, it was still found very useful to us Grasshopper3D and GeometryGym, as it gives a more flexible work process compared to a traditional programme, where the model is remodelled from the bottom in the FEM software.

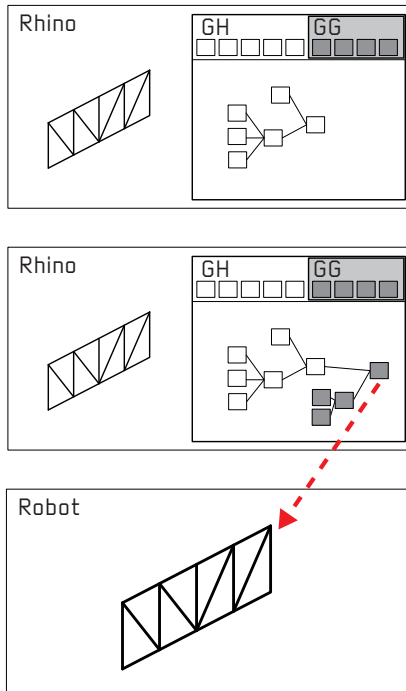


Figure 24. Diagram showing steps from Rhino to Robot.

Rhino to Robot to Rhino

The process from geometry to FEM starts in Rhino. In Rhino the geometry is drawn through the visual plug-in scripting tool Grasshopper3d (GH). The geometry is made by combining components representing the code of different drawing functions. Combining these code representations gives a coherent code describing the geometry (*Figure 24*). The geometry is visualised in the Rhino environment. The code components are combined to the GeometryGym (GG) components. These components add profiles, material properties, support conditions, forces and force combinations – all as adjustable parameters to the geometry and feed them to the FEM software, in this case Robot. For surfaces, a mesh is created in Grasshopper, which Robot uses directly for the finite element mesh (since Robot does not work with NURBS). In Robot, the analyses are performed and the results presented. This

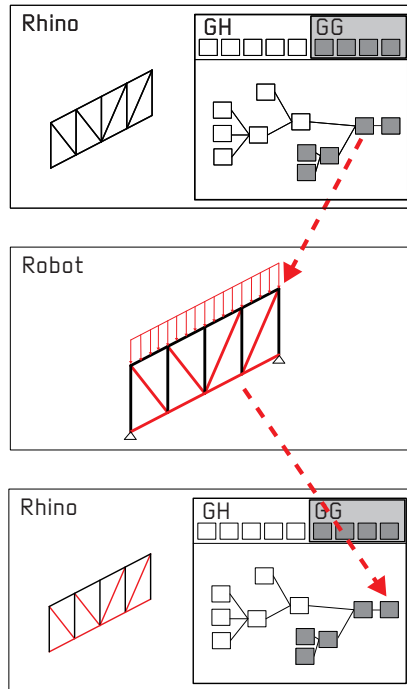


Figure 25. Diagram showing steps from Rhino to Robot to Rhino

can be useful in the very early design phase where geometry may change, and in optimisation cases where only simple load cases are investigated and many options are tried out.

In more complex load cases, it may be an advantage to control the loads directly in Robot, since Robot has greater flexibility for setting up different load types and load cases. In addition, GeometryGym still has some bugs regarding export of load cases. However, it must be assumed that this will be improved in the further development of GeometryGym.

Moreover, GeometryGym makes it possible to recall results from Robot for single parameters. The scrip is built up as previously described and then added a few more components, asking Robot to execute a calculation and then return the result to the GeometryGym component (Figure 25). The output from the recipient component

– the finite element analysis result – can be used as any other parameter in Grasshopper3d. Supports and loads must be defined in GeometryGym, why it is not possible to make modifications in Robot. This option can be combined with other plug-ins such as Galapagos that makes it possible to run optimisation cycles on e.g. member dimension in a truss optimised against the deflection. Although this still is an unstable function, the potential is very clear.

Cases

“BIOVAF”

For the BIOVAF competition proposal, one of the more geometrically challenging areas was an arc-shaped bridge truss structure spanning between two building volumes. The design of the curve, volume, width and height was changed and adjusted while the engineer was looking at the structural dimensions. But instead of giving creative ideas about the structural design that could be beneficial to the design, the engineer was always behind. When he had calculated something, the shape was often changed in the meantime. The engineer also struggled with the geometry and had many issues getting the geometry right in his FEM programme. This resulted in waste of time and frustration for both parts, because of iterations between the engineer and the architect in working out the geometry.

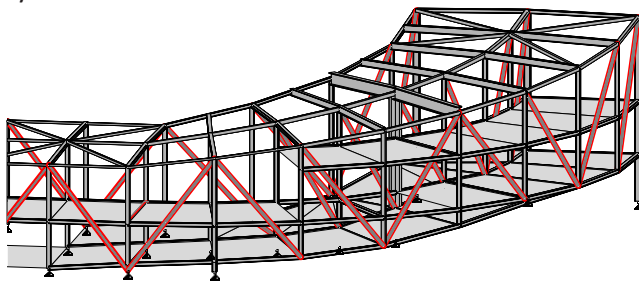


Figure 26. Structure of curved building building part of BIOVAF.

Figure 27. BIOVAF indoor curved building. Visualisation: BIG



The BIOVAF case would have turned out very differently, had a link between the architect model and the engineering model been applied. However, this way of working with data exchange requires the involved parties to be willing to change their work methods. In this case, the engineer would not accept the geometry sent to Robot, because the engineer felt he lost control of how the Robot model was built. Hence, he did not manage the tools.

Nevertheless, to make an example, a parametric model was set up that followed the volume's geometry. Hereby, it was possible to adjust the distance to the façade, the truss member dimensions, the type of truss, the number of divisions in the truss etc.

This model allowed the architectural engineer to try different variations of the geometry to identify the most suitable one. It offered quicker responses on the structure dimensions and performance. It also permitted the architectural engineer to investigate how the architect's changes to the geometry influenced the structural design. In this case, the model's geometry, profile and materials were added by GeometryGym while supports and loads should be added in the FEM software. This was an attempt to give the engineer the control he needed, yet making sure that the geometry was correct. Despite this, the model was still not used. Using this model would have saved the engineer and architect time by not having to double check the geometry and limited their mutual frustrations.

The unwillingness presented in this case is not representative for civil engineers' general attitude. Yet challenges arise when introducing new work methods and tools. It requires time and interdisciplinary collaboration from the very early phase of the design and despite the advantages, it still encounters much resistance (Turrin et al., 2011).

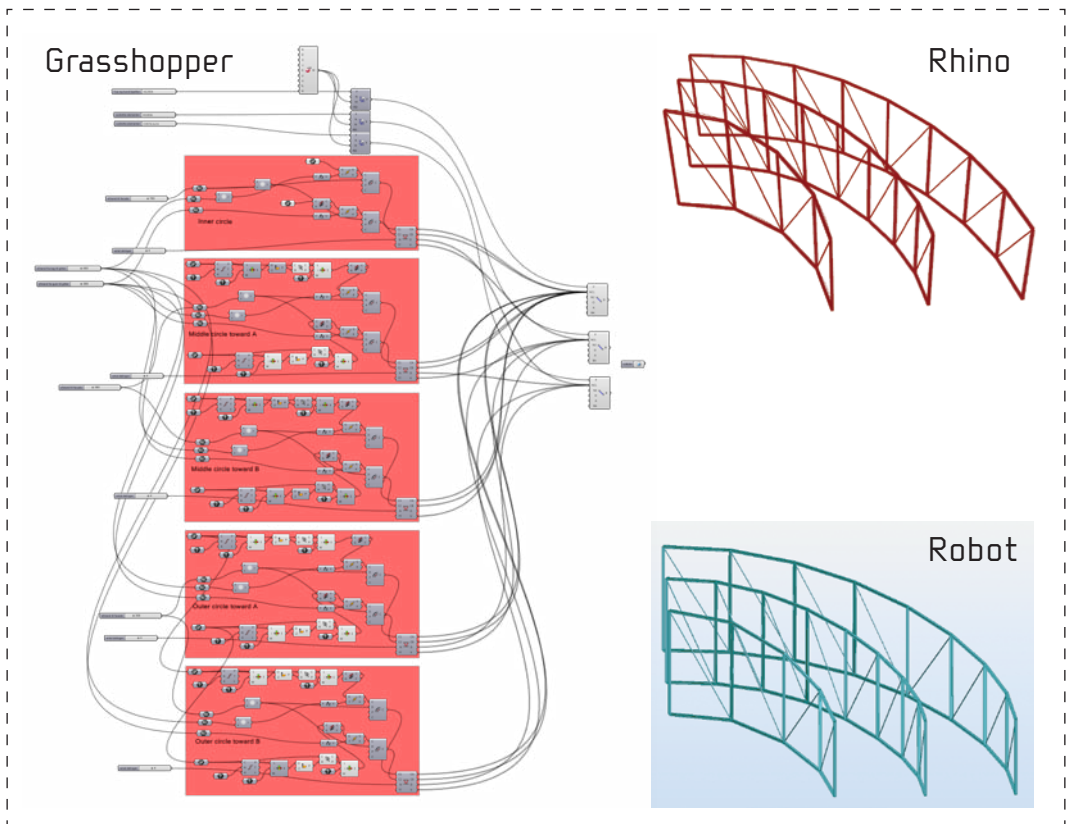


Figure 28. Visualisation of structure in Rhino. Grasshopper script sending the structure to Robot. Structure in Robot.

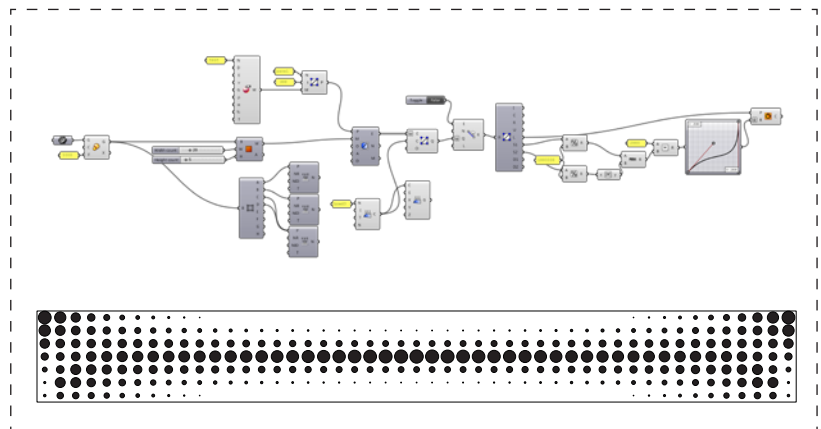
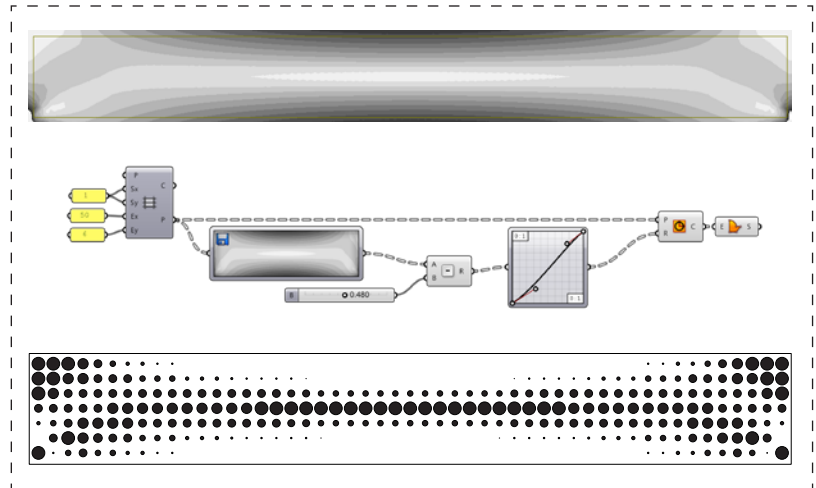
“Experimentarium”

In the Experimentarium competition, the design of the structure and the façade was very closely related. The structure was concrete walls, the surfaces were drawn in Robot and a stress distribution grayscale plot was made. The plot was used in Grasshopper3d as a parameter to define the window hole dimensions in the structure according to the stress concentration. This process was done without a link between Robot and Grasshopper3D. A picture was exported from Robot, then imported it to Grasshopper3D and used as a parameter (*Figure 30*). This process could be automated. If the model was linked between Grasshopper3D and Robot, it would easen testing variations and making updated stress plots, whenever the geometry was changed (*Figure 31*).

An extra loop could illustrate the consequence on stress distribution when holes were implemented or changed. This way the loop could be an active component in the design-making. However, the results cannot be used directly as the analysis is only focused on one parameter. Other parameters such as support conditions will influence the area towards the ends of the wall. Nonetheless, it gives a good indication and a quick and intuitive feeling of how the design and structural forces influence each other.



Figure 29. “Experimentarium” concrete box. Visualisation: BIG



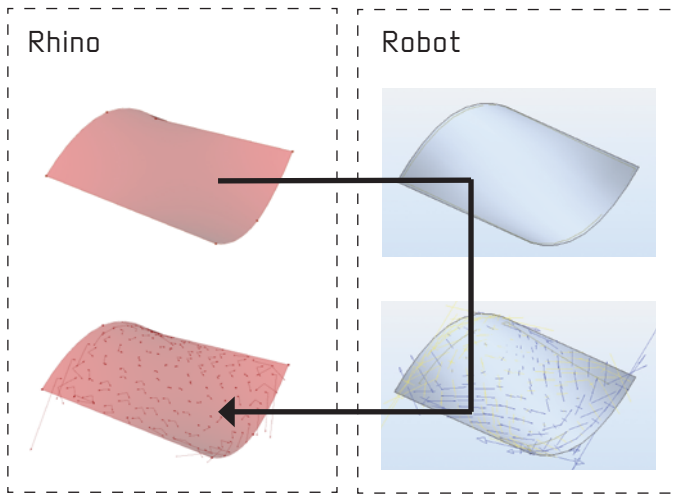


Figure 32. Double curved Grasshopper surface visualised in Rhino. Surface in Robot with loads. Surface in Robot with principal stress vectors. Surface in Rhino with principal vectors recalled for m Robot.

“Super-Light Structures”

In addition to the cases from BIG, a number of studies on bilateral data and geometry transfer between Rhino and Robot were made when the newly patented structural system called Super-Light Structures was developed. The concept of Super-Light Structures is to place strong concrete according to where it is needed, and then fill light aggregate concrete around it (Castberg and Hertz, 2011; Hertz, 2009). A tool to make a finite element analysis of a given geometry and feeding the results in to a parametric design tool, where vectors represent the principle stresses, is highly relevant as it can model the optimal placement of the strong concrete according to principle stresses.

As an example, a double curved surface is modelled in Grasshopper. Supports and loads are added and the surface is sent to Robot. Next, the principal stresses are recalled to the GeometryGym component. From here, Grasshopper components are used to visualise the principal stresses as vectors where the length reflects the size of the stresses in the specific area. Previously, transfer of FEM results was done manually, e.g. in the “Experimentariet” case and the double curved roof shown in *Figure 33*.

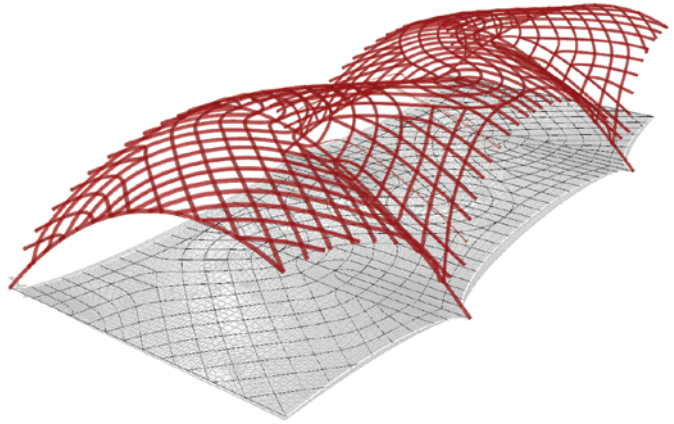


Figure 33. Doubled curved roof with pearl-chain structure modelled manually.

The geometry was made as a rough manual interpretation of the principal stress plot. The principal stress plot from the FEM does not give coherent lines through the divided finite elements on the structure (see *Figure 34*). An interpretation is needed of how the vectors from each little analysed area can be directed to the next area, making a line. The manual method gives freedom to adjust the distance between the lines – but also a roughness to the final grid. Furthermore, the manual procedure is time-consuming and not dynamic. Applying digital link makes the process more dynamic, adaptable to changes in the geometry, quick to work with, and precise. It gives the architectural engineering process a much better flow. However, it also requires a complex algorithm to set up parameters on how the lines (principle stress trajectories) should be made based on the relation between the vectors at each element at the finite element division on the plot of the principle stresses.

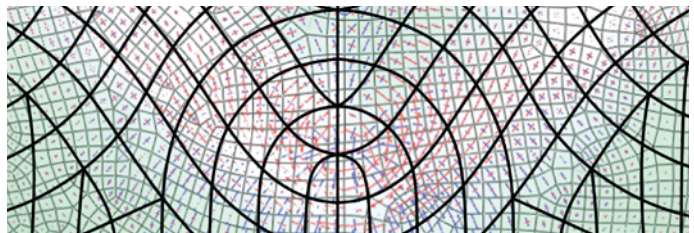


Figure 34. Plot of principal stresses and pearl-chain placement.

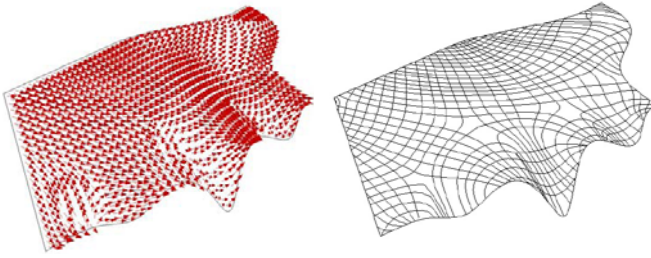


Figure 35. *Principal stresses vectors and principal stress trajectories in Rhino. By: Georgiou*

Georgiou has made a link like the one described, however, it did not focus on Super-Light Structures, only on general optimisation. (Georgiou, 2011; Georgiou et al., 2011) It is not made through GeometryGym but as an independent plug-in to grasshopper3d. This is not accessible but it exemplifies other ways of doing it. GeometryGym has a function that plays with principle stress trajectories but it still remains to be finally developed.

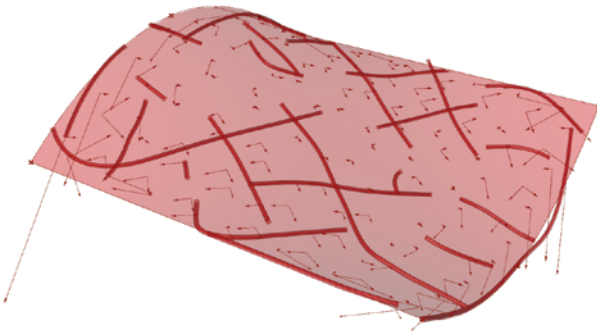


Figure 36. *Principal stress trajectories made in Grasshopper via GeometryGym plug-in.*

The tool is not only relevant for the Super-Light Structural concept but for architectural engineering in general, as the visualisation of stresses and principle stresses gives an intuitive explanation to the theoretically optimal placement of structural components.

Discussion

Clearly, there are already useful software solutions on the market for architectural engineers. Whether the software fulfils the needs is a different story. Some software makes analysis in Rhino, some transfers data to FEM programmes. Both one has positive and negative qualities, but neither one is the obvious choice all the way from the conceptual design to detailed design. The transfer solution is an option, but not the most intuitive one in the conceptual design. GeometryGym is still under development and is limited by poor performance in linking from FEM software to Rhino. However, it is also relevant to look at whether the architect uses the same software all the way through the process. The architect tends to switch to a BIM software, e.g. Autodesk Revit, in the detailed design phase. Nevertheless, more development on the transfer solutions and simple rough calculation tasks in FEM software would be helpful in the early design phases. Additionally, FEM software can be used all the way through the process. In general, there is great room for further development of tools to the architectural engineer to assist him in solving problems with very varied geometry.

Importantly, although the tools can be very intuitive, an architectural engineer strongly is needed to feed the right input and interpret the output (Bjerregaard Jensen and Nielsen, 2011). Zofchak argues that inserting intelligent structural design tools in to architectural design cannot take the place of the structural engineer; rather it will increase the need for him in the design development to set the parameters for the scripts (Zofchak, 2012). At BIG, the tools not only helped to give a quick response, it also helped translating the calculation data into information for the architects. Specifically, it was helpful to present the results in a graphic environment accessible to the architects cf. Oxman(Oxman, 2006).

A different question is whether engineers and architects are willing to adopt new ways of working offered by the new tools. In the cases from BIG, the tools were made accessible but often not applied although they likely would have supported the decision-making of the design. This may of course relate to the involved parties. However, the tools are becoming more known, developed and, hence, more applicable.

Conclusion

The work relation between architects and engineers is getting closer and the architectural engineer supports this approximation. Geometry is a common language across disciplines and essential for interdisciplinary interaction and communication. This requires new tools and a new view on tools. There is software on the market supporting a link between architectural modeling tools, such as Rhino via Grasshopper3d and GeometryGym to a FEM software such as Robot; yet they are still not fully developed. Better integration and a more intuitive connection of the architect and engineering software is desired, especially, the option of making the operation more fluent in either direction.

However, despite their limitations and the fact that the described tools were developed targeting traditional engineering applications, they do offer great advantages to the architectural engineer and the work process. They support quicker responses, essential in the early design process and very useful to the architectural engineer. Furthermore, the tools enable the engineer to represent his results in an architectural language - a great advantage for the communication.

/04/ IMPLEMENTATION

Implementing a new Structural System

Introduction

This chapter describes experiences gained from introducing a new structural system for buildings through participation in projects at BIG. The statement postulating that the construction industry is conservative and the courses for its origin are investigated. Innovation has difficult conditions in the construction industry. The chapter presents an overview of some of the barriers. It is discussed what the typical challenges are, which are met in projects, when introducing a new structural system and what it requires to get the new technology on board in a project.

A conservative profession

Construction industry has a reputation of being conservative and in general not innovative (Blayse and Manley, 2004). The truth of this reputation is not investigated but the reasons that caused it are of interest for this chapter. Innovation has many definitions according to a context. In this context it is relevant to look at the willingness to adopt innovation because Super-Light Structures is not a finished product and it is still being developed. Hereby it shares many of the challenges that innovation in a project team would have to overcome.

Within the construction industry the definition of inno-

vation provided by Slaughter is broadly accepted.

Innovation is the actual use of nontrivial changes and improvement in a process, product, or system that is novel to the institution developing the change(Slaughter, 1998).

A number of issues can be listed as acting against innovation in the construction industry such as; lack of time in a building process, risk and responsibility, regulations and standards, existing product manufactures and the long time it takes to change habits and gain new knowledge. Innovation and development takes time as an example the SL-deck can be mentioned. The development of the SL-deck has taken about four years from the first sketches to the final product suited for mass production and the production facility is in place. A time horizon like this can be very difficult to fit into a typical process of a building development from sketch to finished building. Another significant barrier with relation to time is the relatively short project period, where a design team is set for a project before moving on to a new team for the next project(Atkin, 1999). This discontinuity results in losses of gained knowledge, because all projects are handled as unique and the knowledge gained in previous projects are often not considered due to lack of sharing and lack of time to collect experience(Håkansson and Ingemansson, 2013). This makes it difficult to carry an innovation process through different project teams.

Risk and responsibility plays an enormous role when innovating solutions and new products are brought in play. At the end of the day the customer is paying for the innovation but who is taking the risk of accepting a responsibility is a different story(Atkin, 1999). The consultants can take it, if they are paid a salary that is related to the size of the risk. The producer can take it and reflect in the price of the product, but it can also be shared with the client. No matter which solution is selected, it is important to get a solution all actors are satisfied with. Otherwise the

innovation would probably stop because some actors will oppose the development. It is often seen, that to control a complex building process the responsibility is split out on subcontractors and even small contributions from specialist are actionable(Blayse and Manley, 2004). This will often lead to a choice of well-known solutions instead of innovative untried solutions, because it does not match the risk of suggesting new solutions if the fee is small. Furthermore, this division can especially in bigger projects challenge communication across the professions, which is unfavourable to innovation(Blayse and Manley, 2004).

The construction sector is in many ways regulated and based on standards in order to ensure safety and improve trade across different markets. However, this has a huge drawback when it comes to innovation because it is difficult to change systems and it implies that only certain well tested constructions and products are used(Dubois and Gadde, 2002). Nonetheless, the increasing tendency to use performance-based regulations instead of prescriptive regulations has a chance of promoting innovation(Gann and Salter, 1998). Performance-based regulations are used in the Danish building industry e.g. for deck structures where there are limits for load bearing capacity, minimum time for fire resistance and demands for acoustic performance. All these requirements are performance related and not regulations for a specific type of structure. Nevertheless, known structures have often an advantage because they are well tested and their performance in relation to the requirements is known. Similar regulations regarding structural timber systems in houses of more than two levels was changed in Sweden in 1994 from a prohibition to a requirement that stated how long a building must hold exposed to fire(Bengtson and Håkansson, 2008). This change was done to open for a reintroduction of timber structures hoping that cheaper structures than the concrete based solutions were used. However, the first couple of projects were not cheaper because the reintroduction was more complicated and

time consuming than expected (Bengtson and Håkansson, 2008). Furthermore, the suppliers and producers to the traditional market saw it a threat to their investments, which they tried to protect. It must be expected in general that existing suppliers will act against a development of a competing product. A final lesson learned from the case in Sweden was that it takes long time to change habits and build up a general knowledge base at the actors. This was also reflected in the first cases that turned out more expensive than expected, because of the lack of knowledge and because there on beforehand only has been focus on the product and not on all the actors that have to change their working procedure.

Many barriers to innovation can easily be found in the construction industry, but the industry is also handling a lot of new product all the time. However, this is not categorized as innovation, because they are final products, which do not change the working procedures (Håkansson and Ingemansson, 2013). Innovation and introduction of new products do happen in the construction industry but there is room for improvements and it is good to be aware of which barriers you can come across.

Who to be first?

When introducing a new structural system it is of course very important to consider the order in which the introduction is made. It is relevant to deliberate whether there is a need for a project that will use the product before the production is started, so that the start investments can be partly paid, or alternatively that the production should be in place before the product is introduced to the market. Each solution has its own pros and cons, but in the end it might also be factors out of your reach that determine whether one or another approach is selected. Having a finished product when entering the market makes it easier to join within the short timeframe a project team has on a project, but is also preclude input on develop-

ment or the product from actors who are going to use the product. On the other hand trying to enter a market with an unfinished product can also be very difficult because the project team might not have time to engage in development or the product cannot manage to go in production within the timeframe of the project.

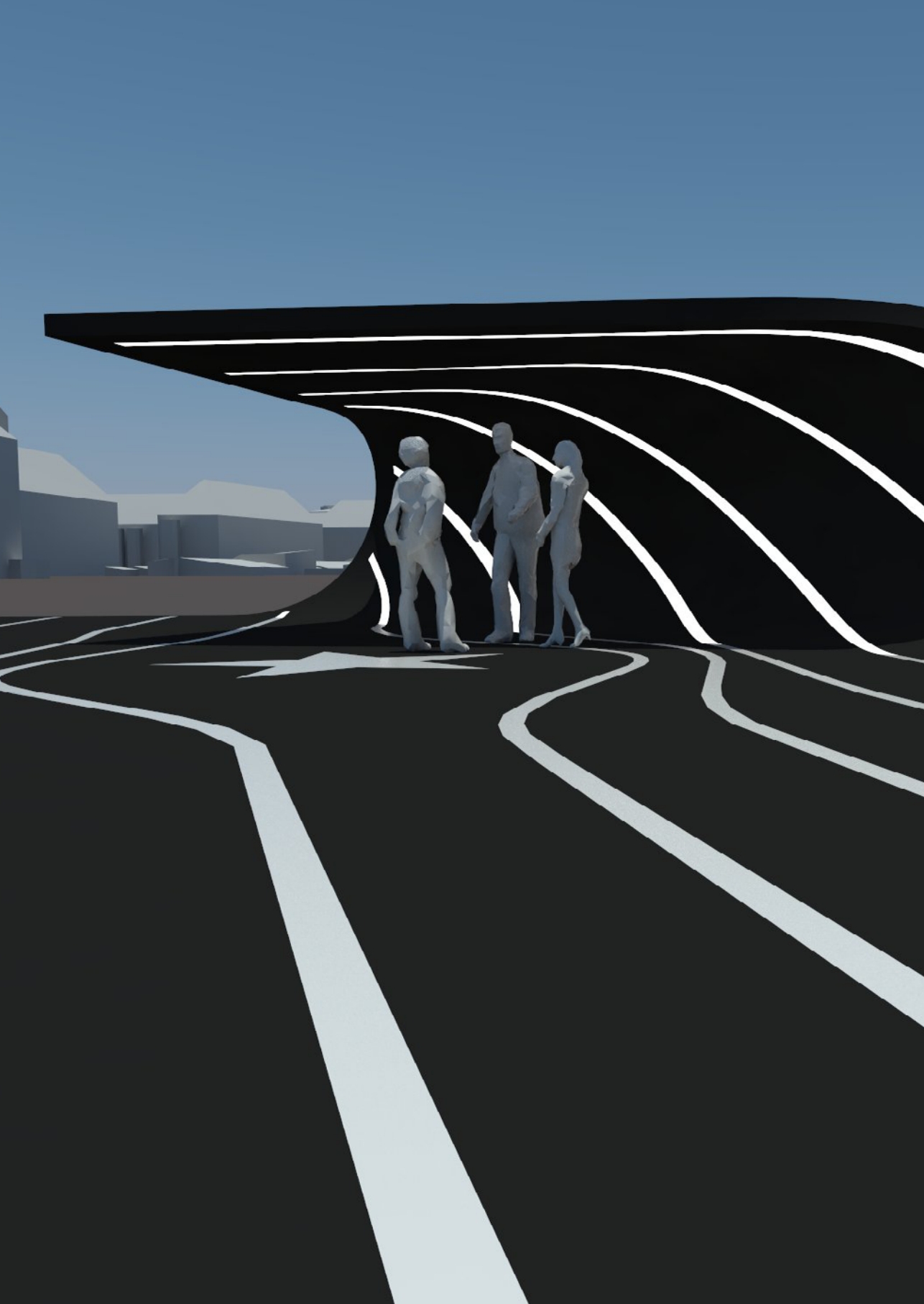
It is also relevant to identify who is going to demand the product in a given case. Is it the architect, the architectural engineer, the structural engineer, the contractor, or the client, or could it be them all that introduce the product to a design? Furthermore, in which stage of the process is it relevant to introduce it? Does the architect dare to suggest a new structural system in a competition, or is too risky because he does not know the clients willingness to take the risk of a new system? Should the architect or other actors suggest it later in the process, where the necessary dialog can be taken about risk and responsibility, or will a late introduction cause that advantages is not utilized because the shape of the building is already fixed based on common knowledge from existing structures. There is of course not a single answer to all these questions, but it is important to consider them and in the following cases it will also be clear that different cases will give different answers. Nonetheless, to get a first building project to present the product in is essential but what makes the first client to take a risk and bring it all the way to execution, is difficult to say.

Cases

Snippen

Snippen is an element in a project called SuperKilen - a park area in Copenhagen – and it works as a mixture of a sculpture and a shelter. It has a shape as a surface corner bended 180 degrees see *Figure 37*. Originally the structure was intended to be in fibre reinforced concrete. However, this was not allowed by the local authorities. Therefore the architect asked if Super-Light Structures could be a solution to the challenging structure. A proposal was designed based on the principle of the pearl-chain system see detailed description on page 94 (Castberg and Hertz, 2011). The proposal fulfilled the architects' vision regarding shape and it was presented to the contractor. The contractor was very dismissive. He found it very difficult to make and meant that posttensioning the structure was very complicated. His augmentation and reaction was clearly a consequence of his lack of knowledge. This became such a big barrier to him that he did not go into a constructive dialog. The client found it interesting but had a weak character and did not want to push the contractor to something that he clearly not had the skills to handle or will to acquire. Besides, the lack of knowledge, the economy, and the risk was also deterrent to the contractor but it was never properly investigated because there was not a serious debate about the solution. The sad outcome became that the structure never was build, because of lack of will for solving the problems that such a structure causes no matter how it is made.

Figure 37. Visualisation of Snippen an element in the project called: Super Kilen. Illustration: BIG



Batteriet

The Batteriet is an enormous project of 120.000m² with a mix of residential and commercial applications placed in Copenhagen. It is a very geometrically complex structure. It has for example cantilevered corridors at each level towards and internal atrium see *Figure 38* (Castberg and Hertz, 2012). A detailed master plan for the site was made that was approved by the local authorities and the design of the actual buildings was stated. From the start of this phase Super-Light Structures was in play as an element that was considered beneficial for realization of the visions. Super-Light Structures was introduced by the author - backed up by the architect, to the engineer as well as the contractor and the client, that in this case was same person. Here the focus was on the SL-deck that was still relatively early in the development stage at the time where the project began. Still there had not been any test executed and the question of where and how to produce the deck was still totally open. The SL-deck had some obvious advantages for the project regarding fire resistance, acoustic performance, and flexibility in shape and cantilevering, which gave strong technical benefits. The structural engineer was positive even though knowledge about the SL-deck was still limited because of lack of test and references. The client was more worried because of the lack of references. After a long period with debates of pros and cons and the introduction of a fund that would cover the risk of extra expenses caused by the implementation of the SL-deck at the first building, the client became convinced that it could be a success. The client even considered starting up his own production of the elements or join as a partner in the company owning the patent of the SLS. Unfortunately, the client was affected by the global financial crises and the huge drop in prices on apartments put the entire project on hold right at the time, where the more detailed design phase of the first building was about to start.

Figure 38. Visualisation of “Batteriet”. Illustration: BIG



BIOVAF

Three institutes at The Technical University of Denmark had to move to a new shared building. For this a competition was made where BIG participated with a proposal. Here it was obvious to see whether the SL-deck could be beneficial to the project, since the SL-deck was invented at DTU. It was therefore assumed that DTU would be positive to an implantation despite the lack of references since DTU had already implemented parts with SL-decks in another building. A design consisting of relatively simple shapes was made. Nonetheless, a number of clear advantages could be listed when comparing the use of SL-decks to traditional hollow-core slabs. (Detailed description in page 122) The architect was positive but the structural engineer was heavily against taking the SL-deck in to the competition proposal. At this time the tests of the SL-deck had been executed with positive results (Hertz et al., n.d.). Even though, the engineer was concerned about the long spans and other technical issues. These concerns were repudiated one by one but the engineer also feared of how the responsibility would be placed and in general not comfortable by suggesting a new system that did not have more references. The architect did not want to give up the advantages, so the SL-deck was used in the competition and the advantages were mentioned in the competition material. The competition was unfortunately not won by BIG so the proposal was never carried out.

Figure 39. *Visualisation of connection between existing and new buildings in the BIOVAF project. Illustration: BIG*



Frederiksborgvej

Frederiksborgvej is a residential project consisting of 100 apartments at 100m². Based on a sketch proposal it was clear to see that it would be beneficial to use SL-deck for the building, because all the walls were angled and the project had huge cantilevered parts (Detailed description in page 130). Furthermore, the fire and acoustic performance of the SL-deck would make it easier to fulfil the requirements. Based on these advantages a dialog was started with the client before the detailed design began. He was very positive and wanted to use the SL-deck based on the advantages presented to him, but furthermore he was even more happy for the fact that the deck did not have any hollow parts. He had had many water damages in previous projects caused by lack of proper draining from hollow-core slabs and alone to avoid this was enough for him to try the SL-deck. A proposal for how the structural system of the building could be solved with SL-deck was made to give a more precise idea of the pros and cons before the detailed design began. Unfortunately, the client lost the rights for the site just as the detailed design phase was about to begin and even though a new client took over the project no decisions has yet been made on how to proceed with the project.

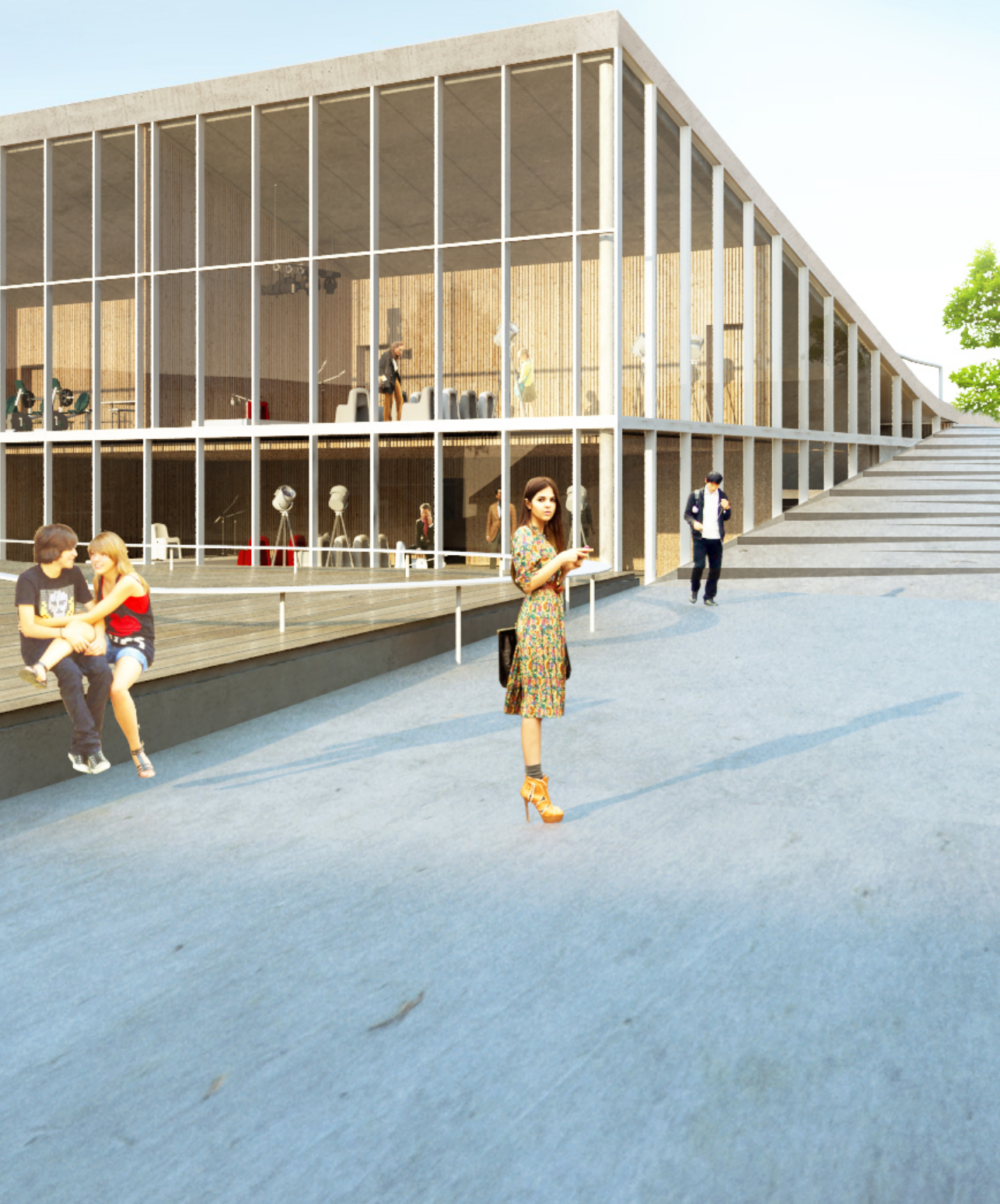
Figure 40. Visualisation of Frederiksborgvej. Illustration: BIG



Gammel Hellerup Gymnasium

The project is an extension to Gammel Hellerup Gymnasium consisting of changing rooms, music rooms, and classrooms. When a sketch proposal was made and sent to the client there was a discussion about using the SL-deck but it was turned down by the architect who wanted exposed in situ cast structures. However, after the contractor had given a price an element solution was reconsidered. As a result the SL-deck was chosen mainly because of the noise damping effect, it could provide, if the light aggregate concrete underside were left exposed. The client accepted to use the element that at this time also was about to go into production. This solution made it possible to save the extra sound panels that otherwise had to be used. This was of such an advantage to the contractor that even though he was concerned about the lack of reference and the expected extra complications associated with new products it was still expected to gain an economical profit. The project with SL-deck incorporated is now in the detailed design phase.

Figure 41. *Visualisation of the extension of Gammel Hellerup Gymnasium. Illustration: BIG*



Generalisation and Discussion

Typically met challenges

Making the described design cases and others not described here, some challenges were raised by the involved parties. One was the lack of references which was mentioned for all the projects where it was introduced. This was a huge issue in Snippen and the BIOVAF project for two reasons one was risk related – is it possible to build? - and another was a practical issue of being able to collect knowledge from others experiences. Fortunately in some cases the parties were able weigh the advantages higher and believed in the concept and were willing to take the risk. It will always be so that the risk is a bigger issue to some than to others. Not to neglect the risk because it is truly there and will properly always be when introducing a new product.

Another common concern is that a new product requires new procedures which inevitable will lead to extra work until knowledge about the product becomes common to the parties involved in the process. It will require extra work of the engineers that will have to learn how to calculate the new structural system and it will require extra work to the contractor that will need to learn how to construct and assemble the new elements. In some cases there was just a general resistance against spending time on new procedures and in some cases it was more an uncertainty about how long time it would take to establish the required knowledge.

Besides from the more knowledge related risk and economically based topics was an uncertainty about how long time it would take to get a productions up and running and the consistency of supply. This is of course relevant related to the relative short timeframes building projects are made within.

On-going and repeating suggestions

The general experience when introducing the Super-Light Structures was that to a start people were defensive and expressed that they preferred known solutions. But by keeping suggesting and explaining the advantages the parties started considering the proposed solutions. When this is said, the result was often that known solutions were preferred because of less uncertainty. This indicates the reputation of being conservative. In general it can be concluded that it is easier to say no than yes and if you want to introduce a product then you need to be persistent.

It is notable that the SL-deck became more and more relevant as the development of the deck progressed and the tests were executed and a plan for the production and finally a producer was found. It may be assumed that this is an argument for finishing a product before entering the market instead of developing it with the clients. On the other hand the inputs from the first project cases concerning what was needed also influenced the design of the SL-deck that is now about to go into production. So it is difficult to say if one approach would be better than the other but it is clear that it is easier to consider the SL-deck in relation to projects, when its performances are documented. Second, in both Frederiksborgvej and the Gammel Hellerup Gymnasium there were some side effects to the product that gained the biggest interest from the parties. Furthermore, it was clear that to get the first reference it requires that several of the parties are positive and no unforeseen parameters from outside are seen to be against it.

Who is going to demand the product?

Whether a new structural system and the benefits it gives may change the way an architect will make his design is a very relevant question. Because it may indicate whether it will lead to more interesting architecture and whether the architects demand for a product supporting the design improves introduction of a new product on the market.

To this question the experience has been that when the architects are designing they are not concerned whether for example a cantilevered part should be constructed in one way or another unless it is huge dimensions. This means that the architect would not be the one to bring a product like the SL-deck into a project already in the sketch phase, but they become very happy when they afterwards are told how to solve the structural problems by means of it. This practise however might change when it becomes more common to use for example the cantilever option that the SL-deck provides and the architect experience that his suggested design is not so often refused for technical reasons when he apply an SL-deck. Furthermore, it was the experience that the architects did not dare to put a new specific structural system into their design in a competition because they feared to be discarded, if the client did not want to take the risk of a new product. Counter-argument could be that BIG's way of working is not representative to the average architect practise, which might be true. The average architect will properly not at first take the freedom of designing and afterwards take discussions about the structural issue, because cantilevered parts often will be expensive to build. If this is the starting point and the architect was told that he could make cantilevered elements without being concerned about the budget, then it would properly affect the architects design to an increased demand for using a new structure like the SL-deck.

If the architect does not demand the SL-deck the engineer can of course suggest it in the team and he probably will. However, the civil engineer has gone through a heavy specialisation during the last decades which has resulted in very good experts but few that can grasp the overview and work across disciplines(Castberg et al., n.d.). This can lead to different types of engineers each suggesting the SL-deck based on advantages within their special field, which will be fine, but an architectural engineer that can suggest the product based on the overview of the con-

sequences in all areas will be preferable to secure coherence in the project. He might even be able to implement it earlier in the process, which can lead to a better utilisation of the SL-decks advantages and to move the limits for a free design.

Constructability of Modern Architecture using Super-Light Structures

This chapter describes four structure cases which utilise Super-Light Structures to support modern architecture. The presented cases utilise Super-Light Structures in a variation of the pearl chain system and the SL-deck, respectively.

The first section of the chapter consists of a conference paper presenting a case utilising the pearl chain concept. Subsequently, three cases using the SL-deck are presented by a conference paper, a written section, and a journal paper, respectively. The first of these cases focuses on cantilevered slabs; the second is a comparison to standard solutions; and the third focuses on integrating beams into the slabs.

By testing Super-Light Structures on BIGs' projects, it is the aim to demonstrate the constructability and the opportunities to support architectural visions by applying Super-Light Structures.

94/ Snippen
108/ Batteriet
122/ BIOVAF
130/ Frederiksborgvej

Conference Paper /1/

Design of Folded Shaped Structure with the newly Patented Concrete Structure concept: Super-Light Structures

Presented at:

IABSE-IASS Symposium

Taller, Longer Lighter

Meeting growing demand with limited resources

London 2011

Authors:

Niels Andreas Castberg

Kristian Hertz

Summary

The use of folded shapes in structures has become more common, but it still costs problems because of construction issues and bending moments. The present paper deals with how the newly patented structural concept Super-Light structures (SLS) can be used to create folded shapes. SLS gives lighter structures and can lead to simpler erection because of the introduction of prefabricated elements. The paper regards two geometries using the SLS concept and compares their static and structural behaviour. Furthermore, material use is compared to a traditional concrete structure for the examined geometries. For both geometries it is found that they are structurally possible and both of them have a considerable material reduction compared to a traditional concrete structure.

Introduction

Folded shapes are used increasingly by architects in modern buildings. However, folded shapes are often associated with construction difficulties due to the bending moment the structure is exposed to. Furthermore, the formwork for the curved form can be complicated and expensive.

The Super-Light Structure concept allows a much more free development of architecture and can among other things be used for folded structures

Super-Light Structures

Super-light Structures is a structural concept where a skeleton of normal to high strength concrete is made and shaped according to force directions and distributions.

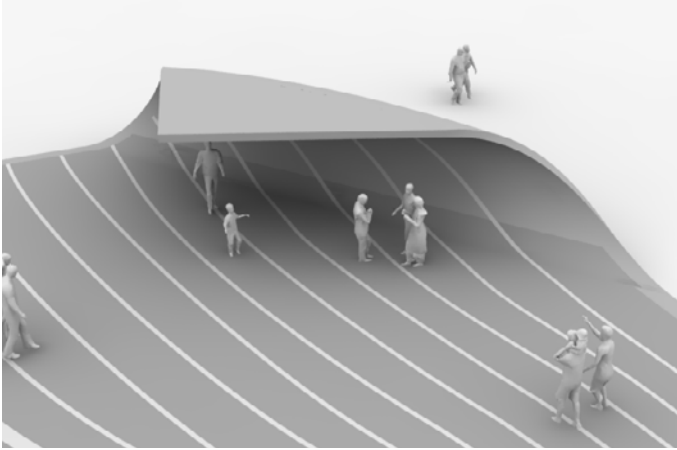


Figure 42. *Visualisation of Snip-pen. Illustration: BIG*

The skeleton is embedded in a light concrete. The light concrete supports the bones in the skeleton and distributes the forces from outer loads to the skeleton. Furthermore, the light concrete can protect the high strength concrete in fire situations. The concept is patented at The Technical University of Denmark by HERTZ in 2009 (Bagger and Hertz, 2010; Hertz and Bagger, 2010; Hertz, 2009a, 2009b, 2008).

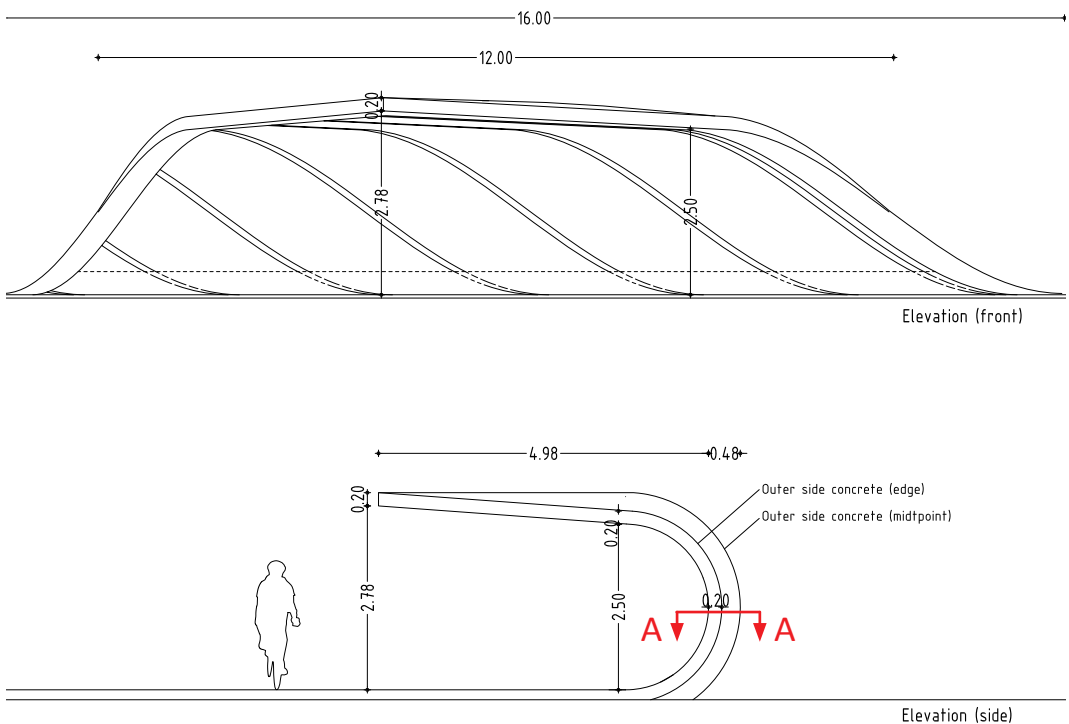
The skeleton system is in the patents solved by applying a pearl-chain concept. Here the “pearls” are the skeleton parts which are held together by a prestressing cable. By this method the skeleton can be pre-tensioned together before the light concrete is cast around it. The pearls can be prefabricated in standard elements that can be assembled according to the shape the architect wants to create. The pearl-chains can also be cast into standard elements of light concrete. By placing the strong concrete according to forces, the arch will be reintroduced as a structural element, but now it can be cast as prefabricated segments so that the price can be at a reasonable level.

The Super light concept gives more freedom to architects and gives more optimal structures, while saving materials and CO₂ (Hertz and Bagger, 2011).

The aim of this paper

This paper deals with how SLS can be used as a structural concept for a folded shape. The paper describes how to make a folded shape with different variations of a ribbed structure that will work as variations of the pearl-chain system. The aim is to clarify the stress performance in the highest loaded cross section, to determine the number of cables needed and their impact on the stresses in the cross section. Finally, the paper will present the difference of concrete used for the examined solutions and for a traditional concrete solution. The research for this paper is done at DTU in cooperation with the architect firm Bjarke Ingels Group, BIG. The studied design is based on is from one of BIG's projects (Super kilen) in Copenhagen.

Figure 43. Elevations of examined shape. Drawings: BIG



Method

An SLS structure with the outer form as shown in *Figure 43* has been analysed using FE software Robot Structural Analysis Professional (ROBOT). The post-tensioned cables have been dimensioned according to Freyssinet (Freyssinet, 2007). The SLS structure has been designed as a number of ribs in strong concrete with light concrete in between see *Figure 44*. The rib's have been designed to carry the formwork without the stabilizing effect of the light concrete. The analysis is limited to cover the rib obtaining the forces from the longest cantilevering. The length of the element is approximately 5 meters from the edge to the midpoint of the arch see *Figure 43*. The ribs are made in a concrete of grade 50.

Examined cross sections

A number of different solutions for the investigated rib's cross section have been investigated to fulfill the demands regarding bending. The examined sections are all section A-A (see *Figure 43*) at the middle of the arch where the largest section forces are found. All the examined ribs are varying from a max height at the middle of the arch to a minimum height at the cantilevered end. Two of the cross sections are chosen based on their buildability and analysed (see *Figure 45*).

In GeoA (see *Figure 45*) the cross section is a simple rectangle reaching from side to side of the outer shape. This section is meant to be produced as a prefabricated element on a casting table with to curved side forms.

In GeoB the cross section is a variation of GeoA. As shown in *Figure 45* the sections is an H shaped with the "web" dimensioned as GeoA. But the fabrication is based on prefabricating the light concrete parts and casting the strong concrete in situ. By this method compression flanges are

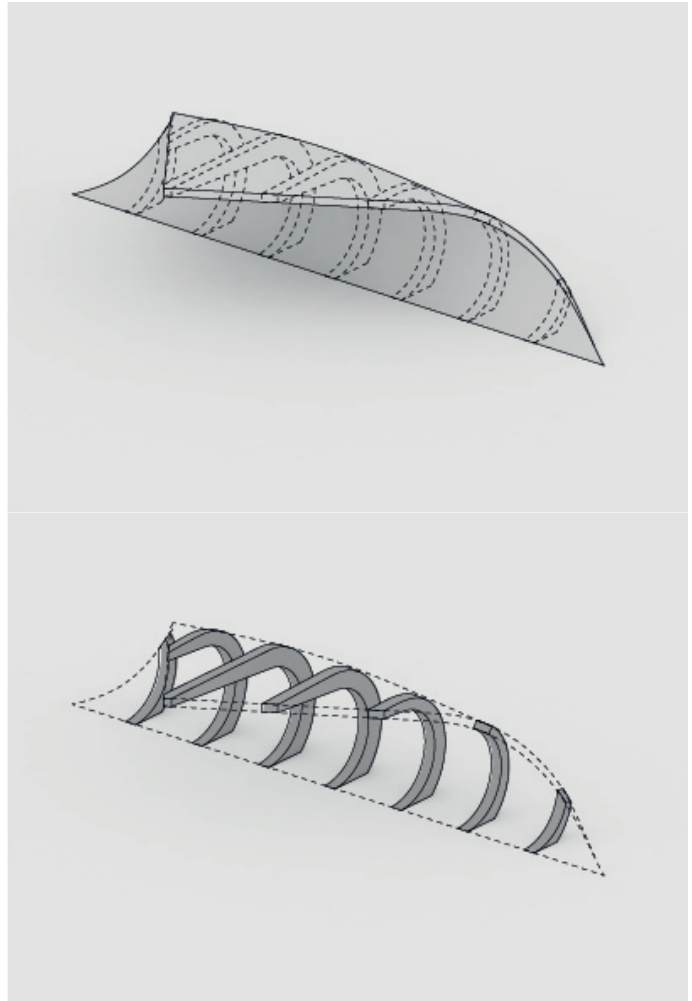
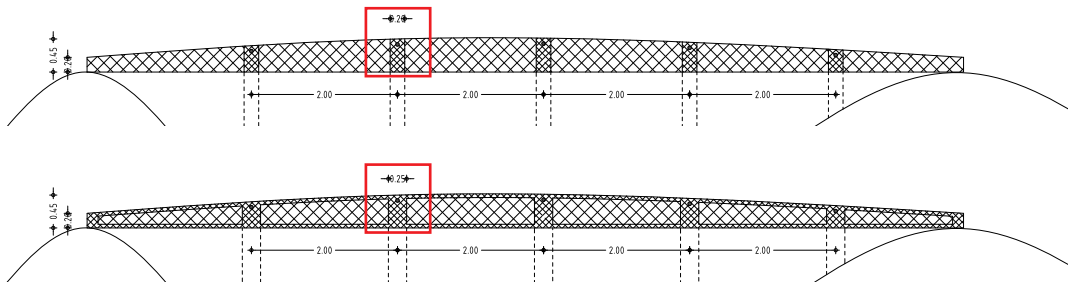


Figure 44. Rib structure for a fold

Figure 45. Cross section variations
GeoA and GeoB



added so the total compression zone is larger than for GeoA. Buckling of the flanges has not been considered an issue because of the stabilization effect of the light concrete.

FEM model

The calculations in ROBOT are linear elastic, and it is assumed that the material stiffness is the same in compression and tension. For the tension zone this will be a valid assumption if post-tension is applied exceeding the calculated tension stress, so the tension zone will actually be in pure compression and hereby obtain the stiffness as in the compression zone. By adding post-tension so that the cross section is in pure compression, cracks are avoided. The materials are modeled as isotropic. The linear calculations correspond to an assumption of small deflections.

The model is based on a 2D section of the entire rib that has been given thickness responding to the different cross sections. The rib has been modeled as a 3-node plane element with thickness of the cross section and a size of maximum 100mm.

The analyzed structure has been exposed by the worst load combination. The load combination consists of dead load, snow, and a live load, which include loads from people jumping on the structure. The load combination is applied to the structure as a uniform load where the horizontal part is exposed to all the loads and the curved part is only exposed to dead load and snow load, see *Figure 46*. A combination without the live load is examined as well because it is relevant to have an understanding of how much influence the live load has on the structure. Wind load is not considered because its influence on the structure is relatively small compared to the other loads.

The rib structure is modeled so that it is supported by a fixed support along the horizontal bottom part of the rib.

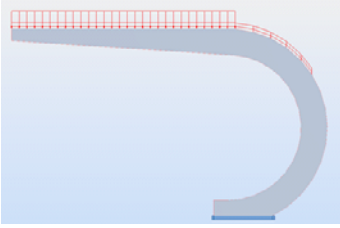


Figure 46. ROBOT load model

Post-tension cables

The post-tension cables are dimensioned according to Freyssinet (Freyssinet, 2007). Because of the small radius of the arch part of the structure the cables are unbonded to limit the loss caused by friction. The friction losses are calculated cf. Eurocode 2 (EN1992-1-1, 1992):

$$\Delta P(x) = P_{\max} (1 - e^{(-\mu(\theta + kx))}) \quad (1)$$

The cables are placed 50 mm from the outer edge of the arch and hereby creates an eccentric force to the section. The cables are utilized to 70% of the tensile strength (Freyssinet, 2007). They are dimensioned for short term loads without creep.

Results

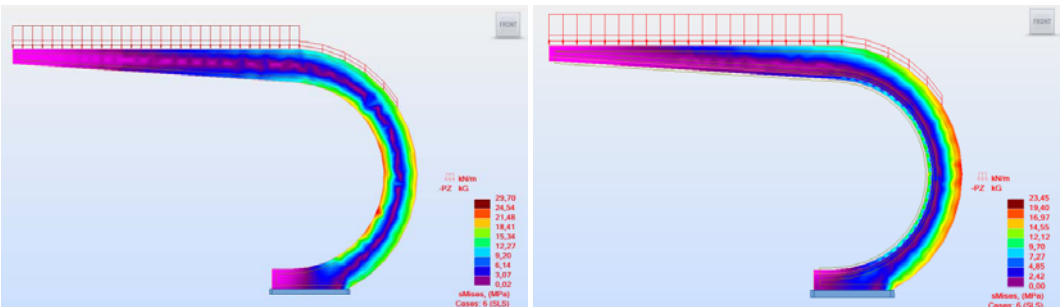


Figure 47. Overall stress distribution of respectively GeoA and GeoB

Data from FE-analysis

The results found by the analysis can be seen in Table 1 and 2. Table 1 present stresses for the load combination described. The stresses are for the section A-A (see Figure 43) at the middle of the arch part of the structure see Figure 48 and Figure 49. Table 2 presents the stresses for the load combination without the live load.

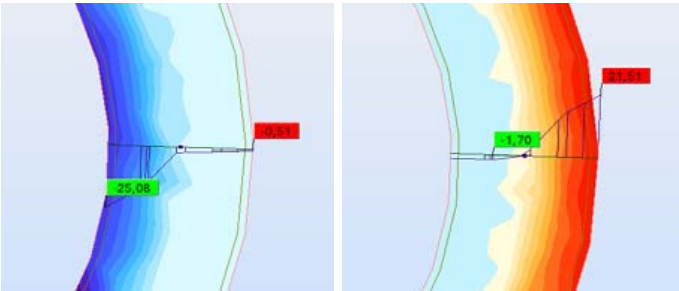


Figure 48. Stresses at section A-A
GeoA

Table 1: Cross section stresses excl. live load

Geometry	Inner arch stresses (N/mm2)	Outer arch stresses (N/mm2)
GeoA	-25,1	21,5
GeoB	-15,8	20,2

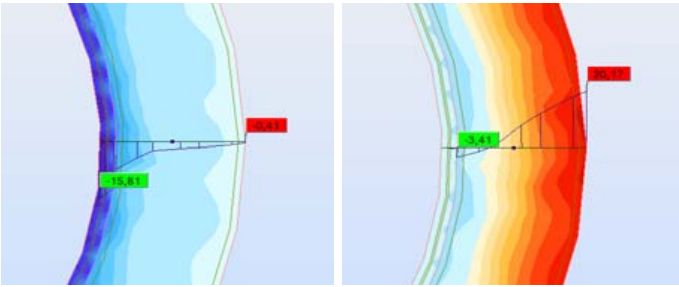


Figure 49. Stresses at section A-A
GeoB

Table 2: Cross section stresses excl. live load

Geometry	Inner arch stresses (N/mm2)	Outer arch stresses (N/mm2)
GeoA	-9,11	7,7
GeoB	-7,5	9,5

As seen in *Figure 48 and Figure 49* the stress distribution varies between GeoA and GeoB. Because of the flange in GeoB the distribution of the compression forces is much more concentrated along the edge of the section. At the same time the compression stress are smaller as seen in Table 1 because of the larger compression zone. From Table 1 it is seen that the post-tension cables have to add more or less the same compression to the outer side of the section to both GeoA and GeoB. The stresses in Table 2 are relevant to observe in relation to the post-tension cables to get an understanding of how the stresses are when the structure is not exposed to live load.

Data from post-tension cable calculations

Based on a placement of the cables 50 mm from the outer side of the arch it has been determined how many cables are needed to prevent the structure from being subjected to tension stresses. By adding 4 D150 cables loaded to 70% of the strength, the stresses presented in Table 3 are achieved.

The cables are loaded by the same tension force so the variation in stresses is caused by the different moments of inertia caused by the different cross sections.

Table 3: Cross section stresses caused by post-tension cables

Geometry	Inner arch stresses (N/mm2)	Outer arch stresses (N/mm2)
GeoA	9,9	-24,7
GeoB	5,4	-25,6

Comparison of results

Table 4: Resolving cross section stresses for full load combination and cables

Geometry	Inner arch stresses (N/mm2)	Outer arch stresses (N/mm2)
GeoA	-15,2	-3,2
GeoB	-10,4	-3,2

In Table 4 is seen the sum of stresses in the cross section when the stresses for the load and the post-tension cables. From Table 4 it is seen in that in both GeoA and GeoB the same number of cables can fulfill the demand of avoiding tension stresses in the outer side of the arch. Furthermore the result of the different compression zone is seen by the variation in the stresses in the inner

Table 5: Resolving cross section stresses for load combination minus live load and cables

Geometry	Inner arch stresses (N/mm2)	Outer arch stresses (N/mm2)
GeoA	0,8	-17
GeoB	-2,1	-5,4

In Table 5 the stresses are shown for the load minus live load and the post-tension load. The result shows that for GeoA is almost not subjected to tension stresses. The small tension that occurs would not cause any cracks because the stresses are so small that it can be obtained by the bending tension strength. For GeoB the cross section is in pure compression.

Table 6: Concrete use

Geometry	Weight of structure (kg)	Material use (%)
GeoA	2002	33
GeoB	3226	54
Traditional	5980	100

One of the reasons for making the SLS concept is to save structural weight and save material. Table 6 presents the concrete weight for the two examined geometries and the weight of the structure if it was made as a traditional reinforced concrete structure. The weight of the traditional structure is set to 100% and GeoA and GeoB are set as a percents' of this.

Discussion

It is found that both of the analyzed geometries are feasible based on the FE-analyzes and the cable calculations. Furthermore it is shown that the structure will not be exposed to tension stresses neither with nor without live load.

Statically the two geometries vary in the compression zone which has a quite large impact on the stress distribution at the inner arch side. GeoA has a rectangular cross section which gives an even stress distribution over the section. GeoB has an H cross section where the compression is mainly obtained by the flange. In the ROBOT model the cross section investigated was only a T section disregarding the upper flange. The dimensioning of the cables was based on the same T section. The cables added compression to the entire cross section, which could have changed the stress distribution for GeoB slightly. For in-

ner GeoB the flanges are taken into account based on the assumption that the light concrete stabilizes the flanges so that buckling does not occur. Only a certain length has been taken to account due to the fact that shear lag effect. The inner flange between the webs will still have some influence on the structural behavior. This behavior has not been taken into account.

The constructions of the two examined geometries rely on very different principles. For GeoA the ribs are meant to be prefabricated, connected and cast to the foundation, and used to support the formwork for the light concrete. This principle is efficient to limit formwork and work at the site, but it requires a very precise prefabrication and mounting. GeoB is meant to be cast in a traditional formwork where light concrete element is placed in between reinforcement. This solution is closer to the traditional but it also requires more formwork, and there is a problem in assuring that the self compacting concrete reaches, all parts of the mould.

As stated, the weight of the examined solutions is down to approximately one third of the traditional solution. This design is based on light concrete of 600kg/m^3 . This concrete has a rather porous surface which has proved to sustain the impact of weather well. If a 900kg/m^3 concrete is chosen instead to get a more closed surface, the material and CO_2 saving will still be considerable.

Future work

The folded cantilevered shape investigated was a shape that can be designed with SLS. It could be interesting as well to see how the stress distributions will vary under different non uniform load cases and different support situations. The examined cases used the pearl-chain concept. Folds that do more than one loop could be considered. These could be produced by means of pearl-chain elements instead of ribs. Besides of folded shapes different

solutions using the pearl-chain system for flat elements could be investigated.

Conclusion

A folded shaped SLS structure was analyzed for two different skeleton cross sections which were based on two different construction methods. The stresses in post-tensioned cables applied in the cross sections were determined. Furthermore, the amount of concrete used for the two geometries was calculated and compared with that of a traditional concrete structure. From the analyses and calculations the following was found:

- Both GeoA and GeoB are feasible solutions to the structure with the suggested dimensions.
- GeoB has smaller stresses because of the larger compression zone.
- GeoA is easier to construct because of more simple geometry and prefabrication.
- Post-tension cables have to be unbonded because of the radius of the arch.
- GeoA uses about 30% and GeoB uses about 50% concrete compared to a traditional structure.

Conference Paper /2/

"The Battery" Designed with Super-Light [concrete] Decks

Presented at:

IASS-APCS Symposium

From Spacial Structures to Space Structures

Seoul - 2012

Authors:

Niels Andreas Castberg

Kristian Hertz

Summary

This paper describes how Super-Light Structures can be used as a structural principle for the buildings in the project 'The Battery' designed by Bjarke Ingels Group. The overall structural concept is described and the advantages of using Super-Light slabs for the project are explored. Especially the cantilevered internal corridors are investigated.

Super-Light Structures is a newly patented structural concrete concept. Slabs based on the concept are the first structural element developed under the patent. The slabs called SL-decks have multiple advantages compared to traditional hollow core slabs. The paper aims to describe the concept of how the deck can be used in these innovative buildings and how the special advantages of the SL-decks are applied.

Introduction

The Battery is a project in central Copenhagen designed by Bjarke Ingels Group (BIG). It consists of 9 mountain shaped buildings with a total floor area of 120.000m². All the buildings have different outer and inner shapes and many are hollowed out by enormous atriums. The mountain shape results in atriums that become narrower towards the top. This shape gives a very complex overall structure that should be able to carry loads to the ground, despite that a large part of the building is not directly supported by a subjacent structure. In addition, the structure should be able to carry pedestrian corridors cantilevered out from every single level towards the atrium. The aim is to use concrete slabs based on the Super-Light Structures (SLS) theory called SL-deck.



Figure 50. The 'Battery' illustration. Illustration: BIG

Cantilevered pedestrian balconies exist at all levels and SL-deck elements are used to make them as slender as possible. SL-decks can be cantilevered from the load bearing planes with no need for supporting members beneath. Hereby, the cantilevered structural height only has the thickness of the slab.

In these types of buildings, it is expected that the Super-Light concept will contribute to make the structure more elegant compared to traditional concrete structures.

Super-Light Structures

SLS is a structural concept patented in 2009 by the Technical University of Denmark (DTU). The rationale behind SLS is to build a skeleton of medium-to-high strength concrete to obtain the forces, place it according to the force distribution and stabilise and protect it by lightweight concrete. SLS offers an up to 50% lighter structure compared to traditional concrete structures (Hertz, 2009a, 2009b, 2008).

Two fundamental patents are obtained; one for the general theory upon which the SL-slabs are developed, and a second patent describing the Pearl-chain system that is a concept for producing and placing the strong concrete parts in a skeleton structure (Hertz, 2009b, 2008).

The general idea of placing the strong material and stabil-

ising it with a lighter concrete has resulted in the SL-decks. The bottom of the SL-deck consists of lightweight concrete shaped as multiple blocks. On top of these normal-to-high strength concrete is cast, constituting a system of small domes and crossing ribs with pressed cables. Hereby, the strong concrete gets the shape of a waffle structure that can be very thin on the top of the domes because of the light concrete stabilising it (Hertz, 2008).

The skeleton system is in the patents solved by applying a pearl chain concept. Here the “pearls” are the skeleton parts held together by a prestressed cable. By applying this method, the skeleton can be assembled by posttensioning and the light concrete subsequently cast around it. The pearls can be prefabricated as standard elements that can be assembled according to the shape of the architect’s choice. The pearl chains can also be cast into standard elements of light concrete. By placing the strong concrete according to forces, the arch will be reintroduced as a structural element, this time being cast as prefabricated cost-friendly segments avoiding the costly curved outer and inner moulds (Bagger and Hertz, 2010; Castberg and Hertz, 2011; Hertz and Bagger, 2010; Hertz, 2009b).

The Super-Light concept allows more freedom to architects and offers more optimal structures, whilst saving materials and CO₂ (Hertz and Bagger, 2011).

The Aim of this Paper

This paper explains how SL-decks can be used as a concept for the ‘Battery’ project and describes the general structural concept. The paper describes concepts in three structural levels:

- The overall stabilising structural concept for the building
- A concept for the connections between walls and cantilevered slabs
- A concept for the slab structure and slabs with an integrated beam

The aim of the paper is to show how the advanced structural challenges of the Battery can be solved using SL-decks. Furthermore, the paper will suggest options for customising SL-decks to contain a beam across the element in the slab structure to allow cantilevering. The research for this paper is undertaken at DTU in cooperation with the architect firm Bjarke Ingels Group, BIG.

Structural Concepts

The structure is divided into an overall stabilising system, a secondary system bringing the loads to the foundation, and finally, a description of the slabs and how they are cantilevered.

Primary Structural Concept

The main structural system will consist of aligned walls to create bearing planes from the top of the atrium to the ground. Due to the different inner and outer shapes, the elements in the bearing planes will all be cantilevered from level to level, narrowing inwards towards the top of the building. This allows an overall arch-shaped resulting force distribution.

The stabilising system consists of a number of thick walls displaced at each level to have an overall expression as a stair. Within this 'stair wall', the forces are distributed to create a half-arch. The 'stair walls' are connected at the level that forms the ceiling of the atrium. Hereby, the structure takes the form of multiple half-arches leaning toward each other, thereby creating a stable structure. This concept allows avoiding the use of columns in the atrium and provides a stable base for the upper part of the house above the arch connection point. The top of the house can be made by a simple wall and plate structure.

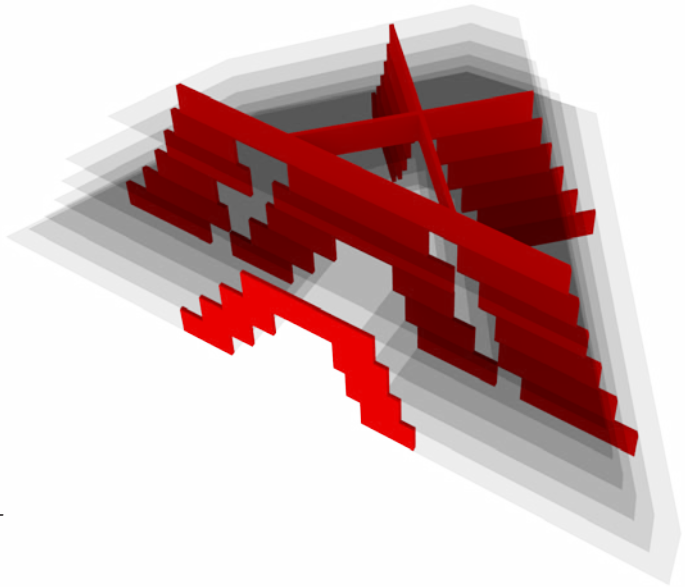


Figure 51. *Overall structural system*

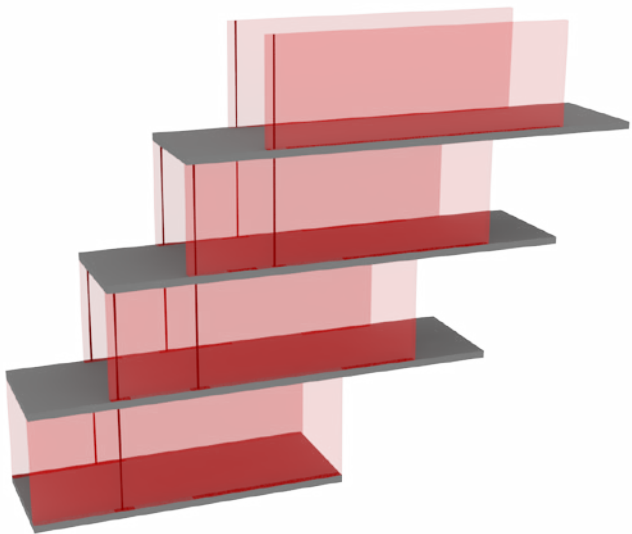


Figure 52. *Tension bars stabilising the cantilevering*



As described, each level of the walls is cantilevered from the underlying level. To obtain this, a set of stabilising tension bars connects the walls in their non-cantilevered ends, each bar connecting to the wall below (*Figure 52*). This stabilisation is primarily needed until all the walls are combined to form an arch. Thus the above described overall stability is first obtained once the full arch is built.

Figure 53. Visualisation towards south. Illustration: BIG

Secondary Structural Concept

The walls not working as part of the stabilising system have their primary function in carrying the vertical forces to the ground. The walls are connected with tension bars in the same way as in the stabilising system, but the walls are thinner (*Figure 54*).

The building described is designed for student accommodation. Therefore, the walls are relatively close in the particular building. Most slab elements span between the walls because of the short distance in this direction. However, in the area with no walls beneath the slabs, the span direction is turned. A part of the slab creates a beam spanning from wall to wall (*Figure 54 and Figure 55*). By turning the span direction of the slab and incorporating a beam, the balcony is solved as a cantilevered slab. In this case a single slab will span between the walls perpendicular to the direction of the factory made prestressed wires

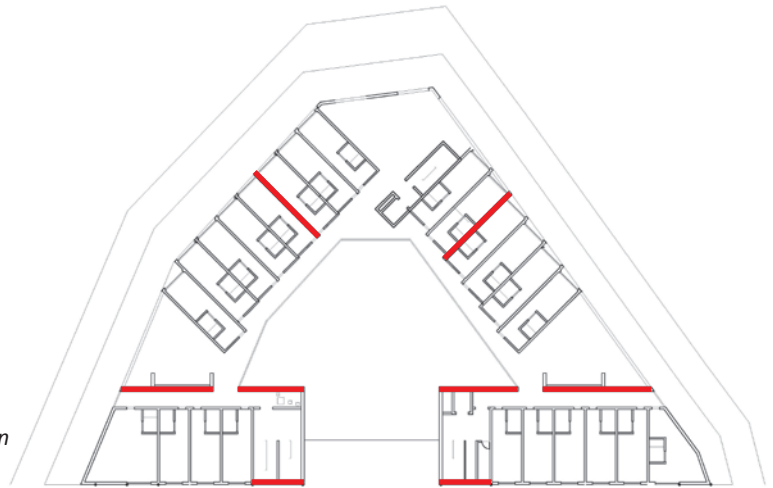


Figure 54. *Typical plan section*

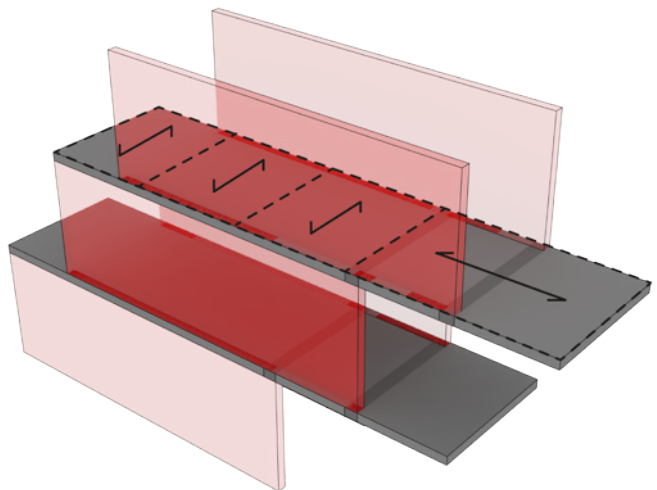


Figure 55. *Illustration of directions of span*

in the slab. Hereby, the solid end of the slab also functions as a beam between the walls as a second support line. This solution is possible as SL-decks allow prestress elements in two directions. The direction of the factory made prestressed wires is chosen to carry the loads from the cantilevered part and the 'beam' supports the slab at the midpoint in the transverse direction.



In cases with longer distances between the walls, slabs can be joined at the construction site by posttensioned connection of the transversal beam prior to lifting them in place. The slabs are joined by adding a posttension bar and tighten the slabs together. The non-cantilevered end of the slab is supported by the slab spanning from wall to wall by the connection described in page 119. The suggested solution allows both the option of one and of multiple joined cantilevered slabs depending on the span between the supporting walls.

Figure 56. *Illustration of atrium. Illustration: BIG*

SL-deck

As described in the introduction, the SL-deck consists of two types of concrete, a light aggregate concrete ($600\text{kg}/\text{m}^3$) and a normal 55MPa concrete ($2300\text{kg}/\text{m}^3$), respectively. The shape of the light concrete is shown on *Figure 57* and *Figure 58*. The design results in many small arches in the transversal direction of the slab. At the same

time, it allows reinforcement in the transversal direction to obtain the outward forces caused by the arches. In the longitudinal directions, pretension wires are placed between the arches. This design offers a slab reinforced in both directions. It is possible to place corrugated tubes in the transversal direction so slabs can be posttensioned transversally. The ends of the slabs are of massive strong concrete, i.e. it is areas of the strong concrete that rest at the supports.

The strong concrete is cast as a plastic mass that makes it easy to cast around moulds for recesses for installations or other specially required shapes. Furthermore, it is possible to fix the slab ends or make the connection continue over a beam. This makes very long spans an option as opposed to traditional simple supported hollow slabs. Furthermore, the combination of light concrete in the bottom and the arch shape gives a very good acoustic performance and a high fire resistance. The flexibility, easily allowing non-regular cuts, and all the other performance advantages are some of the reasons why SL-decks were chosen for the Battery project. Hence, the overall shape of the buildings requires a lot of special elements.

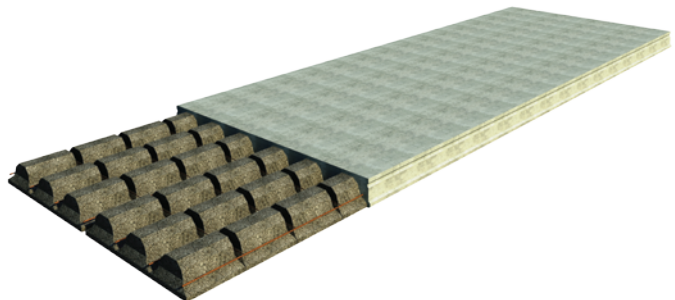


Figure 57. *SL-deck illustration*

Cantilevering SL-decks

One of the SL-deck's advantages is that it can be cantilevered with no need of extra structural height or extra beams beneath the cantilevered part. It can be cantilevered in different ways:

- 1) The slab can be placed across a bearing line and project out into the open.
 - 2) The bearing line can be a part of the slab by incorporating an internal beam.
 - 3) Two slabs can be joined over a bearing line by reinforcement but only as an ordinary reinforcement.
- In this case option 2) is chosen as it offers the cantilevering to be handled with the slab without the need of adding extra elements.

The SL-deck is customised to contain a beam by adding extra distance between two rows of lightweight concrete blocks. Hereby, reinforcement for a beam can be placed in the void *Figure 59*. The beam can either be made by ordinary reinforcement or corrugated tubes can be placed for posttension cables or bars. The choice depends on loads and whether more slabs need to be connected. When the deck is cast with the top layer of strong concrete, the beams are integrated in the structure.

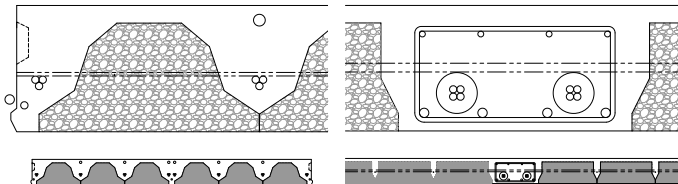


Figure 58. *Transversal section in SL-deck*

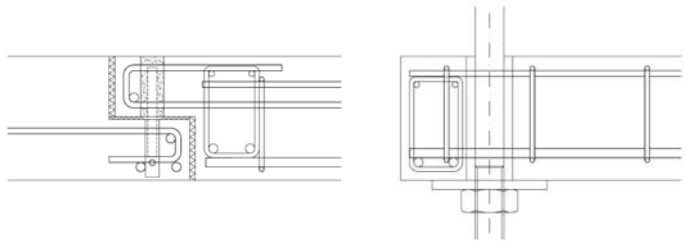
Figure 59. *Longitudinal section in SL-deck with beam*

As described, the non-cantilevered end of the slab is connected to the crossing slab that it is joined to. The connection is done with overlap but level free. (*Figure 60*) The

connection can be fixed which makes it possible to transfer moment forces. The connection can both be made at ends and on the sides of a slab. In cases where more than one slab is needed between the walls, the connection will support the non-cantilevered end of the slab. Hereby, the slabs will be supported in the same points as if only one slab were placed between the walls.

Figure 60. *Level free connections of SL-deck*

Figure 61. *Hung connections of SL-deck, Ill. Jakob E. Christensen.*



The deck is hung from the walls in the beam part. The solution to hang a SL-deck in a point in the strong concrete is known from another project currently under construction. The solution can be seen at *Figure 61*. Here the slab hung in the solid part at the end of the slab in one point only, but the principle remains the same. In the Battery, instead of one bar, the connection will be made by a number of bolts to distribute the stresses and offer more uniform support to the beam. The connection is possible as the casting of the slab allows adding extra reinforcement in certain areas as previously described.

Conclusion

The structural concept for a case building in the Battery project and the application of the SL-deck has been presented. With respect to the overall structure, there may be a possibility for an optimisation of walls with the pearl-chain system, but the presented solution is buildable and further optimisation will require further analyses of how

the walls are loaded in uneven load cases. The SL-deck solution is durable, and another project, currently under construction, use details similar to some of the customisations suggested in this paper. The internal beam solution is possible for the spans in the Battery Project and will also be available for connection of slabs with posttensioning, however, the loads on the balcony are large and will constitute the limiting factor for the span.

The paper describes how cost-effective SL-decks offer a more elegant and flexible solution of key problems in the buildings of the Battery compared to solutions using traditional slabs and beams.

BIOVAF

Introduction

BIOVAF is a new building complex at DTU where three institutes are moved to from locations around Copenhagen. A competition was held for the BIOVAF complex that BIG participated in with a proposal. This section will give a short introduction to the competition proposal, the structural system and the use of SL-deck in the proposal. The project consists of two existing buildings that need modernisation and new building volumes of 20.000m². This section will describe how the SL-deck performs in comparison with standard hollow core slab and the advantages of choosing the SL-deck are presented.

The design

BIG's proposal contains three new straight volumes (the sticks) which are copying the building rhythm at the DTU campus. The sticks are connected by a curved volume (the snake), see *Figure 62*. The sticks consist of labs and offices and the snake consist of a canteen, a conference room, classrooms and lounge areas.

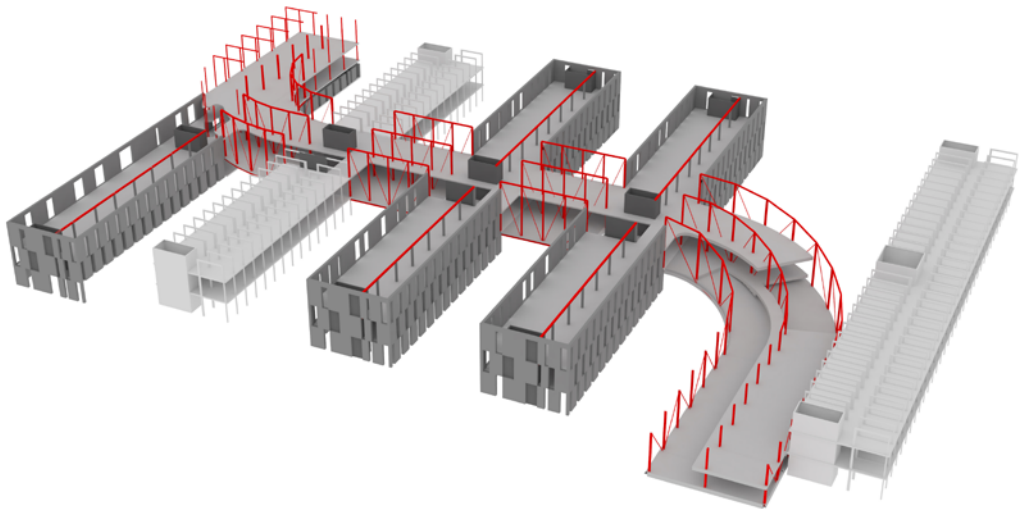
Figure 62. Model photo of the BIOVAF project. Photo: BIG



Primary structural concept

The structural system is kept relatively simple. The stick volumes have loadbearing facades consisting of a concrete inner wall with a bricklayer on the outside. A column beam line is dividing the building in the longitudinal direction with a span of 10.150m and one of 5.35m. The horizontal forces are obtained by the walls and the staircases. For the deck is used SL-deck, that is fixed over the middle beam. The snake is based on a truss structure in three layers respectively in the facades and one in the middle, see *Figure 63*. The horizontal stabilisation of the snake is obtained in the stick facades and staircases. The deck is solved with SL-deck elements that for the lower level is fixed over the beam and for the upper level is cantilevered out from the middle truss to create the corridor.

Figure 63. BIOVAF's overall structural concept. The dark grey is load-bearing walls. The red elements are steel. The light grey is SL-decks and the structure of the two existing buildings is white.



Use of SL-decks

For the BIOVAF project the final decision of choosing the SL-deck was taken late in the process. This led to a design that was not fully optimized for exploiting the advantages of the SL-deck as an alternative solution with hollow core slabs was kept in play. Nevertheless, there were still some significant advantages in using the SL-deck.

For the sticks it was possible to make the deck with standard SL-deck with a height of 220mm despite the long span. This was possible because the elements were connected at the middle beam by reinforcement bars in the upper side of the elements, hereby they were acting as a continuous element that gained a negative moment at the beam support and hereby limited the deflection. In contrast, the solution with hollow core slabs had to be simply supported which meant that the deflection of a 220mm high element was too big. The result was that the solution with standard hollow core slabs needed to be with a height of 270mm from the static point of view. This increase in height had a significant influence on the material use. Per square meter the difference between the hollow core slab and the SL-deck was 55kg/m² for the entire

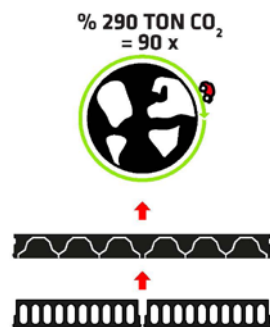


Figure 64. Illustration of how much CO₂ that is saved by using SL-deck in front of hollow core slabs

volume which gave a total saving of 1115ton of concrete equal to 50 concrete trucks by selecting the SL-deck instead of the standard hollow core slabs. Looking at the CO₂ emission the savings were equal to 13kg/m²(Hertz and Bagger, 2011) resulting in a total saving of 290ton CO₂ which is approximately what a VW Lupo would use if it drove 90 times around the earth.

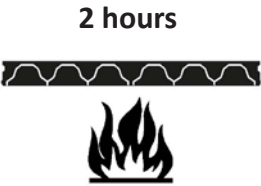


Figure 65. The SL-deck can fulfil the demand for two hours fire exposure

One of the stick volumes was in three levels which increased the requirement for fire resistance to two hours(BR10, 2010). By using the hollow core slabs this could only be achieved by adding extra fire protection whereas the SL-deck fulfilled the fire resistance requirements without adding additional fire protection. Furthermore, some of the labs in the sticks had special requirements for fire that also necessitated extra fire insulation for the hollow core solution. However, this requirement was also fulfilled by the SL-deck(Halldorsson, 2012; Hertz et al., n.d.), and consequently the extra insulation could be saved. By applying the SL-deck, BIOVAF was, furthermore, given the flexibility to add more labs in the stick volumes subsequently without being concerned about fulfilling fire regulations subsequently without being concerned about fulfilling fire regulations.

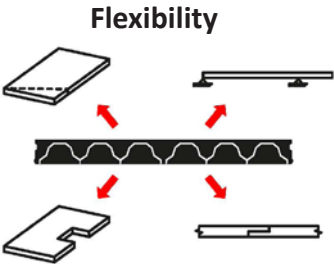


Figure 66. The SL-deck has great flexibility that was utilised for cantilevering and curved shapes of the project.

The flexibility of joins, shapes and cantilevering which the SL-deck provides was furthermore to the advantages. As already mentioned the deck elements in the sticks and ad the lower level of the snake were fixed over the beam support but especially for the snake the advantages was utilised. The cantilevered corridor which was going all the way through at the first level of the snake was easy to make with the SL-deck. The SL-deck was just cantilevered without the need of extra beams as opposite to the hollow core solution where the cantilevered part was supported with beams that increased the construction height. Furthermore, the curved part of the snake was easy to make with the SL-deck due to the way the SL-decks are cast which makes it is easy to create curved and angled elements whereas the Hollow core slabs have to be cut after production which sets some limitations to the shapes.

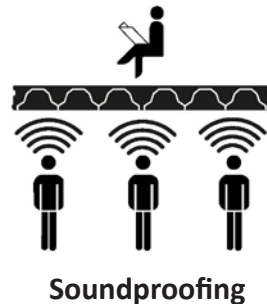


Figure 67. *The SL-deck's acoustic performance was to advantages to for the mixed used of rooms next to each other*

The soundproofing effect of the SL-deck was also an advantage taking into consideration in the BIOVAF project. The sound regulations for offices, labs, classrooms, conference rooms, canteen, and lounge areas could be fulfilled without the use of SL-decks. Nevertheless, the SL-deck was preferable due to their airborne sound insulation of 55dB which secures a good working environment in all of the facilities neighbouring each other despite their very different noise levels.

Finally, the construction time used when mounting the SL-deck is generally significantly shorter than traditional

1.2 meter elements because of the width of 2.4 meter. This results in half the number of lifts at the construction site which has a direct influence on the construction time.

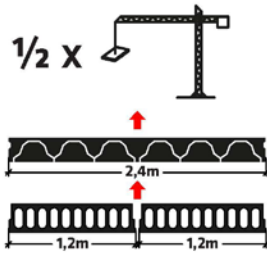


Figure 68. *The width of the SL-deck could reduce the construction period and number of joints*

Conclusion

The BIOVAF project demonstrates how the use of SL-deck can be beneficial to the environment, the flexibility of a building, the construction process and the working environment. The project demonstrates that the SL-deck has some advantages over the standard hollow core slab used today. Unfortunately, the competition was not won by BIG and consequently the project was not carried out. However, the comparison between the SL-deck and the hollow core slab that was made possible because the two solutions were kept in play until late in the process, made it possible to make this overview of how the SL-deck can have a beneficial influence on several factors.

Paper /3/

A Case Study for using
the SL-deck Elements
for the Residential
Building Design
Frederiksborgvej by BIG

Submitted to:

Archictural Science Review

Authors:

Niels Andreas Castberg

Kristian Hertz

Abstract

Super-Light Structures are a newly patented structural system that combines strong concrete and light weight aggregate concrete by taking advantage of the material properties and the natural distribution of forces. This paper presents how the SL-deck - based on the theory for Super-Light Structures - is used to solve the structure in the Bjarke Ingels Group (BIG) project: Frederiksborgvej. The project demonstrates how the SL-deck can be used to resolve several specific issues and, thus, the Frederiksborgvej project is representative to display the benefits and possibilities of using the SL-deck in contradiction to traditional precast slabs. The Frederiksborgvej project includes a concept for cantilevering, integration of beams, fixing of slab ends, and joining elements for the SL-deck, all of which are solutions that with traditional slabs would have resulted in extra elements and less elegant solutions but with the SL-deck these challenges can be handle within the slab element.

Introduction

This paper presents how the newly patented structural concept called Super-Light Structures(Hertz, 2009a, 2009a) developed by Hertz is implemented as the structural principle in form of the deck elements for the residential project called Frederiksborgvej by the well-recognised architect practise Bjarke Ingels Group (BIG). The paper will show how the different advantages of the structural system are incorporated in the slab solutions and how this has limited the number of beams, solved the structure for cantilevering within the slab structure, and positively influenced the fire and acoustic performance of

the structure.

The principle of Super-Light Structures is to make a structure of two types of concrete; a strong concrete and a lightweight aggregate concrete respectively. The strong concrete is placed with respect to how forces are optimally distributed. In this way the strong concrete creates a loadbearing skeleton (Castberg and Hertz, 2011; Hertz, 2009b, 2009b). The light aggregate concrete is cast to stabilise and protect the skeleton. Hereby a structure is created that consists of two materials, which are used according to their material performance. The compression strength of the strong concrete is used to adopt forces in the best way, which is often in the shape of arches. The limited strength of the light aggregate concrete is used to stabilise the strong concrete – acting in the flow of the natural force distribution - why less strength is needed for the stabilisation. At the same time the airiness of the lightweight aggregate concrete is used to protect the skeleton against fire and improve acoustic performance (Chandra and Berntsson, 2002). Based on these principles there has been developed a new deck element called SL-deck (Hertz et al., n.d.).

The SL-deck consists of a layer of light aggregate concrete blocks which have an arch shape upwards and are divided for placement of transversal reinforcement for each 50 cm see *Figure 69*. The slab is reinforced in the longitudinal direction by prestressed wires placed in the cavities between the arches. Plastic strong concrete is cast on top of the light aggregate concrete blocks. This design creates arches in the transversal direction that is carried by the prestressed 'beams' formed by the cavities between the blocks in the longitudinal direction. The transversal slack reinforcement neutralizes the horizontal transversal forces from the arches and prevents longitudinal cracking of the element (Andersen and Jensen, 2011; Christensen and Hertz, 2012; Halldorsson, 2012; Tassello, 2011).

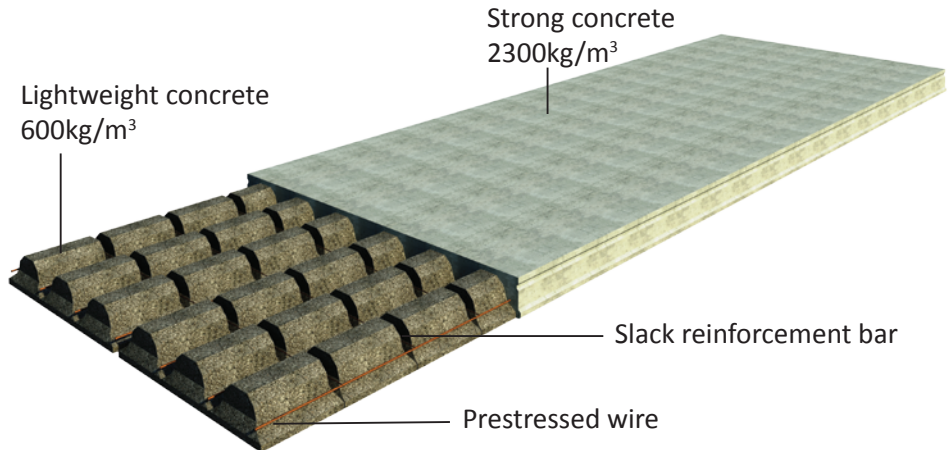


Figure 69. *Description of the SL-decks components*

The arch design of the lightweight aggregate concrete and the connection with the strong concrete is beneficial to the acoustic performance of the element(Christensen et al., 2012, 2011). The acoustic performance is experimentally tested to have an air sound insulation of 56dB which is enough to fulfil the Danish requirements of 55dB between flats in residential buildings(Dansk Standard, 2008).

The lightweight aggregate concrete also serves as fire insulation of the strong concrete, hereby providing the SL-deck with a fire resistance measured for two hours(Hertz et al., 2013, n.d.) which fulfil the Danish requirements for buildings(BR10, 2010). The design and production method for the SL-deck entail a number of options which makes the SL-deck very flexible for incorporation of internal beams(Castberg and Hertz, 2012) and holes, different connection and cantilevering options etc. The paper investigates how these opportunities for the slab design can be utilised in the investigated case project.

The Frederiksborgvej project is a residential block with a number of distinctive characteristics that makes it very interesting for testing the SL-deck's capabilities. The vision



of the architect is to create a transparent feeling of the building by perceiving it as a number of boxes which are pulled apart. This leads to a design with a lot of cantilevered building parts and shifts where deck structures are facing outdoor climate on the top side or the bottom side. Furthermore, the building has a section that is curved along a free span. These characteristics make Frederiksborgvej a suitable case to demonstrate the flexibility of the SL-deck compared to more rigid traditional precast solutions. The project also contributes with knowledge of how the SL-deck can support and improve a designers' creative freedom regarding shapes that generally contain structural challenges when using traditional slab solu-

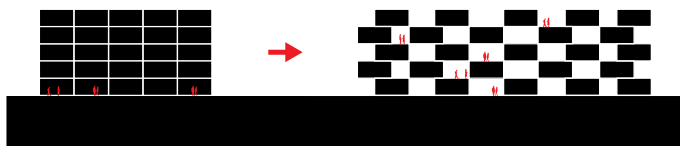


Figure 70. The architectural concept with shifted boxes. Diagram: BIG



Figure 71. Visualisation of the building from south. Illustration: BIG

tions, if at all possible using such solutions.

The Frederiksborgvej project is a five storey building with a total height of 16 meters and 100 apartments of an average size of 100 m². An apartment is expressed in the facade as one box and a void towards the next box. The architect had a very clear and strong vision for the points where the boxes join. The boxes should give the impression that they only met in a corner point and overlapping was not allowed. If the vision should be possible it required that the slabs were placed at different levels, so that the underside of the box was at the same level as the upper side of the next box. Hereby a slab in one floor would shift level because it would consist of both upper sides and under sides of the boxes. Furthermore, a goal was to avoid diagonal structures supporting the cantilevered boxes.

The paper is based on the PhD work of the author - with focus on architectural engineering and development of

Super-Light Structures that was carried out in cooperation with BIG - and a master thesis 'The Building of super-light structures SL-deck elements'(Guerrero and Obeidi, 2013) by Guerrero and Obeidi. The case project was examined during the conceptual stage which made an on-going dialog with the architect about adjustments to the design possible. The solutions presented in this article have been developed and calculated as a result of this work. As the paper describes a development using a newly invented structural system, the research has mainly been carried out by the inventor and the literature is, consequently, limited to publications of the few members of the research team.

Method

The method applied in this paper is an analysis of the building design from the architect focussing on creating a general structural concept for the building, which utilizes the opportunities of the SL-deck most efficiently and which identifies the areas that impose structural challenges. This analysis of the design has been done in an on-going dialog with the architect. For each of the problems identified a number of well-known or new solutions were developed and investigated. The investigations resulted in a scheme with positive and negative effects for each problematic area. Based on the schemes the solutions to apply in the structural concept were chosen. This paper presents the chosen solutions.

In general the design was based on the Danish regulations and Eurocodes(EN1992-1-1, 1992). The solutions were hand calculated, 3D modelled and geometrically investigated. A considerable part of the investigation was conducted to ensure that the solutions were functional in 3D and was buildable. Finally, the overall structural analy-

sis of the building was investigated in a 3D finite element analysis. The SL-deck applied consisted of a lightweight aggregate concrete with a density of 600kg/m^3 and a strong concrete with the density of 2300kg/m^3 , which in this case was a normal concrete with a strength of 55MPa . The SL-deck element has a standard width of 2400mm and thickness of 220mm .

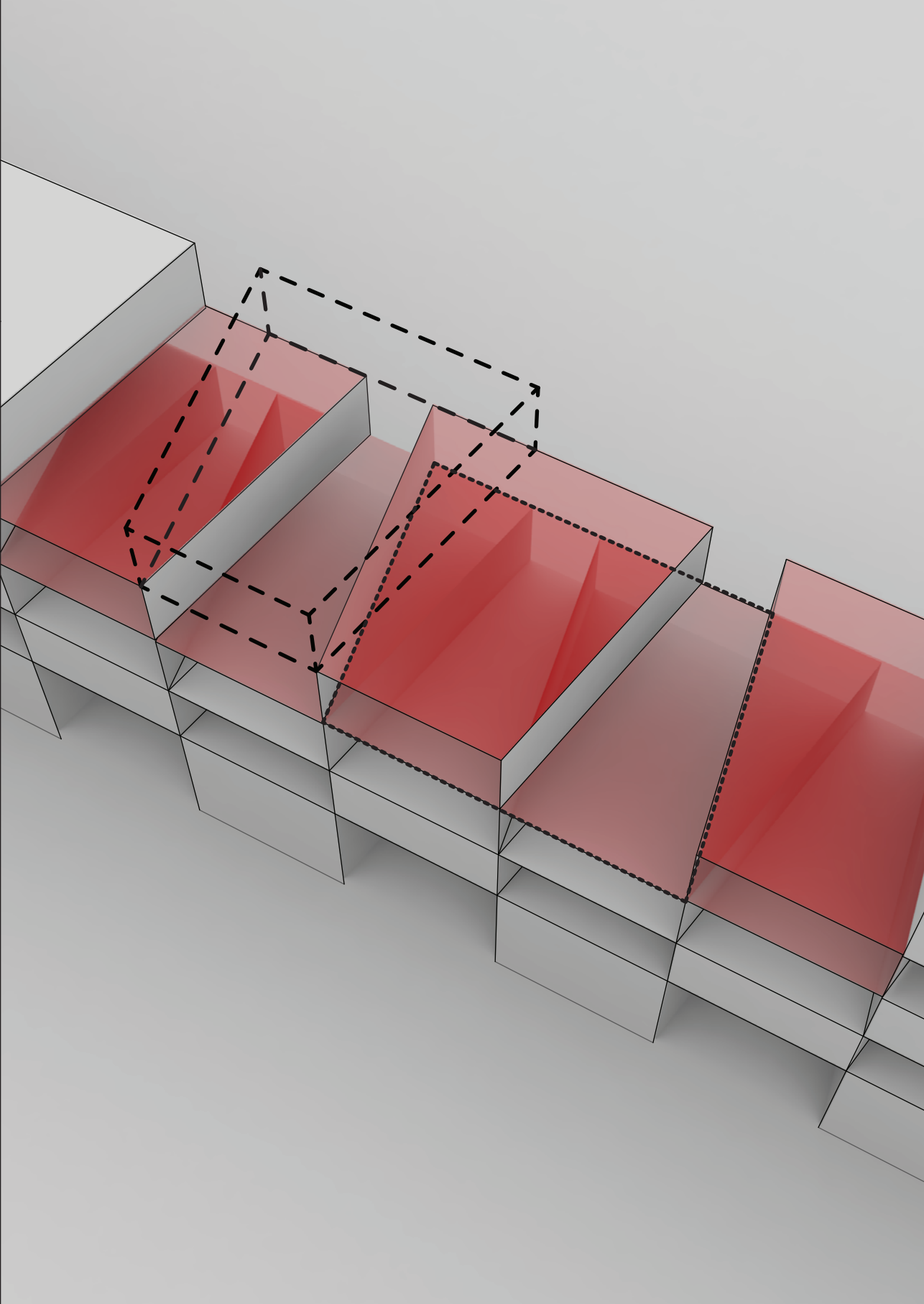
The presented solutions are based on calculations and no physical experiments have been made in relation to this case. The development of the standard SL-deck without modifications has been done with experiments of bending and shear resistance, and fire and acoustic performance. These test results are not a part of this article but can be found in the article Super-light concrete Decks(Hertz et al., n.d.). The calculation methods applied in the Frederiksborgvej case have been verified by these experiments. The paper will not focus on the calculations on the standard SL-deck element but on the changes in form of incorporated beams.

The building geometry and overalls structural system

The building design was analysed with focus on the overall structural concept, the slab direction and division related to the design, the curved part of the building, the cantilevered balconies, and the cantilevered sections at the gable. Even though the design looks relatively simple at a first glance it has some notable challenges. As already mentioned, the geometry is based on boxes that are pulled apart. The boxes are trapezium shaped with a narrow side facing the street. This creates a new opposite trapezium shape between the boxes that is used for balconies and living rooms. Since the boxes are shifting from level to level the walls are not continuous through the height of the building. Towards the street side the end of the walls are on top of each other and some walls are added toward the backside of the building that make the walls partly continuous up through the building. This count for the straight parts of the building but for the curved part connecting points of the walls also exists. The two longitudinal facades of the building are shifting between balconies and bays which make almost half of the floor area near the facade shifting between indoor and outdoor. This issue is described further in “The Balconies” on page 144. “Cantilevered gable boxes” on page 148 describes the structural solution of the building end designed with cantilevered boxes pointing out from the gable façade.

For the overall structural system a column beam structure was considered because of the inconsistent wall pattern. Two support lines could be made following the inner edge of the balconies and the SL-deck could span from façade to façade with the balconies and bays as cantilevering parts in both ends. This, however, was not the preferred solution because it was not possible to place the columns without spoiling the floor plans. Furthermore, it led to

Figure 72. Overall 3D model showing the shifted boxes and the void rooms created. The small dotted line is the outline of an unit.



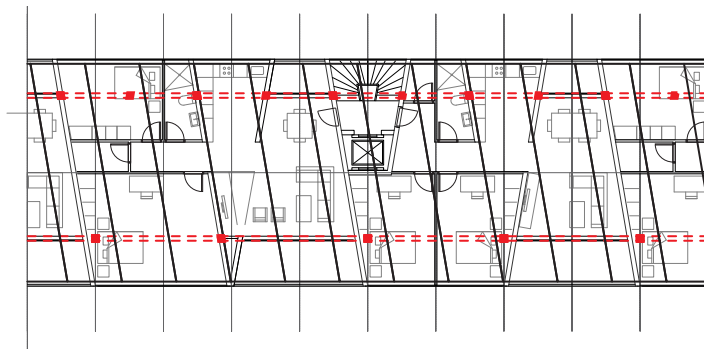


Figure 73. Plan solution with two longitudinal bearing lines and cantilevered SL-deck in both sides

a number of unpractical geometrical solutions where the building curved, and in relation to the balconies and cantilevered boxes it could not solve the issue with staggered floor levels described in “The Balconies” on page 144.

Instead it was chosen to place the slaps in the longitudinal direction of the building and use the walls as load-bearing. *Figure 74 and Figure 75* demonstrates that the curved parts of the building are easier solved with this solution. The SL-decks continues over some of the walls and are joint using fixed connections over other walls. The contiguous slab also limits the displacements of the deck and the number of deck elements spanning from wall to wall are reduced. Hereby the number of crane lifts is minimized. The area of the SL-deck that is resting on a wall is produced with a solid section of the strong concrete. In practice, this is solved by making a space between the lightweight aggregate concrete blocks. When the strong concrete is cast the void is filled up.

As seen at *Figure 76* and mentioned above, it is not all support lines from the walls that are present at all levels. The bearings omitted would have been located in the middle of the rooms and, consequently, it was a wish to avoid beams at these places. This was solved by making slabs with integrated beams, see *Figure 77*.

The beam is made by creating a space between the light-



Figure 74. Plan section in the curved part showing transversal deck solution

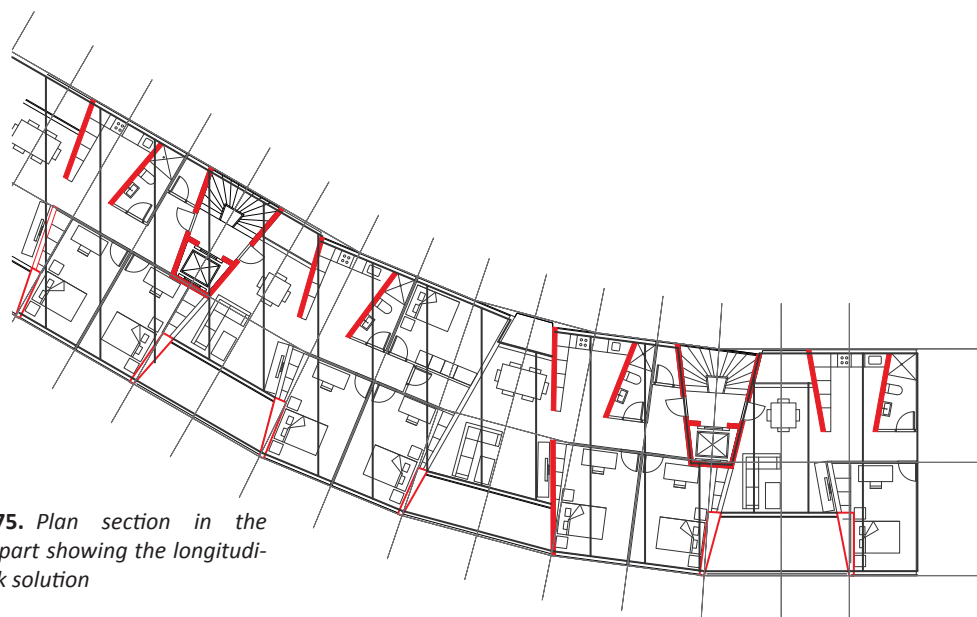


Figure 75. Plan section in the curved part showing the longitudinal deck solution

weight aggregate concrete blocks equal to the width required for the beam. The void is reinforced as if the beam was produced individually to the SL-deck. In the case of *Figure 76* the beam is spanning across two slabs. This could be solved by using one of two types of special connections; either a reinforced slack or a post tensioned solution. Unfortunately, these details cannot be described any further due to patent applications. When mounting the elements a temporary support is placed to support the two deck elements in the right position.

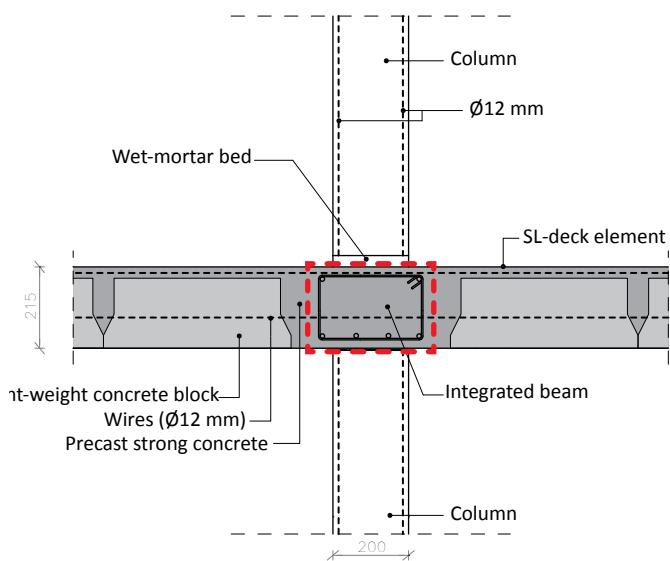
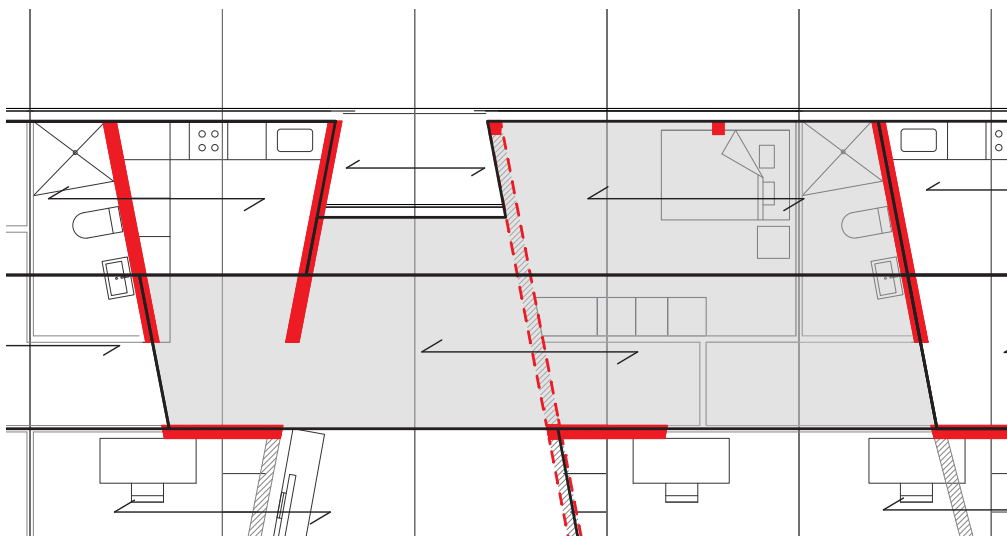
The beam shown at *Figure 76* is the longest simple supported integrated beam. Its span is 3.92 meters. The dead load of the beam and deck area is $q=29.8\text{kN/m}$ which makes the beam subjected to a negative moment of 87.4kNm . This can be obtained by adding 4x ϕ 12mm slack reinforcements, see *Figure 77*.

The project applies relatively short spans of up to 6 meters. However, the SL-deck used in the project has a length of 12 meters to make it is easier to manage and save time on mounting the fewer elements. The elements are as described fixed end supported by the next element in the joints at the supports. This results in long coherent elements with a number of supports or short elements with fixed ends. The SL-deck design is not optimized for negative moments but can in most cases obtain them without a change of the design is required.

The deck element is loaded by a total moment of 71kNm . The suggested element design has 7 wires at the bottom and 3 wires at the top of each 12mm which gives a capacity of 171kNm at the middle and 129kNm at the ends of the element. Since the ends are fixed the total capacity of the element is 300kNm which makes the element capable of obtaining the load. The calculation method is verified by the experimental work described in Super-light concrete decks (Hertz et al., n.d.).

Figure 76. Plan section showing the beam integrated in the SL-deck across two elements

Figure 77. Detail of beam integrated in the SL-deck



The Balconies

The architect had some strong geometrical wishes for the details connecting the balconies and bays. The box corners should only meet in a single point which was a structural challenge. The Danish building regulations require a level free access to a balcony and the architect at the same time wanted only one level in the apartments. Due to requirements for water draining from balconies and the level free access requirement, the structural level has to be lower than the indoor level. Furthermore, the slab shifts between being inside and outside which means that the insulation has to switch from being on one side to the other in a way that increases the problems in creating a level free deck.

The walls of the box sides meet in the balcony corner point. Instead of letting the walls continue to the façade two columns were added; a wide column at the inner corner of the balcony and a small square column at the mid end of the balcony slab. Walls and beams from the inner parts of the building are supported by the wide column and the square one participate in supporting the balcony, see *Figure 79*. This solution was chosen because it did not

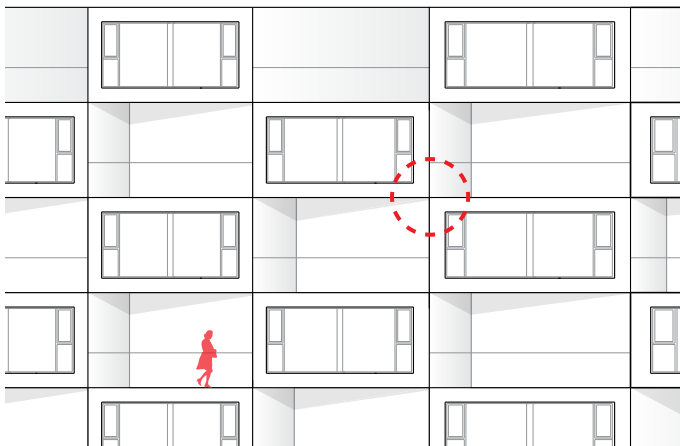


Figure 78. Façade elevation showing the point between two boxes.
Illustration: BIG

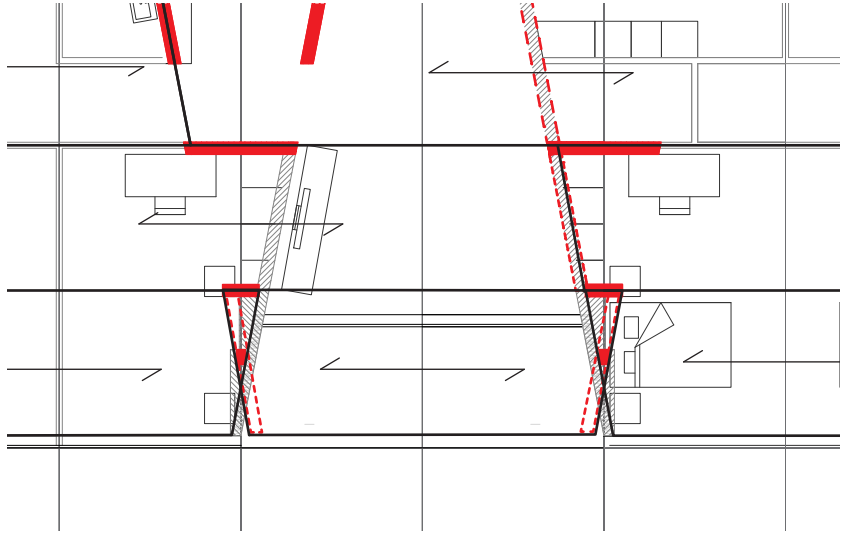


Figure 79. *Plan section of balcony area with displaced SL-deck*

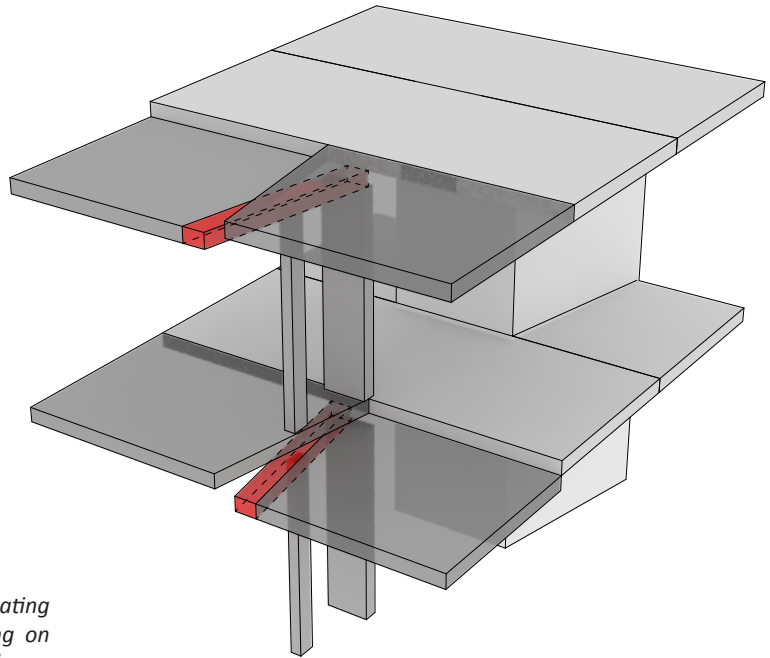


Figure 80. *3D model illustrating how the upper slab is resting on the lower with the integrated beam*

create any continues line up through the façade and hereby the visual expression of the boxes that shift from level to level is maintained. The issue regarding maintaining the same floor level at the balcony and indoor was solved by displacing the balcony element at a lower position by a magnitude equal to the thickness of the slab. A beam was integrated in the ends of the slab that makes the balcony deck function as support for the bay deck element, see *Figure 80*.

In this way the integration of a beam in the slab provides the linear support which the balcony element would otherwise have required from the wall and at the same time the solution creates a linear support for the bay deck element.

The integrated end beam is partly cantilevered and subjected to a negative moment of $M=-81.6\text{kN/m}$ at the support. With a suggested cross-section as shown in *Figure 81* with 5 slack reinforcements of 12mm the deflection was 1mm at the end of the cantilevered part.

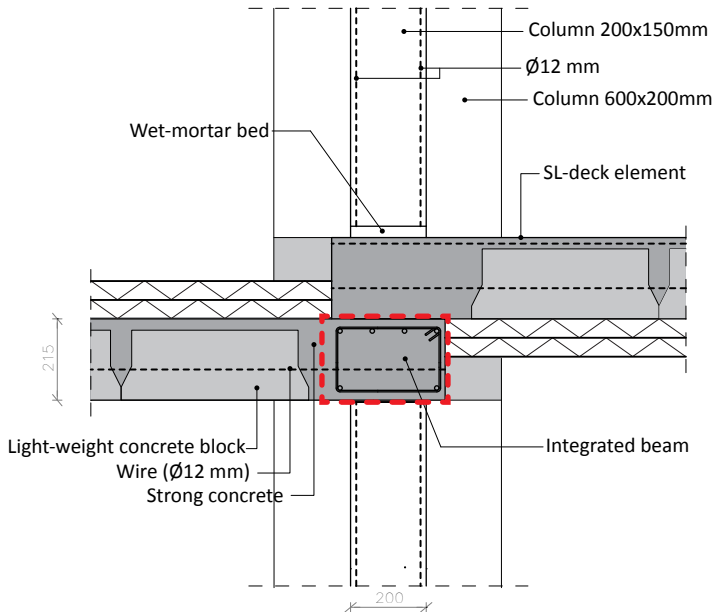


Figure 81. Detail showing how the slabs are resting on each other

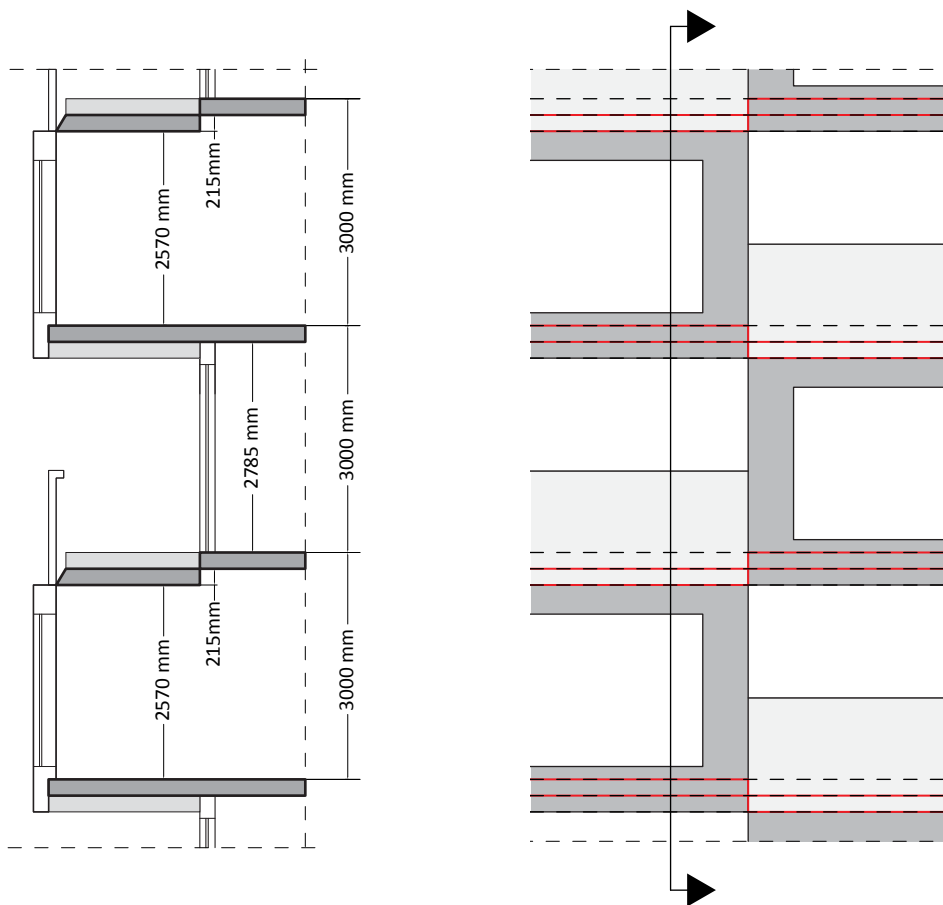


Figure 82. *Elevation and section showing the displaced balcony elements*

Cantilevered gable boxes

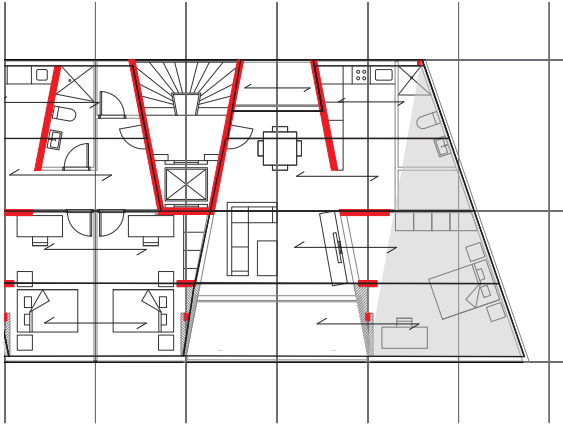


Figure 83. Section plan where the cantilevered area is marked light grey

At the gable two boxes are cantilevered from the façade as seen at *Figure 83* and *Figure 85*. I was the goal to avoid diagonal supporting structures in the windows. The cantilevering has a maximum length of 5.35 meter to the street side which is reduced to zero at the backside of the building because of the trapezoid shape of the boxes. The standard 220 mm thick SL-deck can be cantilevered up to 4 meters for a standard residential load of 4kN/m^2 depending on façade type etc.(Abeo, 2013).

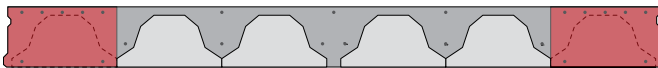


Figure 84. Section of SL-deck with integrated beams in the longitudinal direction

To handle the long span and the weight of the façade at the end, a row of light weight blocks in each side of the SL-deck element were replaced with internal beams. The concept was the same as described in “The Balconies” on page 144 just in the other direction. This made it possible to prestress the cables at the factory producing the elements, as it was now in the longitudinal direction of the casting table, see *Figure 84*.

Figure 85. Visualisation of gable with cantilevered boxes. Illustration: BIG



Applying a design with two integrated beams per element results in a load at the longest beam of 8.02kN/m and a point load from the façade of 8.14kN. This load resulted in a negative moment at $M=-155.7\text{kNm}$ at the support. This could be resisted by adding 10 prestressed wires of 12mm, giving a maximum deflection of 52 mm. This deflection is too large, but the deflection could be reduced by adding a steel frame in the light wall and in the roof structure which improved the stiffness of the structure sufficiently to make the deflection acceptable. Hereby it became possible to handle the forces from a huge cantilevered slab without increasing the height of the slab.

At the cantilevered end of the deck element a corrugated tube is placed in a massive transversal groove of the elements. Hereby the assemblies between the elements can be post tensioned in order to secure that the cantilevered part functions as a whole. This will prevent deck elements in moving independently when varied and it will contribute to the stiffness of the entire cantilevered surface and help to reduce deflections.

The presented solution solves the problem with the cantilevering but it requires the SL-deck element to be a coherent element - consisting of the cantilevered part and the balcony part - to the second support at the balcony edge. This interferes with the balcony solution presented in "The Balconies", because the elements are not shifting level, see *Figure 86*. When this article was written, this was nevertheless the preferred solution and the level issue was solved by using thin high performance insulation in the small areas related to this problem. However, the overlap of the elements in the balcony solution from "The Balconies" makes it is possible to swift deck height and then bolt the elements together in the overlap. This is possible because the end of the deck element is solid strong concrete and therefor can be fixed together and transfer the moments and twist which this part is exposed to in the strong concrete via the slack reinforcement.

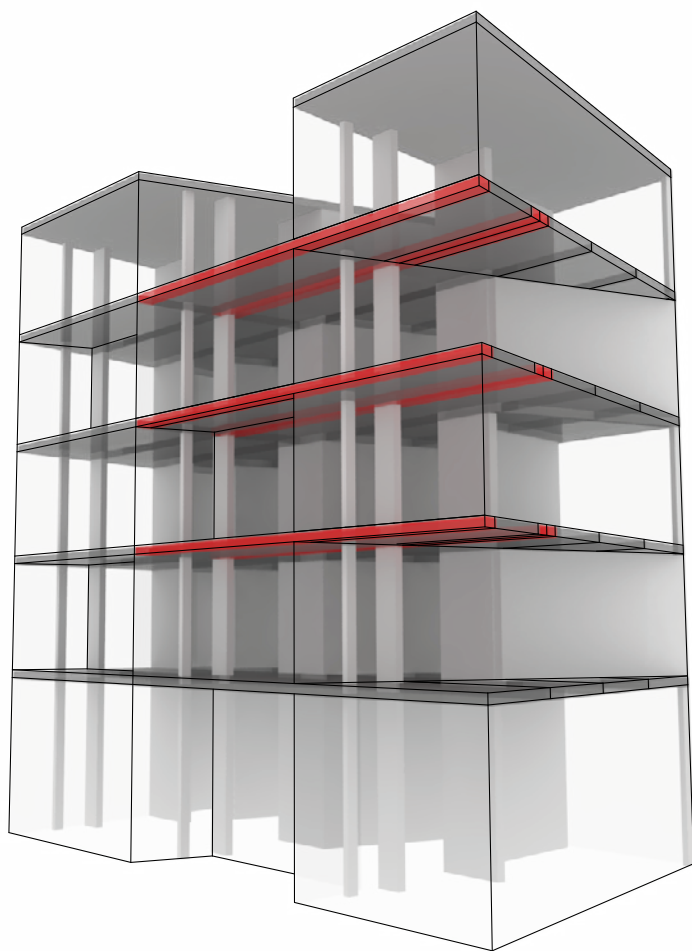


Figure 86. *3D illustration of cantilevered elements with integrated beams marked red*

Conclusion

The paper presents a number of solutions which apply the new SL-deck structure in the design of the Frederiksborgvej project. The paper shows that by incorporating a number of changes to the SL-deck, the SL-deck is capable of resolving structural problems that would lead to use of extra external structural elements, if traditional slab solutions were applied. The applied changes to the SL-deck consist for example of incorporation of beams which makes it possible to use prefabricated deck elements in new constellations and at the same time fulfil new extreme requirements from the support conditions. The solutions may appear as well-known for in-situ cast concrete but they are new as integrated in factory produced deck elements. This has been made possible by the new deck design of the SL-deck element and the way it is produced, as the machine producing the elements is simply programmed to omit light aggregate blocks, where massive strong concrete should be cast. This means that the integrated beams make it easy to create precast elements that contain a lot of the advantages of in-situ cast constructions. This reduces construction time and expands the solutions that can be made by precast elements. Some of the changes to the SL-deck element applied in the Frederiksborgvej project have been used in another building project and some of the presented concepts are still only calculated. This paper shows some characteristic examples of how a demanding architectural project can be supported by an architectural engineering approach during the early phase of the design process by making use of the structural system of the SL-deck which has deliberately been designed in order to provide improved flexibility.

Discussion and conclusion

In the transition from science to practice, it is key to acknowledge that they are two different worlds with two different realities. The realities represent different world views, different prioritisations and strives for different goals. To introduce Super-Light Structures, an academically-developed concept, was significantly more time-consuming than expected and was subject to many adjustments to fit into the practical world, even though the concept was introduced in the light of architectural engineering. Architectural engineering, intended to bridge the architect-engineer gap, in this context also had to bridge the gap between academia and practice. This latter dimension proved a greater challenge than anticipated; however, it also led to the important acknowledgment of how the reality looks from different standpoints. Where the academia aims for the theoretically optimal solution, the practice is influenced by parameters, such as economy, production, the look in relation to the architectural vision etc. Nevertheless, the two-stringed main hypothesis was: *“Architectural engineering gives rise to better architecture”* and *“Super-Light Structures support and enable a challenging architecture”*. To grasp the complexity of the hypothesis, the discussion and conclusion are handled according to the aims and structure of the thesis.

Architectural Engineering

Architects and engineers have very different approaches to problem-solving; approaches that reflect their mind-sets and how they communicate problems. This has both been described in literature and observed in the followed design cases. Implementation of architectural engineering does have a significant influence on the architect-engineer work process and the design development. This can be concluded based on the followed cases where an engineering-based dialogue anchored in a shared understanding and communicated in a language understood by architects, lead to important design improvements. Furthermore, the literature is supportive of the fact it generally is beneficial to integrate engineering knowledge early in a design process. However, civil engineers usually do not possess the skills to interact in the early stages. This may be due to communication problems and lack of understanding of the architectural decision-making, as well as the architects' limited ability to explain their decisions. However, the architectural engineer is trained in both mind-sets, enabling him to interact in the early design phases. Notably, it often proved a question of how results were presented. Adding simple explanations, obvious to the expert - but not to the recipient, made a significant difference. Nonetheless, in the Danish context, the architectural engineer is still a new player that needs to prove and settle his position.

Design

Digital tools for building design have become a significant part of the design process and have major impact on how it is executed. Geometry is a common language between architects and engineers, why it is very important to have tools able to communicate via geometry. The architectural engineering work process is different from that of classical civil engineering because it is based on less well-defined shapes and more on rough calculations. Furthermore, at the beginning of a project, more designs are investigated within a short timeframe which requires software tools capable of handling this. The examined tools give a huge advantage to an architectural engineer by the option of transferring geometries from architectural to FEM software. This option saves much time and upgrades the architectural engineer's possibilities to act when the design can change rapidly. The possibility of combining the transfer with a parametric script adds an extra dimension to the tools' flexibility, which further enables a structural model that follows the architectural model. Furthermore, design of a pearl-chain system is strengthened by the possibility of transferring results from FEM software to the architectural software and drawing the principal stresses as vectors, which subsequently can be integrated as parameters in the script. Nonetheless, the presented tools still need further development. The tools introduce a graphic, intuitive, way of facing scripting, despite that it is time-consuming to learn to master. In addition, it takes time to implement new work routines. However, the tools described do make a positive difference to the design process.

Implementation

Innovation and development of new products take time and because of the way the building industry is organised: long timeframes have harsh times. Design teams are set up for a single project that often has a relatively short time interval, after which the team splits up and joins new teams for the next projects. This process makes it very difficult to carry a product development through multiple teams and projects. Testing a new development leads to extra work, simply because it requires new work procedures to handle new solutions. Furthermore, the risk and the economy often prove a barrier for the participants. Nevertheless, some are willing to take the risk since the aim of new solutions is to perform better, which will create value to the client. The introduction of Super-Light Structures was confronted by many barriers and was very time-consuming. It did offer significant advantages in the cases where it was introduced. Nevertheless, it became very clear that there were many factors affecting the decision of using Super-Light Structures that were difficult to influence or control. Nonetheless, for the Gammel Hellerup Gymnasium project, the SL-deck was implemented in the final solution, planned to be built in the spring of 2014. Whether the implementation of Super-Light Structures will change how architects make their designs is still too early to conclude. So far, it has not been the case, however, there is a fair chance that once the possibilities of the system become more implemented in the architects' basic knowledge, it will have an impact on future designs.

Constructability

A number of cases have shown how the Super-Light Structures are implemented in different situations. The cases demonstrate a variation of Super-Light Structures' performance abilities. A variation of the pearl-chain system showed two different approaches to achieve the combination of strong and light weight concrete. Unfortunately, no other building projects followed at BIG gave rise to further investigation of the system, which obviously has a huge potential, but still requires further development before it will be applicable in a broader context. Cases with the SL-decks were investigated as well, and the constructability is shown in the variable solutions presented. The SL-deck supported the architectural visions in the cases it was applied in, and the flexibility made it possible to make smart solutions. Solutions that contained cantilevering - with and without integrated beams, hanged connections, level free connections, various integrated beams, connections of beams across different elements etc. All solutions that made it possible to minimise the construction height since external beams could be avoided. The solutions present a flexibility of these precast elements, which are normally only known from in situ cast solutions. This alone offers a strong position regarding constructability. Other advantages such as fire and acoustic performance are making the SL-deck highly relevant and applicable. However, the possibilities of developing the element are far from being fully exploited. More connection options should be developed, the possibility to produce the element in different heights and use of the element in bridges etc. are still to be further examined.

Generally speaking, the hypothesis was honoured. The architectural engineering does give rise to a better architecture via the ability to interact and apply engineering knowledge in the early design phases. The Super-Light Structures do support and enable challenging architecture via the flexibility, the system's advantages and for the SL-deck, its new production methods that keeps the price down.

The thesis, however, does not give the answer to how architectural engineering should be implemented in general, or when it will be common for architects to take advantage of Super-Light Structures. What is known is that inevitably, it will take time to change habits in the construction industry.

This PhD has documented and contributed with new knowledge about architectural engineering in a Danish context. Furthermore, it has contributed with new knowledge about Super-Light Structures and how it can be utilised for supporting architecture. Hopefully, this knowledge will strengthen the implementation of architectural engineering and continue to influence the development of Super-Light Structures, contributing to the vision of a better and more varied architecture.

БИБЛИОГРАФИЯ

Bibliography

Abeo, 2013. The SL-deck.

Andersen, D.K., Jensen, J.S., 2011. Udvidelse af Lyngby Rådhus mhp. Super-lette konstruktioner og Energidesign. Technical University of Denmark.

Atkin, B., 1999. Innovation in the Construction Sector. European Council for Construction Research, Development and Innovation.

Au, F., 2012. A Necessary Resistance within Architectural-Engineer Collaboration, in: Kara, H., Georgoulas, A. (Eds.), *Interdisciplinary Design New Lessons from Architecture and Engineering*. Actar/birkhauser.

Autodesk [WWW Document], 2013. URL <http://www.autodesk.com/products/autodesk-simulation-family/features/robot-structural-analysis> (accessed 8.6.13).

Bagger, A., Hertz, K.D., 2010. Structural behaviour of super-light structures, in: *Spacial Structures - Temporary and Permanent*. Presented at the IASS Symposium 2010, Shanghai, pp. 2697–2708.

Bengtson, A., Håkansson, H., 2008. An Interactive View Of Innovations: Adopting A New Timer Solution In An Old Concrete Context. *IMP J.* 2008, 19–35.

Bertram, P., 2009. Intuitiv metode. Kunstakademiets Arkitektskole, København.

Bjerregaard Jensen, L.M., 2007. CDIO projects at DTU architectural engineering - two traditions and one evolving, in: *REFLEKTORI 2007*. Presented at the REFLEKTORI 2007, Helsinki, pp. 192–195.

Bjerregaard Jensen, L.M., Nielsen, T.R., 2011. Obstacles and New Opportunities for Integrated Design, in: Interdisciplinary Design. Presented at the 21st CIRP Design Conference, Kaist, Korea, pp. 32–35.

Blayse, A.M., Manley, K., 2004. Key influences on construction innovation. *Constr. Innov. Inf. Process Manag.* 4, 143–154.

Bucciarelli, L.L., 2002. Between thought and object in engineering design. *Des. Stud.* 23, 219–231.

Buijs, J.A., 1987. Innovation can be taught. *Res. Policy* 16, 303–314.

Building Regulations, 2010.

Castberg, N.A., n.d. How Digital Tools Can Help Optimizing the Workflow and Process of Architectural Engineering. Be Publ.

Castberg, N.A., Hertz, K.D., 2011. Folded shapes with Super-Light Structures, in: Taller, Longer, Lighter Meeting Growing Demand with Limited Resources. Presented at the IABSE-IASS 2011 London Symposium Report, London, p. 343.

Castberg, N.A., Hertz, K.D., 2012. “The Battery” designed with Super-Light (concrete) Decks, in: From Spatial Structures to Space Structures. Presented at the IASS-APCS 2012, Seoul, p. 231.

Castberg, N.A., Hertz, K.D., Rønne, C., n.d. How Architectural Engineering can be Beneficial to a Design Process. Be Publ.

Chandra, S., Berntsson, L., 2002. Lightweight aggregate concrete: science, technology, and applications. Noyes Publications/William Andrew Pub.

Christensen, J.E., Hertz, K.D., 2012. Super-Light Prefabricated Deck Element Integrated in Traditional Concrete Prefabricated Element Construction. Be Publ.

Christensen, J.E., Hertz, K.D., Brunskog, J., 2011. Airborne and impact sound transmission in super-light structures. 40th Int. Congr. Expo. Noise Control Eng. 2011 INTER-NOISE 2011 3, 2085–2090.

Christensen, J.E., Hertz, K.D., Brunskog, J., 2012. Simulation of flanking transmission in super-light structures for airborne and impact sound. Inter Noise 2012.

Dansk Standard, 2008. DS 490 Sound classifications of dwelling, Bygningsreglementet-BR10.

Davenport, T.H., Prusak, L., 2000. Working Knowledge: How Organizations Manage what They Know. Harvard Business Press.

Dong, A., 2005. The latent semantic approach to studying design team communication. Des. Stud. 26, 445–461.

Dubois, A., Gadde, L.-E., 2002. The construction industry as a loosely coupled system: Implications for productivity and innovation. Constr. Manag. Econ. 20, 621–631.

EN1992-1-1, 1992. Eurocode 2. Design of concrete structures Part 1. General rules and rules for buildings.

Freyssinet, 2007. European Technical Approval No. ETA-06/0226.

Gann, D.M., Salter, A., 1998. Learning and Innovation Management in Project-Based, Service-Enhanced Firms. Int. J. Innov. Manag. 2, 431–454.

Geometry Gym [WWW Document], 2013. URL <http://geometrygym.blogspot.dk/> (accessed 8.6.13).

Georgiou, O., 2011. Interactive Structural Analysis and Form finding, in: Taller, Longer, Lighter Meeting Growing Demand with Limited Resources. Presented at the IABSE-IASS 2011 London Symposium Report, London, p. 234.

Georgiou, O., Richens, P., Shepherd, P., 2011. Performance Based Interactive Analysis, in: Design Modelling Symposium. Presented at the Design Modelling Symposium, Berlin.

Goldschmidt, G., 1994. On visual design thinking: the visual kinds of architecture. *Des. Stud.* 15, 158–174.

Grasshopper3d [WWW Document], 2013. URL <http://www.grasshopper3d.com/page/tutorials-1> (accessed 8.6.13).

Guerrero, A.M., Obeidi, Y.A., 2013. The Building of super-light structures SL-deck elements (M.Sc. Thesis). Technical University of Denmark, Kgs. Lyngby.

Halldorsson, E., 2012. Load-bearing capacity of super-light decks (M.Sc. Thesis). University of Iceland, Faculty of Civil and Environmental Engineering.

Harding, J., Joyce, S., Shepherd, P., Williams, C., 2012. Thinking Topologically at Early Stage Parametric Design, in: Hesselgren, L., Sharma, S., Wallner, J. (Eds.), *Advances in Architectural Geometry 2012*. Springer, Vienna London.

Herbert, G., 1999. Architect-Engineer Relationships: Overlaps and Interactions. *Arch. Sci. Rev.* 42.

Hertz, K.D., 2008. Light-weight load-bearing structure. PCT/EP2008/066013.

Hertz, K.D., 2009a. Super-light concrete with pearl-chains. *Mag. Concr. Res.* 61, 655–663.

Hertz, K.D., 2009b. Light-weight load-bearing structures reinforced by core elements made of segments and a method of casting such structures. PCT/EP2009/052987.

Hertz, K.D., Bagger, A., 2010. Super-light structures with pearl-chain reinforcement, in: Spacial Structures - Temporary and Permanent. Presented at the IASS Symposium 2010, Shanghai.

Hertz, K.D., Bagger, A., 2011. CO2 emissions from Super-light Structures. Proc. Int. Assoc. Shell Spat. Struct. IABSE-IASS Symp. 2011 "Taller Longer Light.

Hertz, K.D., Campeanu, B., Giraudo, M., Giuliani, L., 2013. Modelling and assessment of the response of super-light elements to fire, in: The Fifth International Conference on Structural Engineering, Mechanics and Computation. Presented at the SEMC 2013, Cape Town.

Hertz, K.D., Castberg, N.A., Christensen, J., n.d. Super-Light concrete decks. Be Publ.

Holzer, D., 2010a. Optioneering in Collaborative Design Practice. Int. J. Arch. Comput. 8, 165–182.

Holzer, D., 2010b. Optioneering in Collaborative Design Practice. Int. J. Arch. Comput. 8, 165–182.

Holzer, D., Downing, S., 2010. Optioneering: A New Basis for Engagement Between Architects and Their Collaborators. Arch. Des. 80, 60–63.

Hudson, R., Shepherd, P., Hines, D., 2011. Aviva Stadium: A case study in integrated parametric design. Int. J. Arch. Comput. 9, 187–203.

Håkansson, H., Ingemansson, M., 2013. Industrial renewal within the construction network. Constr. Manag. Econ. 31, 40–61.

Kara, H., 2010. ON DESIGN ENGINEERING. Arch. Des. 46–51.

Karamba3d [WWW Document], 2013. . KARAMBA3D. URL <http://www.karamba3d.com/> (accessed 8.6.13).

Kleinsmann, M., Valkenburg, Buijs, 2007. Why do(n't) actors in collaborative design understand each other? An empirical study towards a better understanding of collaborative design. CoDes. (UK) 3, 59–73.

Kleinsmann, M., Valkenburg, R., 2008. Barriers and enablers for creating shared understanding in co-design projects. Des. Stud. 29, 369–386.

Kongebro, S., 2012. Design med viden, 1st ed.

Lachauer, L., Jungjohann, H., Kotnik, T., 2011. Interactive Parametric Tools for Structural Design, in: Taller, Longer, Lighter Meeting Growing Demand with Limited Resources. Presented at the IABSE-IASS 2011 London Symposium Report, London, p. 299.

Larsen, O.P., Tyas, A., 2003. Conceptual structural design: bridging the gap between architects and engineers. Thomas Telford, London.

Mirtchin, J., 2011. Generative Models Utilized for Superior Design Development, in: Taller, Longer, Lighter Meeting Growing Demand with Limited Resources. Presented at the IABSE-IASS 2011 London Symposium Report, London, p. 182.

Moum, A., 2010. Design team stories: Exploring interdisciplinary use of 3D object models in practice. Autom. Constr. 19, 554–569.

Nonaka, I., 1994. A Dynamic Theory of Organizational Knowledge Creation. Organ. Sci. 5.

Nonaka, I., Konno, N., 1998. The concept of “ba”: Building a foundation for knowledge creation. *Calif. Manage. Rev.* 40, 40–+.

Oxman, R., 2006. Theory and design in the first digital age. *Des. Stud.* 27, 229–265.

Parthenios, P., 2005. *Conceptual Design Tools for Architects* (PhD Thesis). Harvard Design School.

Passas, C., 2012. *Design the Cloud: Cross-disciplinary Approach to Design*, in: Kara, H., Georgoulas, A. (Eds.), *Interdisciplinary Design New Lessons from Architecture and Engineering*. Actar/birkhauser.

Pfammatter, U., 2000. *The making of the modern architect and engineer, The origins and development of a scientific and industrially oriented education*. Birkhäuser, Basel.

Rhinoceros [WWW Document], 2013. URL <http://www.rhino3d.com/training/Denmark/> (accessed 8.8.13).

Salvadori, Ma., 1989. ARCHITECTS versus ENGINEERS, in: *Bridging the Gap*.

Sattrup, P.A., 2011. *Architectural Research Paradigms - an overview and a research example*, in: *When Architects and Designers Write/Draw/Build a PhD*. Presented at the *When Architects and Designers Write/Draw/Build a PhD*, Aarhus.

Sattrup, P.A., 2012. *Sustainability - energy optimization - daylight and solar gains* (PhD Thesis). Royal Danish Academy of Fine Art, Copenhagen.

Scan-and-Solve [WWW Document], n.d. URL <http://www.scan-and-solve.com/> (accessed 8.6.13).

Schön, D.A., 1983. *The Reflective Practitioner. How Pro-*

professionals Think in Action. New York, Basic Books.,.

Shea, K., Aish, R., Gourtovaia, M., 2005. Towards integrated performance-driven generative design tools. *Autom. Constr.* 14, 253–264.

Slaughter, E.S., 1998. Models of construction innovation. *J. Constr. Eng. Manag.* 124.

Sobek, W., 2008. Structural Design - Advanced aesthetics and research into terra incognita.

Tassello, A., 2011. Load-bearing capacity of super-light slabs (M.Sc. Thesis). Technical University of Denmark and University of Padoca.

Turrin, M., von Buelow, P., Stouffs, R., 2011. Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *Adv. Eng. Informatics* 25, 656–675.

Valkenburg, R., Dorst, K., 1998. The reflective practice of design teams. *Des. Stud.* 19, 249–271.

Valkenburg, R.C., 1998. Shared understanding as a condition for team design. *Autom. Constr.* 7, 111–121.

Yin, R.K., 2009. Case study research / design and methods. Sage Publications, Los Angeles.

Zofchak, J.S., 2012. Integrated Design: A Computational Approach to the Structural and Architectural Design of Diagrid Structures, in: Kara, H., Georgoulas, A. (Eds.), *Interdisciplinary Design New Lessons from Architecture and Engineering*. Actar/birkhauser.

List of figures

Figure 1. Picture of BIG Copenhagen office space. Photo: BIG	8
Figure 2. Research diagram	11
Figure 3. Strong concrete 'pearls' tighten up with wires to form an arch skeleton	12
Figure 4. 'Pearl-chain' skeleton embedded with light aggregate concrete. The light concrete transfers the load to the skeleton, that transfer the load to the supports.	12
Figure 5. The light aggregate blocks form an arch, that work as a permanent mould. The forces will follow the arches and the transversal reinforcement will obtain the outgoing force.	14
Figure 6. In the longitudinal directions will the 'beams' in between the blocks transfer the load to the support at the ends.	14
Figure 7. Production of test elements. Photo: K. Hertz	16
Figure 8. Diagram showing the structure of the thesis and how the papers are placed in the overall structure.	19
Figure 9. Nonakas' SECI model	27
Figure 10. Nonakas' "Ba" model for interaction between people	27
Figure 11. Bar-system of the design process. Bars represent focus areas in relation to the process.	28
Figure 12. The architect works with and shifts between all bars during the design process.	30
Figure 13. The structural engineer enters the process late and works only within his own focus area.	31
Figure 14. The (structural) architectural engineer enters at the beginning of the process and works across bars that are influenced by his main focus bar.	34
Figure 15. Two early concept models and two later stage models. Photo: BIG	35
Figure 16. Diagrams explaining the development of the final concept. Illustrations: BIG	35
Figure 17. The overall structural concept and a concept solution for the balconies with new structural system. Visualisations top right and bottom left: BIG	36
Figure 18. BIOVAF: the overall structural system and the curved 'snake' part. Visualisations top right and bottom left: BIG	37
Figure 19. "Experimentariet": The boxes on top of the existing structure. Photo: BIG	38
Figure 20. The steps from the beam underneath the garden level - to the arch explanations - to the upwards arch.	39
Figure 21. A section of the roof garden with the upward-bending arch structure. Illustration: BIG	39
Figure 22. A stress plot transferred in to a hollow pattern reflecting the concentration of stresses.	40
Figure 23. Model photo of the concrete box with the facade expressing the stresses. Photo: BIG	41
Figure 24. Diagram showing steps from Rhino to Robot.	54
Figure 25. Diagram showing steps from Rhino to Robot to Rhino	55
Figure 26. Structure of curved building building part of BIOVAF.	56
Figure 27. BIOVAF indoor curved building. Visualisation: BIG	56
Figure 28. Visualisation of structure in Rhino. Grasshopper script sending the structure to Robot. Structure in Robot.	59

Figure 29. "Experimentarier" concrete box. Visualisation: BIG	60
Figure 30. Stress plot form Robot imported as picture into Grasshopper script and used to control holes dimension	61
Figure 31. Grasshopper script that send geometry and structural to Robot - recall the result and used them in the scrip for control of the holes' diameter.	61
Figure 32. Double curved Grasshopper surface visualised in Rhino. Surface in Robot with loads. Surface in Robot with principal stress vectors. Surface I Rhino with principal vectors recalled for m Robot.	62
Figure 33. Doubled curved roof with pearl-chain structure modelled manually.	63
Figure 34. Plot of principal stresses and pearl-chain placement.	63
Figure 35. Principal stresses vectors and principal stress trajectories in Rhino. By: Georgiou	64
Figure 36. Principal stress trajectories made in Grasshopper via GeometryGym plug-in.	64
Figure 37. Visualisation of Snippen an element in the project called: Super Kilen. Illustration: BIG	76
Figure 38. Visualisation of "Batteriet". Illustration: BIG	78
Figure 39. Visualisation of connection between existing and new buildings in the BIOVAF project. Illustration: BIG	80
Figure 40. Visualisation of Frederiksborgvej. Illustration: BIG	82
Figure 41. Visualisation of the extension of Gammel Hellerup Gymnasium. Illustration: BIG	84
Figure 42. Visualisation of Snippen. Illustration: BIG	96
Figure 43. Elevations of examined shape. Drawings: BIG	97
Figure 44. Rib structure for a fold	99
Figure 45. Cross section variations GeoA and GeoB	99
Figure 46. ROBOT load model	101
Figure 47. Overall stress distribution of respectively GeoA and GeoB	101
Figure 48. Stresses at section A-A GeoA	102
Figure 49. Stresses at section A-A GeoB	102
Figure 50. The 'Battery' illustration. Illustration: BIG	110
Figure 51. Overall structural system	113
Figure 52. Tension bars stabilising the cantilevering	113
Figure 53. Visualisaion towards south. Illustration: BIG	114
Figure 54. Typical plan section	115
Figure 55. Illustration of directions of span	115
Figure 56. Illustration of atrium. Illustration: BIG	116
Figure 57. SL-deck illustration	117
Figure 58. Transversal section in SL-deck	118
Figure 59. Longitudinal section in SL-deck sith beam	118
Figure 60. Level free connections of SL-deck	119
Figure 61. Hung connections of SL-deck, Ill. Jakob E. Christensen.	119
Figure 62. Model photo of the BIOVAF project. Photo: BIG	122

<i>Figure 63. BIOVAF's overall structural concept. The dark grey is loadbearing walls. The red elements are steel. The light grey is SL-decks and the structure of the two existing buildings is white.</i>	124
<i>Figure 64. Illustration of how much CO2 that is saved by using SL-deck in front of hollow core slabs</i>	125
<i>Figure 65. The SL-deck can fulfil the demand for two hours fire exposure</i>	126
<i>Figure 66. The SL-deck has great flexibility that was utilised for cantilevering and curved shapes of the project.</i>	126
<i>Figure 67. The SL-deck's acoustic performance was to advantages to for the mixed used of rooms next to each other</i>	127
<i>Figure 68. The width of the SL-deck could reduce the construction period and number of joints</i>	128
<i>Figure 69. Description of the SL-decks components</i>	133
<i>Figure 70. The architectural concept with shifted boxes. Diagram: BIG</i>	134
<i>Figure 71. Visualisation of the building from south. Illustration: BIG</i>	135
<i>Figure 72. Overall 3D model showing the shifted boxes and the void rooms created. The small doted line is the outline of an unit.</i>	138
<i>Figure 73. Plan solution with two longitudinal bearing lines and cantilevered SL-deck in both sides</i>	140
<i>Figure 74. Plan section in the curved part showing transversal deck solution</i>	141
<i>Figure 75. Plan section in the curved part showing the longitudinal deck solution</i>	141
<i>Figure 76. Plan section showing the beam integrated in the SL-deck across two elements</i>	142
<i>Figure 77. Detail of beam integrated in the SL-deck</i>	142
<i>Figure 78. Façade elevation showing the point between two boxes. Illustration: BIG</i>	144
<i>Figure 79. Plan section of balcony area with displaced SL-deck</i>	145
<i>Figure 80. 3D model illustrating how the upper slab is resting on the lower with the integrated beam</i>	145
<i>Figure 81. Detail showing how the slabs are resting on each other</i>	146
<i>Figure 82. Elevation and section showing the displaced balcony elements</i>	147
<i>Figure 83. Section plan where the cantilevered area is marked light grey</i>	148
<i>Figure 84. Section of SL-deck with integrated beams in the longitudinal direction</i>	148
<i>Figure 85. Visualisation of gable with cantilevered boxes. Illustration: BIG</i>	148
<i>Figure 86. 3D illustration of cantilevered elements with integrated beams marked red</i>	151

Journal Paper

Super-Light Concrete Decks

Submitted for:
Structural Concrete
Ernst & Sohn

Authors:
Kristian Hertz
Niels Andreas Castberg
Jacob Christensen

Kristian Hertz (Main Author)
 Andreas Castberg (Co-Author 1)
 Jacob Christensen (Co-Author 2)

Super-light concrete decks

This paper presents investigations made at the Technical University of Denmark (DTU) on a prototype series of a super-light prestressed concrete deck element called the SL-Deck.

The intension of making a new prefabricated deck element is to improve performance with respect to flexibility, sound insulation, and fire resistance compared with present day prefabricated structures.

Full-scale tests and theoretical investigations show that the deck structure performs as intended, and that it is possible to assess by calculation the load-bearing capacity in bending and shear, and assess the pull-out strength of prestressing reinforcement, the fire resistance, and the acoustical insulation. Based on the results of the investigations recommendations are given for further development of the structure before a full automatic mass production is established.

Keywords Super-light structures; Deck structures; Precast concrete; Lightweight concrete; Prestressed concrete; Structural design; Testing structural elements.

Dieser Beitrag präsentiert Untersuchungen gemacht an der Technischen Universität Dänemarks (DTU) an einem Prototyp Serie eines super-leichten Spannbeton Deck Element der SL-Deck genannt ist.

Die Intension der Entwicklung eines neuen Deck Element ist, um die Leistung in Bezug auf Flexibilität, Schallschutz und Brandschutz im Vergleich mit den heutigen vorgefertigten Deck Konstruktionen zu verbessern. Vollausschlag Prüfungen und theoretischen Untersuchungen zeigen, dass die Leistung wie vorgesehen ist, und dass es möglich ist, durch Berechnung zu Beurteilen der Tragfähigkeit in Biege- und Verschiebung-, und zu bewerten das Verankerung Stärke des Spannbewehrung, die Feuerbeständigkeit, und die akustische Isolierung. Basierend auf den Ergebnissen der Untersuchungen Empfehlungen sind gegeben für die weitere Entwicklung der Konstruktion, bevor eine vollautomatische Massenproduktion etabliert ist.

Keywords Super-leicht Konstruktion; Deck Konstruktion; Fertigteil Beton; Leichtbeton; Spannbeton; Tragwerksplanung; Prüfung.

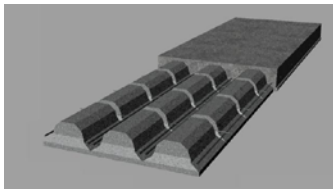


Figure 1. Principle of a 215 mm thick, 1200 mm wide prototype SL-Deck with 3 rows of light-aggregate blocks.

1 Introduction

Super-light is a short name for a general structural technology, where arches of a strong concrete carry the load and where a concrete of less strength fills out the shape, stabilizes the arches for buckling, and protects them for impact and fire.

It allows an engineer to place a strong concrete, where he wants compression forces to be, while the shape of the entire

structure is filled out by a light-aggregate concrete that stabilizes the strong parts and may act as permanent moulds for casting the strong parts Hertz [1], [2], [3].

DTU has patented the general technology and a university spin-out company Abeo Ltd. is established to develop applications and introduce them for the industry. The company won the Clean Tech Open Global Ideas competition in San Francisco November 2010, because super-light structures with their application of more than one type of concrete in structural elements allow a minimization of the weight of the structure as well as the amount of cement applied. A result of this is often a reduction of 20-50% of the embodied energy and produced CO₂ for long spans compared to the building of a normal massive concrete structure, and a larger reduction compared to the building of a similar steel structure (Hertz and Bagger [4]).

The dominating present day technology for prefabricated deck elements in a country like Denmark is the hollow-core slab. However recent changes of the Building Regulations requires an improved sound insulation that can only be obtained by increasing the mass per square metre, where a su-

per-light structure can reduce noise to heat because the strong and weak concretes have different eigenfrequencies. Furthermore, the increased requirement for heat insulation of buildings has the negative effect that energy from fires is kept within the compartment increasing the impact from fire on the structure. A performance based fire safety design therefore requires an increased structural fire resistance often leading to external insulation.

Finally, architects and consumers would like to apply special shapes, long free spans, and to incorporate services in deck structures. This calls for a flexibility that is often hindered by the casting process applied for hollow-core slabs, where the concrete has to be self-supporting immediately after the holes are extruded, and where the elements are cut in length by a saw. This means that cross-reinforcement, massive zones and special cavities are not easy to establish, and curved shapes cannot be made.

In many countries with a relatively low price of labour hollowed tile block stones are applied as permanent moulds for in-situ cast slack reinforced concrete rib decks. These structures are basically different from the super-light and do not have the benefits of a sufficient sound insulation, fire resistance, pretension, and prefabrication, as aimed at by developing the SL-Deck.

The SL-Deck should not only be able to carry sufficient dead and live load, but at the same time it should have a sufficient fire resistance and acoustical insulation for airborne and impact noise (Christensen and Hertz [5], Castberg and Hertz [6]). In addition, it should be flexible in use, quick to place in the final building and possible to produce at a reasonable price using a modern automatic production technology unlike the one applied for the prototype series.

This paper describes investigations made by DTU on a prototype series of SL-decks produced by Abeo in order to show, to what extent the functional requirements are met and in order to adjust the design before an automatic production process is developed.

The aim of the research is therefore to investigate if the postulated benefits of the new elements can be obtained, and to observe if any unforeseen behaviour is found for these super-light structures when subjected to extreme impacts.



Figure 2. Casting of SL-deck prototype test elements.

2 Prototype SL-Deck

The prototype SL-Deck contains blocks of a light aggregate concrete of density 600 kg/m^3 and compressive strength 3 MPa with a curved surface. A block stone factory made the light-aggregate blocks using a special mould in an automatic compression block stone machine.

A concrete element factory produced the pre-tensioned SL-Deck elements on a 100 m long and 1.2 m wide track, where they placed blocks and preliminary mould sides by hand, placed prestressing wires in the grooves between the light blocks with a full cover thickness to the surface of these, and placed slack cross reinforcement on top of them (Tasello[7]).



Figure 3. Close-up of block stones and reinforcement before casting strong concrete.

The bottom flange of the light aggregate concrete blocks gives an additional cover of 30 mm as a fire protection of the reinforcement. The wires were 12.5 mm thick. They had an ultimate strength of 1860 MPa , and were pretensioned to 1163 MPa .

Mould pieces were placed across the track to separate the elements in length and leaving a zone of at least 100 mm long massive concrete in each end of each element in order to improve anchorage of the prestressing wires and to improve stress distribution and shear resistance at the supports.

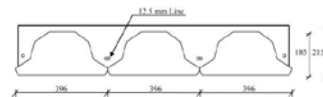


Figure 4. Cross-section of prototype element. All measures in mm.

Then a self-compacting concrete of compressive strength 50 MPa was cast to the final thickness 215 mm of the deck. Because of the curved surface of the light aggregate concrete blocks, the strong concrete cast on top of them will form arches. These arches are kept in place by the cross reinforcement. They are stabilized by the blocks, and transfer the load of the deck to concrete rib beams formed between the blocks along the deck.

The time interval between new castings on the same track was 24 hours .

Since the SL-Deck unlike a hollow-core slab has a cross-reinforcement, it should be possible to cast it as 2.4 m wide without stability problems at production or at the building

Structural Concrete

site. Here a 1.2 m hollow-core track was available determining the width of the prototype.

Each test specimen was a 215 mm thick and 1.2 m wide with 3 light aggregate blocks across the width where each block was 396 mm wide, 500 mm long, and 185 mm high.



Figure 5. Bending test rig with a SL-Deck element.

3 Moment resistance

The research group tested prototypes of the SL-Deck mechanically in order to investigate whether the deck will break in a tough and ductile manner with a reasonable warning and to unveil any unforeseen effects, when the structure is loaded to its ultimate capacity. The tests should also indicate whether it is reliable to apply commonly accepted methods for estimating the load-bearing capacity.

The span length of the elements used for bending test was 4 m between the centre lines of the supports and they were reinforced by 6 prestressing wires of diameter 12.5 mm and characteristic strength 1860 MPa. The strong concrete had a characteristic compressive strength of 50 MPa, and the compressive strength of the light-aggregate concrete was 3 MPa.

Two jacks applied a load at the midpoint of the span through a steel beam distributing the stresses across the width of the deck element.

Mechanical and electronic gauges measured deflections at the midpoint.

An ordinary ultimate design calculation according to the Eurocode EN1992-1-1 [8] gives a characteristic failure moment minus the moment from dead load of 125.6 kNm.

The ultimate failure moment was measured as 146.3 and 147.8 kNm. The test results are therefore approximately 16% safe compared with calculation (Tassello [7], Lauricina [9], Halldorsson [10]).



Figure 6. Ultimate bending failure of a SL-Deck element.

The fracture was ductile with a gradual crack formation during the last part of the loading period. This proves that the specimen responded as a coherent structure and no sign of separation occurred between strong- and light-aggregate concrete.

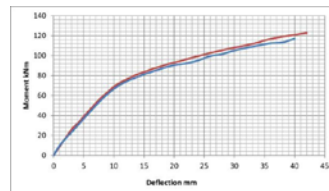


Figure 7. Applied moment load vs. deflection.

Figure 7 shows the relation between deflection and applied moment exclusive dead load as measured by electronic gauges for the first 40 mm deflection. The ultimate moment resistance occurred at a deflection of 200 mm. The relation was almost linear up to approximately 70 kNm, where cracks in the light aggregate blocks became visible. This means that the stiffness in bending of the deck element can be predicted approximately by means of an elastic model for a service load. (Using safety factors of 1.2 for reinforcement, 1.4 for concrete and 1.5 for load you get that the ultimate calculated moment resistance corresponds to 68.1 kNm as max service load).

The initial flexural stiffness of the composite cross section was calculated as 10.7 MNm² and the secant stiffness at 70 kNm moment load was measured as 9.33 MNm² which is a reasonable agreement.



Figure 8. Shear resistance test with a SL-Deck element.

4 Shear resistance

Like other prefabricated pretensioned deck elements, a SL-Deck has no shear reinforcement. The structure therefore transfers shear forces by means of compression- and tension stresses in the strong- as well as in the light-aggregate concrete and across the interface between the two materials.

We made a test to investigate whether the structure can transfer a calculated ultimate shear force in an area, where anchorage does not reduce the capacity in order to separate this from the anchorage problem that is treated by another test. This is especially relevant for the SL-Deck because the possibility of making massive zones allows it to have fixed end supports and to be applied as continuous slabs over several supports, where pull-out strength is not an issue.

The specimen was therefore loaded close to a support with a long anchorage zone extending from the support. The distance between the load and the support was chosen in order to make space for the shear transfer mechanism consisting of inclined compression and tension and in order to test a cross section with light-aggregate blocks. Because we needed this distance, we knew that we could not obtain a pure shear failure without having a bending failure too, but we considered this distance important for the application of the result.

A SL-element with a span length of 1.985 m and reinforced by 6 prestressing wires of diameter 12.5 mm was loaded at a point 0.485 m from the centre of the nearest support. The distance from the centre of the support to the end of the element was 0.35 m of which 0.10 m at the end was massive concrete without light-aggregate concrete blocks.

As foreseen, the failure mode was combined bending and shear. However, the test showed, that a shear force of 269 kN could be transferred in a zone, where light aggregate blocks are in the cross-section (Halldorsson [10]).

The shear capacity obtained by calculation is 215 kN. The test therefore indicates that it is safe to calculate the shear resistance. By comparison with the moment resistance, the test showed that shear failure of the cross-section only becomes decisive for theoretical span-widths of less than 1 m, which means that shear resistance seldom will decide the dimensions in practise, if anchorage is not a problem.



Figure 9. Pull-out test with a SL-Deck element.

5 Pull-out resistance

Although SL-Deck elements allow fixed-end supports and continuous slabs, it is still possible to apply a simple support, which until now is most common for prefabricated deck elements. Often a simple support has a small bearing-depth because a wall or a console, on which the element is placed, has a limited width. The anchorage of the pre-tensioned prestressing wires is therefore of interest.

The main author gives in Hertz [11] a general design method for assessing anchorage capacity as a minimum of splitting strength and bond strength. Splitting develops cracks radial from the reinforcing bar to one or more surfaces and it depends on the cross-section. Bond-failure means that the bar is pulled out of a round hole and it depends on the concrete and the corrugations on the bar. The paper describes how to calculate the maximum bond resistance for deformed bars as an ultimate shear stress on the surface of the bar of 0.65 times the compressive strength of the concrete.



Figure 10. Conical bond test specimen with prestressing wire and cracks from fire exposure.

This theoretical value is calculated from plain strain crushing under 45° to the bar axis and it fits with results of the bond test ("Cuff-test") described in the paper.

If the reinforcing bar does not have sufficient corrugations, the bond capacity is smaller.

It is measured by the test, and the paper shows values for common bars at normal- and at fire conditions. However, prestressing wires were not included in this test series.

A later special project (Figure 10) therefore tested bond strength of prestressing wires Hertz [12] showing a factor of approximately 0.40 instead of the theoretical maximum of 0.65 for deformed bars.



Figure 11. Pull-out test with a SL-Deck element

A pull-out test is made for a SL-Deck element in order to investigate whether the anchorage capacity and thereby the ultimate reaction of a small support can be calculated.

A SL-element with a span length of 1.995 m and reinforced by 6 prestressing wires of diameter 12.5 mm was loaded in a point 0.500 m from the centre of the support. The distance from the centre of the support to the end of the element was 0.040 m. The outmost 0.10 m of the element was massive concrete without light aggregate blocks, which is a minimum for SL-Decks in order to ensure the anchorage and shear capacity. A crack developed as foreseen from the load to the edge of the support (Figure 11), and the ultimate failure mode was in bending due to bond failure of the prestressing lines for a reaction at the support of 132 kN. This proves that no splitting failure occurs and that bond failure, which is the maximum anchorage capacity for the prestressing wires in any cross-section, is the failure mode.

The bond failure was in the 0.10 m long massive part of the slab, since the crack had a thickness equal to the sliding measured from the end of all the wires of 20 mm.

This gives a bond strength equal to the anchorage strength for the 6 wires of 501 kN at 0.1 m or a bond strength factor of 0.425 for a 50 MPa concrete. It confirms that the anchorage capacity can be calculated on the safe side as a bond strength equal to 0.40 times the characteristic compressive strength of the concrete times the perimeter of the wires. This also determines a magnitude and angle of a compressive force in the deck at the support and thereby an ultimate reaction. As foreseen, this reaction is smaller than the shear load that could be taken by the cross section of the element in the shear test without anchorage failure. Anchorage therefore has to be considered as a failure mode, as it has to be for other pre-tensioned deck elements for small depths of the support.

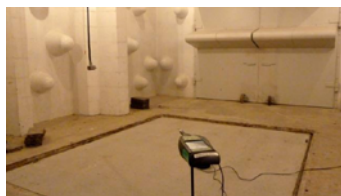


Figure 12. SL-Deck exposed to a white noise in the floor of a sound-hard room. Noise transmission is measured to another sound-hard room below.

6 Acoustical properties

In the SL-Deck, the strong concrete constitutes a series of arches or vaults over the curved light-aggregate blocks. Since a vault is stiffer than a plane plate, the eigenfrequency of it is higher, which is beneficial because the most difficult frequencies to make sound insulation for are in the low end of the spectrum.

Furthermore, the porous light aggregate concrete has an internal loss factor, which is 2-3 times higher than the internal loss factor of normal concrete. Additionally, the light aggregate concrete will further increase the damping as it is acting as a damping layer as described by Cremer and Heckl [13] (page 243-247).

A new method for estimating these effects is developed by Christensen et al [14].

By means of this and by full-scale tests in the acoustical laboratory of DTU-Electro we found that a prototype SL-deck of 315 kg/m² gives an acoustical airborne insulation of 55 dB.

The SL-Deck was cast into a standard frame and placed in the floor of a sound-hard room as seen in Figure 12, where a white noise was emitted, and the sound level was measured in specific points of a sound-hard room beneath.

The calculated and measured value 55 dB of the sound insulation is just equal to the new Danish requirement for acoustical insulation in domestic buildings. For comparison, some factories producing existing concrete deck elements decide to increase the mass of their decks up to 440 kg/m² in order to meet this new requirement.



Figure 13. Impact-noise machine on a SL-Deck.

Since flange transmission in the walls and additional insulation in the floors to be placed on the deck elements may influence the result in negative and positive directions, the research indicated that it would be recommendable to increase the weight of the SL-decks to about 340 kg/m² to be sure that the requirements are met everywhere in practise. This may be done by increasing the density of the light-aggregate concrete in the elements from 600 to 700 kg/m³.

Then impact noise (or step noise) reduction was measured using a standardized impact noise machine (Figure 13).

The impact noise level was measured as 79 dB from which

you should subtract a damping of a floor. Application of a floor consisting of 22 mm chipboard on 30 mm mineral wool gives a damping of 29 or 32 dB for two different commercially available qualities. This leads to a step-noise level of 50 dB or 47 dB, which is less than the maximum of 53 dB allowed according to new Danish standards. This shows that the step-noise level of the prototype elements is acceptable.



Figure 14. Unharmed SL-Deck after 135 min standard fire exposure with 17.6 kN/m² load.

7 Fire safety

Two 6.4 m long, 1.2 m wide and 215 mm thick prototype elements with 6 prestressing wires of diameter 12.5 mm were placed simply supported with a fire exposed span of 6 m on a fire test oven at the Danish Institute of Fire Technology. The grooves on all four edges were insulated with mineral wool, which means that the contribution to the load-bearing capacity from casting reinforced grooves did not influence this test.

The elements sustained a live- and semi-live load as required for domestic buildings of 2.5 kN/m² in addition to the dead load of the elements of 3 kN/m² for 120 minutes.

At this time the deck elements had a final deflection of 25 mm.

Then the load was increased to 17.6 kN/m² with a deflection of 200 mm and unloaded back to a deflection of 35 mm at 135 minutes of standard fire exposure.

The elements were unharmed after the fire test.

This shows that the elements have a fire resistance of at least 120 minutes.

The results accord safely with calculations according to Hertz [11], [12], [15], [16] and the Eurocode 1992-1-2 [17], if a load of 17.6 kN/m² is applied (Halldorsson [10], Rocca [18], Carstensen et al [19]).

The test therefore indicates that the elements will also have a fire resistance of more than 240 minutes as you can get from the same calculations for domestic load of 2.5 kN/m².

Fire safety becomes increasingly important for load-bearing structures these years, because application of low-energy windows that do not break in fire, heavy insulation in the facades, light-weight aerated concrete walls and impact noise

insulated floors means that fires become more hot and give rise to long time exposures, which means violent damages on structures (Hertz [20]).

However, the result is far better than anything observed before for a precast deck element, so this may open up for a recommendation of reducing the bottom cover of light-aggregate concrete from 30 to 20 mm increasing strength and stiffness.

8 Conclusions

Mechanical tests are made of 215 mm thick prototypes of the SL-Deck for bending, shear, and pull-out of reinforcement at small bearings and to discover any unforeseen behaviour before a final design for production is decided.

The deck showed a ductile behaviour to ultimate limit conditions for the mechanical tests, and the load-bearing capacity appears to be safe compared to the calculated so that it can be predicted by calculation. No unforeseen behaviour was observed.

Acoustic tests show that a SL-Deck with a weight of 315 kg/m² has an airborne noise insulation of 55 dB and an impact noise level of 79 dB, which by means of standard floors may give a total impact-noise level of 47-50 dB. The SL-Deck should therefore be able to fulfil the Danish noise requirements of maximum of 53 dB impact noise and minimum 55 dB airborne sound insulation.

A standard fire test demonstrated a load-bearing capacity of 17 kN/m² after 135 minutes standard fire exposure and it thereby indicated a resistance of more than 240 minutes for a domestic live load of 2.5 kN/m².

The test series indicates that some of the important properties of a deck can be estimated by calculation, and that the construction seems to have a fair chance to meet the requirements.

Because the deck has a cross-reinforcement making it stable in production and at the building site, it is suggested to increase the width to 2.4 m in the further development of the deck, because this can decrease the number crane lifts and the amount of grooves to be cast at the building site.

It is recommended to increase the density of the light aggregate blocks about 10% in order to be safe with respect to unforeseen flange transmission of noise in actual buildings.

The large fire resistance time gives rise to suggest a reduction of the thickness of the bottom flange of light-aggregate concrete from 30 to 20 mm in order to increase the load-bearing capacity and the stiffness at normal temperatures allowing longer span lengths.

The investigation indicates these recommendations to be considered for the further development of the deck element as a basis for a mass-production.

References

- [1] HERTZ, K.D.: SUPER-LIGHT CONCRETE WITH PEARL-CHAINS. MAGAZINE OF CONCRETE RESEARCH, OCTOBER 2009, 61, No. 8, pp.655-663.
- [2] HERTZ, K.D.: LIGHT-WEIGHT LOAD-BEARING STRUCTURE. PCT (PATENT COOPERATION TREATY) APPLICATION NO. PCT/EP2008/066013. NOVEMBER 2008. PCT PATENT, JANUARY 2010.
- [3] HERTZ, K.D.: *Light-weight load-bearing structures reinforced by core elements made of segments and a method of casting such structures*. PCT (PATENT COOPERATION TREATY) APPLICATION NO. PCT/EP2009/052987 MARCH 2009. PCT PATENT, OCTOBER 2010.
- [4] HERTZ, K.D. BAGGER, A.: *CO₂ emission from super-light structures*. PROCEEDINGS OF THE IABSE-IASS SYMPOSIUM, LONDON SEPTEMBER 2011.
- [5] CRISTENSEN, J.E. HERTZ, K.D.: *Super-Light Prefabricated Deck Element Integrated in Traditional Concrete Prefabricated Element Construction*. PROCEEDINGS OF IASS-APCS SYMPOSIUM IN SEOUL KOREA, MAY 2012. 7 p.
- [6] CASTBERG, A. HERTZ, K.D.: *"The Battery" Designed with Super-Light Decks*. PROCEEDINGS OF IASS-APCS SYMPOSIUM IN SEOUL KOREA MAY 2012. 7 p.
- [7] TASSELLO, A.: *Load-bearing capacity of super-light slabs*. M.Sc. PROJECT. DEPARTMENT OF CIVIL ENGINEERING, DTU AND UNIV. OF PADOVA, 2011.
- [8] EN1992-1-1: *Eurocode 2. Design of concrete structures Part 1.1 General rules and rules for buildings*. CEN BRUSSELS. SEPTEMBER 2004.
- [9] LAURICINA, D.: *Analisi di elementi strutturali super-leggeri in c.a.p. ai fini della sostenibilità: utilizzo del codice di calcolo DIANA*. UNIVERSITÀ DEGLI STUDI DI ROMA, LA SAPIENZA, FACOLTÀ DI INGEGNERIA. 2010. 354 p.
- [10] HALLDORSSON, E.: *Load-bearing capacity of super-light decks*. FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING, UNIVERSITY OF ICELAND. 60p. REYKJAVIK JANUARY 2012.
- [11] HERTZ, K.D.: *The anchorage capacity of reinforcing bars at normal and high temperatures*. MAGAZINE OF CONCRETE RESEARCH, DECEMBER 1982, 34, No. 121, pp.213-220.
- [12] HERTZ, K.D.: *Bond strength of prestressing wires in fire. (In Danish Vedhæfningsstyrke af spændliner ved brandpåvirkning)*. DEPARTMENT OF CIVIL ENGINEERING, TECHNICAL UNIVERSITY OF DENMARK REPORT SR 05-12, AUGUST 2005, 10p.
- [13] CREMER, L. HECKL, M. UNGAR, E.E.: *Structure-Borne Sound*, SECOND EDITION SPRINGER-VERLAG 1973, 528p.
- [14] CHRISTENSEN, J.E. HERTZ, K.D. BRUNSKOG, J.: *Airborne and impact sound transmission in super-light structures*. PROCEEDINGS OF INTER-NOISE 2011. OSAKA SEPTEMBER 2011.
- [15] HERTZ, K.D.: *Concrete strength for fire safety design*. MAGAZINE OF CONCRETE RESEARCH 57, No.8, 445-453. THOMAS TELFORD LTD. OCTOBER 2005.
- [16] HERTZ, K.D.: *Reinforcement data for fire safety design*. MAGAZINE OF CONCRETE RESEARCH 56, No.8, 453-459. THOMAS TELFORD LTD. OCTOBER 2004.
- [17] EN1992-1-2: *Eurocode 2. Design of concrete structures Part 1.2 Structural fire design*. CEN BRUSSELS. SEPTEMBER 2004.
- [18] ROCCA, N.: *Risposta al fuoco di elementi strutturali superleggeri e in C.A.P.: Modellazione termo-meccanica con il codice di calcolo DIANA*. UNIVERSITÀ DEGLI STUDI DI ROMA, LA SAPIENZA, FACOLTÀ DI INGEGNERIA. 2010. 269 p.
- [19] CARSTENSEN, J.V. GIULIANI, L. HERTZ, K.D.: *Fire Resistance of a Super-Light Deck Element: Finite Element Investigation and Related Modelling Issues*, 2ND FIRE SAFETY DAY, UNIVERSITY OF LUND, LUND, SWEDEN, APRIL 2012.
- [20] HERTZ, K.D.: *Parametric fires for structural design*. FIRE TECHNOLOGY. VOL. 48, No. 4 pp 807-823. SPRINGER SCIENCE, 2012.

Conference Paper /1/

Design of Folded Shaped Structure with the newly Patented Concrete Structure concept: Super-Light Structures

Precented at:

IABSE-IASS Symposium

Taller, Longer Lighter

Meeting growing demand with limited resources

London 2011

Authors:

Niels Andreas Castberg

Kristian Hertz

Design of folded shaped structure with the newly patented concrete structure concept: Super-Light Structures

Andreas CASTBERG

PhD student Techn. Univ. of Denmark, Civ. Engineering, Build. 118, DTU, DK-2800 Kgs. Lyngby, Denmark.

nanc@byg.dtu.dk

Andreas Castberg, born 1982, PhD student, MSc Architectural Engineering in structural building design. Research in design with Super-light Structures, in cooperation with architect firm Bjarke Ingels Group (BIG).



Kristian HERTZ

Professor Techn. Univ. of Denmark, Civ. Engineering, Build. 118, DTU, DK-2800 Kgs. Lyngby, Denmark.

khz@byg.dtu.dk

Kristian Hertz, born 1950, consulting engineer and Professor in structural building design, inventor of super-light structures. Research in fire exposed concrete structures, CAD, and innovative structures.



Summary

The use of folded shapes in structures has become more common, but it still costs problems because of construction issues and bending moments. The present paper deals with how the newly patented structural concept Super-Light structures (SLS) can be used to create folded shapes. SLS gives lighter structures and can lead to simpler erection because of the introduction of prefabricated elements. The paper regards two geometries using the SLS concept and compares their static and structural behaviour. Furthermore, material use is compared to a traditional concrete structure for the examined geometries. For both geometries it is found that they are structurally possible and both of them have a considerable material reduction compared to a traditional concrete structure.

Keywords: *Super-light Structures; folded shapes; concrete; finite element*

1. Introduction

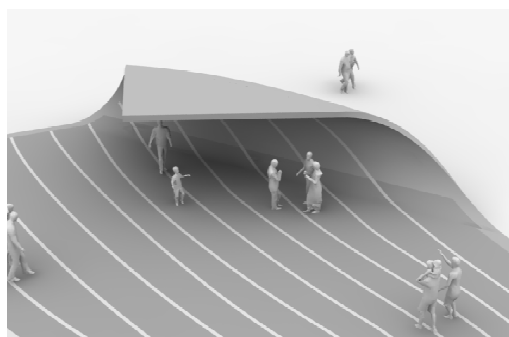


Fig. 1: Illustration BIG

Folded shapes are used increasingly by architects in modern buildings. However, folded shapes are often associated with construction difficulties due to the bending moment the structure is exposed to. Furthermore, the formwork for the curved form can be complicated and expensive. The Super-Light Structure concept allows a much more free development of architecture and can among other things be used for folded structures.

1.1 Super-Light Structures

Super-light Structures is a structural concept where a skeleton of normal to high strength concrete is made and shaped according to force directions and distributions. The skeleton is embedded in a light concrete. The light concrete supports the bones in the skeleton and distributes the forces from outer loads to the skeleton. Furthermore, the light concrete can protect the high strength concrete in fire situations. The concept is patented at The Technical University of Denmark by HERTZ in 2009 [1-5].

The skeleton system is in the patents solved by applying a pearl-chain concept. Here the “pearls” are the skeleton parts which are held together by a prestressing cable. By this method the skeleton can be pre-tensioned together before the light concrete is cast around it. The pearls can be prefabricated in standard elements that can be assembled according to the shape the architect wants to create. The pearl-chains can also be cast into standard elements of light concrete. By placing the strong concrete according to forces, the arch will be reintroduced as a structural element, but now it can be cast as prefabricated segments so that the price can be at a reasonable level.

The Super light concept gives more freedom to architects and gives more optimal structures, while saving materials and CO₂[6].

1.2 The aim of this paper

This paper deals with how SLS can be used as a structural concept for a folded shape. The paper describes how to make a folded shape with different variations of a ribbed structure that will work as variations of the pearl-chain system. The aim is to clarify the stress performance in the highest loaded cross section, to determine the number of cables needed and their impact on the stresses in the cross section. Finally, the paper will present the difference of concrete used for the examined solutions and for a traditional concrete solution. The research for this paper is done at DTU in cooperation with the architect firm Bjarke Ingels Group, BIG. The studied design is based on is from one of BIG’s projects (Super kilen) in Copenhagen.

2. Method

An SLS structure with the outer form as shown in fig. 2 has been analysed using FE software Robot Structural Analysis Professional (ROBOT). The post-tensioned cables have been dimensioned according to Freyssinet [7]. The SLS structure has been designed as a number of ribs in strong concrete with light concrete in between see fig. 3. The rib’s have been designed to carry the formwork without the stabilizing effect of the light concrete. The analysis is limited to cover the rib obtaining the forces from the longest cantilevering. The length of the element is approximately 5 meters from the edge to the midpoint of the arch see fig 2. The ribs are made in a concrete of grade 50.

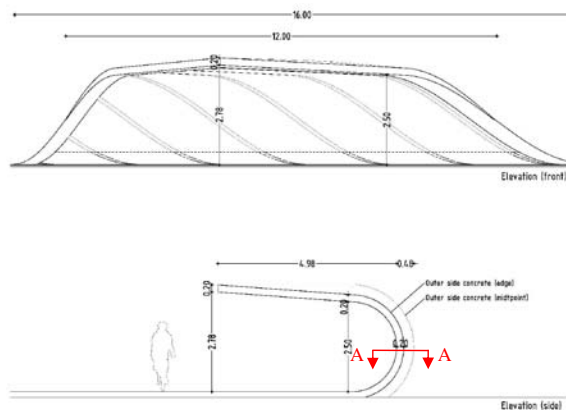


Fig. 2: Elevations of examined shape. Illustration BIG

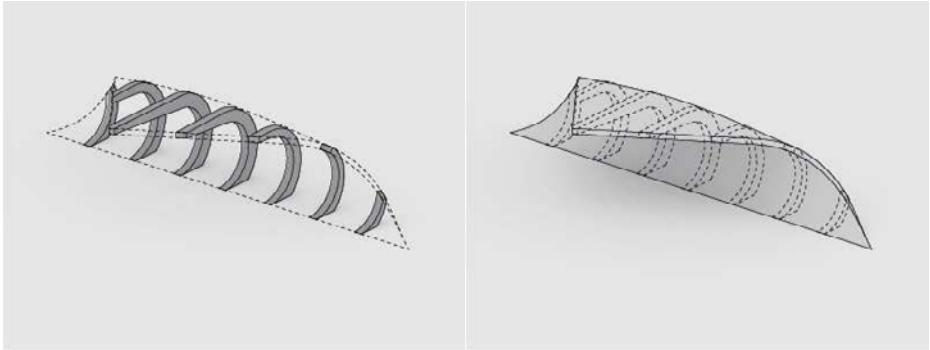


Fig. 3: Rib structure for a fold

2.1 Examined cross sections

A number of different solutions for the investigated rib's cross section have been investigated to fulfill the demands regarding bending. The examined sections are all section A-A (see. fig 2) at the middle of the arch where the largest section forces are found. All the examined ribs are varying from a max height at the middle of the arch to a minimum height at the cantilevered end. Two of the cross sections are chosen based on their buildability and analysed (see fig4).

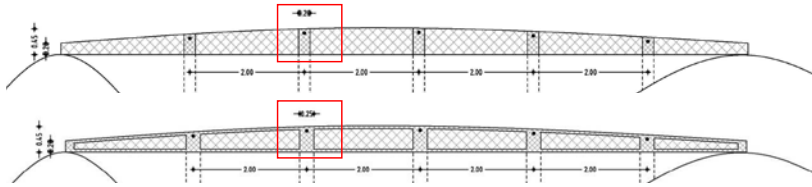


Fig. 4: Cross section variations GeoA and GeoB

In GeoA (see fig 4) the cross section is a simple rectangle reaching from side to side of the outer shape. This section is meant to be produced as a prefabricated element on a casting table with to curved side forms.

In GeoB the cross section is a variation of GeoA. As shown in fig 4 the sections is an H shaped with the “web” dimensioned as GeoA. But the fabrication is based on prefabricating the light concrete parts and casting the strong concrete in situ. By this method compression flanges are added so the total compression zone is larger than for GeoA. Buckling of the flanges has not been considered an issue because of the stabilization effect of the light concrete.

2.2 FEM model

The calculations in ROBOT are linear elastic, and it is assumed that the material stiffness is the same in compression and tension. For the tension zone this will be a valid assumption if post-tension is applied exceeding the calculated tension stress, so the tension zone will actually be in pure compression and hereby obtain the stiffness as in the compression zone. By adding post-tension so that the cross section is in pure compression, cracks are avoided. The materials are modeled as isotopic. The linear calculations correspond to an assumption of small deflections.

The model is based on a 2D section of the entire rib that has been given thickness responding to the different cross sections. The rib has been modeled as a 3-node plane element with thickness of the cross section and a size of maximum 100mm.

The analyzed structure has been exposed by the worst load combination. The load combination consists of dead load, snow, and a live load, which include loads from people jumping on the structure. The load combination is applied to the structure as a uniform load where the horizontal part is exposed to all the loads and the curved part is only exposed to dead load and snow load, see fig 5. A combination without the live load is examined as well because it is relevant to have an understanding of how much influence the live load has on the structure. Wind load is not considered because its influence on the structure is relatively small compared to the other loads.

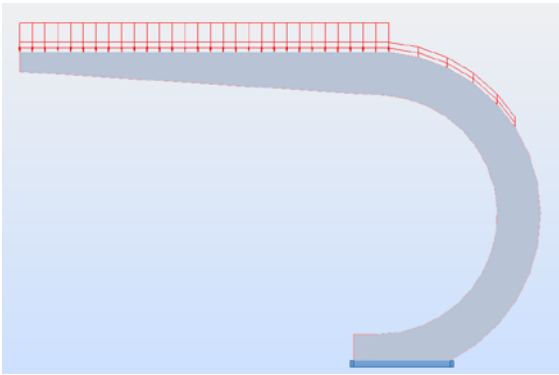


Fig. 5: ROBOT load model

The rib structure is modeled so that it is supported by a fixed support along the horizontal bottom part of the rib.

2.3 Post-tension cables

The post-tension cables are dimensioned according to Freyssinet [7]. Because of the small radius of the arch part of the structure the cables are unbonded to limit the loss caused by friction. The friction losses are calculated cf. Eurocode 2 [8]:

$$\Delta P(x) = P_{\max}(1 - e^{(-\mu(\theta + kx))}) \quad (1)$$

The cables are placed 50 mm from the outer edge of the arch and hereby creates an eccentric force to the section. The cables are utilized to 70% of the tensile strength [7]. They are dimensioned for short term loads without creep.

3. Results

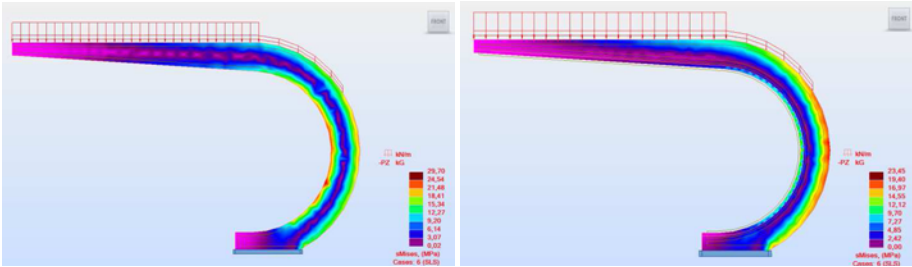


Fig. 6: Overall stress distribution of respectively GeoA and GeoB

3.1 Data from FE-analysis

The results found by the analysis can be seen in Table 1 and 2. Table 1 present stresses for the load combination described. The stresses are for the section A-A (see fig. 2) at the middle of the arch part of the structure see fig 7 and 8. Table 2 presents the stresses for the load combination without the live load.



Fig. 7: Stresses at section A-A GeoA

Table 1: Cross section stresses incl. live load

Geometry	Inner arch stresses (N/mm ²)	Outer arch stresses (N/mm ²)
GeoA	-25,1	21,5
GeoB	-15,8	20,2

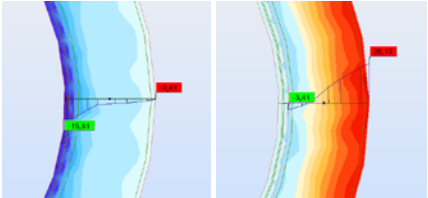


Fig. 8: Stresses at section A-A GeoB

Table 2: Cross section stresses excl. live load

Geometry	Inner arch stresses (N/mm ²)	Outer arch stresses (N/mm ²)
GeoA	-9,11	7,7
GeoB	-7,5	9,5

As seen in fig 7 and 8 the stress distribution varies between GeoA and GeoB. Because of the flange in GeoB the distribution of the compression forces is much more concentrated along the edge of the section. At the same time the compression stress are smaller as seen in Table 1 because of the larger compression zone. From Table 1 it is seen that the post-tension cables have to add more or less the same compression to the outer side of the section to both GeoA and GeoB. The stresses in Table 2 are relevant to observe in relation to the post-tension cables get an understanding of how the stresses are when the structure is not exposed to live load.

3.2 Data from post-tension cable calculations

Based on a placement of the cables 50 mm for the outer side of the arch it has been determined how many cables are needed to prevent the structure from being subjected to tension stresses. By adding 4 D150 cables loaded to 70% of the strength, the stresses presented in Table 3 are achieved.

Table 3: Cross section stresses caused by post-tension cables

Geometry	Inner arch stresses (N/mm ²)	Outer arch stresses (N/mm ²)
GeoA	9,9	-24,7
GeoB	5,4	-25,6

The cables are loaded by the same tension force so the variation in stresses is caused by the different moments of inertia caused by the different cross sections.

3.3 Comparison of results

Table 4: Resolving cross section stresses for full load combination and cables

Geometry	Inner arch stresses (N/mm ²)	Outer arch stresses (N/mm ²)
GeoA	-15,2	-3,2
GeoB	-10,4	-3,2

arch side.

In Table 4 is seen the sum of stresses in the cross section when the stresses for the load and the post-tension cables. From Table 4 it is seen in that in both GeoA and GeoB the same number of cables can fulfill the demand of avoiding tension stresses in the outer side of the arch. Furthermore the result of the different compression zone is seen by the variation in the stresses in the inner

Table 5: Resolving cross section stresses for load combination minus live load and cables

Geometry	Inner arch stresses (N/mm ²)	Outer arch stresses (N/mm ²)
GeoA	0,8	-17
GeoB	-2,1	-5,4

In Table 5 the stresses are shown for the load minus live load and the post-tension load. The result shows that for GeoA is almost not subjected to tension stresses. The small tension that occurs would not cause any cracks because the stresses are so small that it can be obtained by the bending tension strength. For GeoB the cross section is in pure compression.

Table 6: Concrete use

Geometry	Weight of structure (kg)	Material use (%)
GeoA	2002	33
GeoB	3226	54
Traditional	5980	100

One of the reasons for making the SLS concept is to save structural weight and save material. Table 6 presents the concrete weight for the two examined geometries and the weight of the structure if it was made as a traditional reinforced concrete structure. The weight of the traditional structure is set to 100% and GeoA and GeoB are set as a percents' of this.

4. Discussion

It is found that both of the analyzed geometries are feasible based on the FE-analyzes and the cable calculations. Furthermore it is shown that the structure will not be exposed to tension stresses neither with nor without live load.

Statically the two geometries vary in the compression zone which has a quite large impact on the stress distribution at the inner arch side. GeoA has a rectangular cross section which gives an even stress distribution over the section. GeoB has an H cross section where the compression is mainly obtained by the flange. In the ROBOT model the cross section investigated was only a T section disregarding the upper flange. The dimensioning of the cables was based on the same T section. The cables added compression to the entire cross section, which could have changed the stress distribution for GeoB slightly. For inner GeoB the flanges are taken into account based on the assumption that the light concrete stabilizes the flanges so that buckling does not occur. Only a certain length has been taken to account due to the fact that shear lag effect. The inner flange between the webs will still have some influence on the structural behavior. This behavior has not been taken into account.

The constructions of the two examined geometries rely on very different principles. For GeoA the ribs are meant to be prefabricated, connected and cast to the foundation, and used to support the formwork for the light concrete. This principle is efficient to limit formwork and work at the site, but it requires a very precise prefabrication and mounting. GeoB is meant to be cast in a traditional formwork where light concrete element is placed in between reinforcement. This solution is closer to the traditional but it also requires more formwork, and there is a problem in assuring that the self compacting concrete reaches, all parts of the mould.

As stated, the weight of the examined solutions is down to approximately one third of the traditional solution. This design is based on light concrete of 600kg/m^3 . This concrete has a rather porous surface which has proved to sustain the impact of weather well. If a 900kg/m^3 concrete is chosen instead to get a more closed surface, the material and CO_2 saving will still be considerable.

4.1 Future work

The folded cantilevered shape investigated was a shape that can be designed with SLS. It could be interesting as well to see how the stress distributions will vary under different non uniform load cases and different support situations. The examined cases used the pearl-chain concept. Folds that do more than one loop could be considered. These could be produced by means of pearl-chain elements instead of ribs. Besides of folded shapes different solutions using the pearl-chain system for flat elements could be investigated.

5. Conclusion

A folded shaped SLS structure was analyzed for two different skeleton cross sections which were based on two different construction methods. The stresses in post-tensioned cables applied in the cross sections were determined. Furthermore, the amount of concrete used for the two geometries was calculated and compared with that of a traditional concrete structure. From the analyses and calculations the following was found:

- Both GeoA and GeoB are feasible solutions to the structure with the suggested dimensions.
- GeoB has smaller stresses because of the larger compression zone.
- GeoA is easier to construct because of more simple geometry and prefabrication.
- Post-tension cables have to be unbonded because of the radius of the arch.
- GeoA uses about 30% and GeoB uses about 50% concrete compared to a traditional structure.

6. References

- [1] HERTZ K.D., "Super-light concrete with pearl-chains", Magazine of Concrete Research 61, No.8. 655-663. Thomas Telford Ltd. October 2009.
- [2] HERTZ K.D., "Light-Weight Load-Bearing Structures" (Super-light Structures). Application no. EP 07388085.8. European Patent Office, Munich. November 2007. Application no 61/004278 US Patent and Trademark Office. November 2007. PCT (Patent Cooperation Treaty) Application PCT/EP2008/066013, 21. November 2008. Patent January 2010.
- [3] HERTZ K.D., "Light-weight load-bearing structures reinforced by core elements made of segments and a method of casting such structures" (Pearl-Chain Reinforcement). Application no. EP 08160304.5. European Patent Office, Munich. July 2008. Application no 61/080445 US Patent and Trademark Office. July 2008. PCT (Patent Cooperation Treaty) Application PCT/EP2009/052987, 13. March 2009. (Patent pending).
- [4] HERTZ K.D., BAGGER A., "Super-light structures with pearl-chain reinforcement", Spatial Structures – Permanent and Temporary. Shanghai, China, 2010. International Association for Shell and Spatial Structures (IASS).
- [5] BAGGER A., HERTZ K.D., "Structural behaviour of super-light structures", Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010, Shanghai. November 8-12 2010 Shanghai, China.
- [6] HERTZ K.D., BAGGER A., "CO₂ emission from Super-light Structures", Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2011, London. September 20-23 2011 London, England.
- [7] FREYSSINET, "European Technical Approval No. ETA-06/0226", European Organisation for Technical Approvals, valid from 2007.
- [8] EN1992-1-1, "Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings". European committee for standardization, December 2004.

Conference Paper /2/

"The Battery" Designed with Super-Light (con- crete) Decks

Presented at:

IASS-APCS Symposium
From Spatial Structures to Space Structures
Seoul - 2012

Authors:

Niels Andreas Castberg
Kristian Hertz

"The Battery" designed with Super-Light (concrete) Decks

Andreas CASTBERG¹ and Kristian D. HERTZ²

¹ Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, nanc@byg.dtu.dk

² Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark, khz@byg.dtu.dk

Summary

This paper describes how Super-Light structures can be used as a structural principle for the buildings in the project 'The Battery' designed by Bjarke Ingels Group. The overall structural concept is described and the advantages of using super-light slabs for the project are explored. Especially the cantilevered internal corridors are investigated.

Super-Light Structures is a newly patented structural concrete concept. Slabs based on the concept are the first structural element developed under the patent. The slabs called SL-decks have multiple advantages compared to traditional hollow core slabs. The paper aims to describe the concept of how the deck can be used in these innovative buildings and how the special advantages of the SL-decks are applied.

Keywords: *Super-Light Structures, concrete, cantilevered slabs*

1. Introduction

The Battery is a project in central Copenhagen designed by Bjarke Ingels Group (BIG). It consists of 9 mountain shaped buildings with a total floor area of 120.000m². All the buildings have different outer and inner shapes and many are hollowed out by enormous atriums. The mountain shape results in atriums that become narrower towards the top. This shape gives a very complex overall structure that should be able to carry loads to the ground, despite that a large part of the building is not directly supported by a subjacent structure. In addition, the structure should be able to carry pedestrian corridors cantilevered out from every single level towards the atrium. The aim is to use concrete slabs based on the Super-Light Structures (SLS) theory called SL-deck.

Cantilevered pedestrian balconies exist at all levels and SL-deck elements are used to make them as slender as possible. SL-decks can be cantilevered from the load bearing planes with no need for supporting members beneath. Hereby, the cantilevered structural height only has the thickness of the slab.

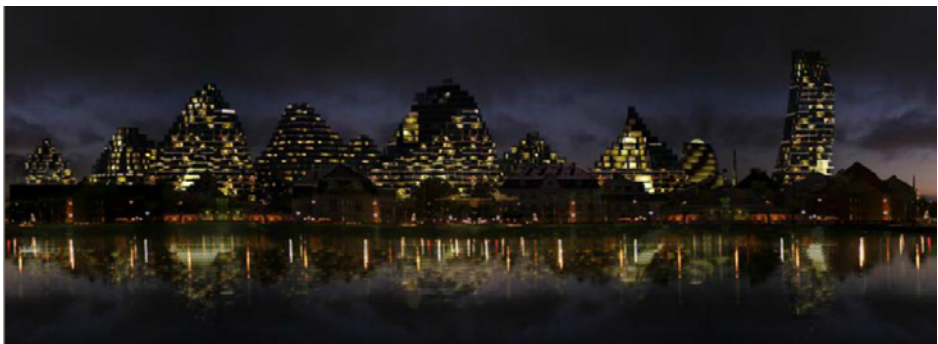


Figure 1: The 'Battery' illustration by BIG

In these types of buildings, it is expected that the Super-light concept will contribute to make the structure more elegant compared to traditional concrete structures.

1.1 Super-Light Structures

SLS is a structural concept patented in 2009 by the Technical University of Denmark (DTU). The rationale behind SLS is to build a skeleton of medium-to-high strength concrete to obtain the forces, place it according to the force distribution and stabilise and protect it by lightweight concrete. SLS offers an up to 50% lighter structure compared to traditional concrete structures [1-3].

Two fundamental patents are obtained; one for the general theory upon which the SL-slabs are developed, and a second patent describing the Pearl-chain system that is a concept for producing and placing the strong concrete parts in a skeleton structure [2,3].

The general idea of placing the strong material and stabilising it with a lighter concrete has resulted in the SL-decks. The bottom of the SL-deck consists of lightweight concrete shaped as multiple blocks. On top of these normal-to-high strength concrete is cast, constituting a system of small domes and crossing ribs with pressed cables. Hereby, the strong concrete gets the shape of a waffle structure that can be very thin on the top of the domes because of the light concrete stabilising it [2].

The skeleton system is in the patents solved by applying a pearl chain concept. Here the “pearls” are the skeleton parts held together by a prestressed cable. By applying this method, the skeleton can be assembled by posttensioning and the light concrete subsequently cast around it. The pearls can be prefabricated as standard elements that can be assembled according to the shape of the architect’s choice. The pearl chains can also be cast into standard elements of light concrete. By placing the strong concrete according to forces, the arch will be reintroduced as a structural element, this time being cast as prefabricated cost-friendly segments avoiding the costly curved outer and inner moulds [3-6].

The Super-Light concept allows more freedom to architects and offers more optimal structures, whilst saving materials and CO₂ [7].

1.2 The Aim of this Paper

This paper explains how SL-decks can be used as a concept for the ‘Battery’ project and describes the general structural concept. The paper describes concepts in three structural levels:

- The overall stabilising structural concept for the building
- A concept for the connections between walls and cantilevered slabs
- A concept for the slab structure and slabs with an integrated beam

The aim of the paper is to show how the advanced structural challenges of the Battery can be solved using SL-decks. Furthermore, the paper will suggest options for customising SL-decks to contain a beam across the element in the slab structure to allow cantilevering. The research for this paper is undertaken at DTU in cooperation with the architect firm Bjarke Ingels Group, BIG.

2. Structural Concepts

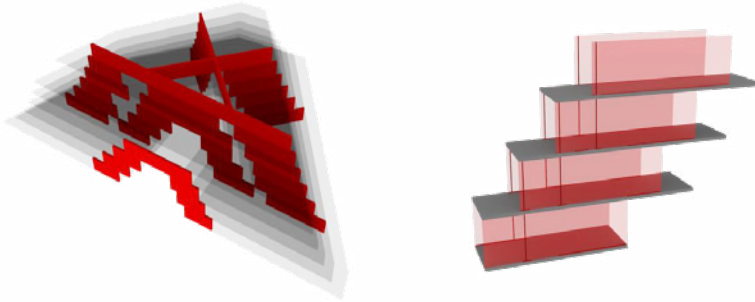


Figure 2+3: Overall structural system and Tension bars stabilising the cantilevering.

The structure is divided into an overall stabilising system, a secondary system bringing the loads to the foundation, and finally, a description of the slabs and how they are cantilevered.

2.1 Primary Structural Concept

The main structural system will consist of aligned walls to create bearing planes from the top of the atrium to the ground. Due to the different inner and outer shapes, the elements in the bearing planes will all be cantilevered from level to level, narrowing inwards towards the top of the building. This allows an overall arch-shaped resulting force distribution.

The stabilising system consists of a number of thick walls displaced at each level to have an overall expression as a stair. Within this 'stair wall', the forces are distributed to create a half-arch. The 'stair walls' are connected at the level that forms the ceiling of the atrium. Hereby, the structure takes the form of multiple half-arches leaning toward each other, thereby creating a stable structure. This concept allows avoiding the use of columns in the atrium and provides a stable base for the upper part of the house above the arch connection point. The top of the house can be made by a simple wall and plate structure.

As described, each level of the walls is cantilevered from the underlying level. To obtain this, a set of stabilising tension bars connects the walls in their non-cantilevered ends, each bar connecting to the wall below (*Figure 2*). This stabilisation is primarily needed until all the walls are combined to form an arch. Thus the above described overall stability is first obtained once the full arch is built.



Figure 4: Illustration by BIG

2.2 Secondary Structural Concept

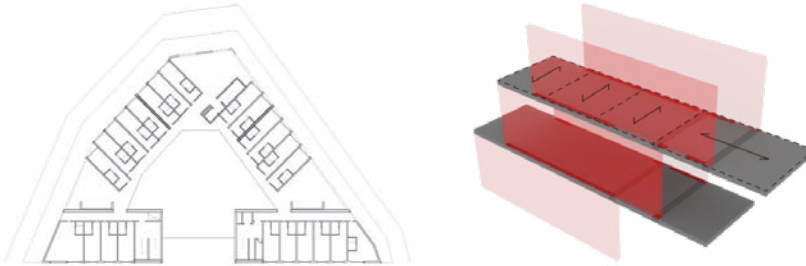


Figure 5+6: Plan + Illustration of directions of span.

The walls *not* working as part of the stabilising system have their primary function in carrying the vertical forces to the ground. The walls are connected with tension bars in the same way as in the stabilising system, but the walls are thinner (Figure 5+6: Plan + Illustration of direction).

The building described is designed for student accommodation. Therefore, the walls are relatively close in the particular building. Most slab elements span between the walls because of the short distance in this direction. However, in the area with no walls beneath the slabs, the span direction is turned. A part of the slab creates a beam spanning from wall to wall (Figure 5+6: Plan + Illustration of direction). By turning the span direction of the slab and incorporating a beam, the balcony is solved as a cantilevered slab. In this case a single slab will span between the walls perpendicular to the direction of the factory made prestressed wires in the slab. Hereby, the solid end of the slab also functions as a beam between the walls as a second support line. This solution is possible as SL-decks allow prestress elements in two directions. The direction of the factory made prestressed wires is chosen to carry the loads from the cantilevered part and the 'beam' supports the slab at the midpoint in the transverse direction.

In cases with longer distances between the walls, slabs can be joined at the construction site by posttensioned connection of the transversal beam prior to lifting them in place. The slabs are joined by adding a posttension bar and tighten the slabs together. The non-cantilevered end of the slab is supported by the slab spanning from wall to wall by the connection described in section 2.4. The suggested solution allows both the option of one and of multiple joined cantilevered slabs



Figure 7: Illustration of atrium by BIG

depending on the span between the supporting walls.

2.3 SL-deck

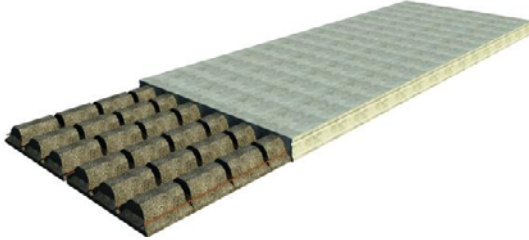


Figure 8: SL-deck illustration by Abeo.

As described in the introduction, the SL-deck consists of two types of concrete, a light aggregate concrete (600kg/m³) and a normal 55MPa concrete (2300kg/m³), respectively. The shape of the light concrete is shown on *Figure 8+9*. The design results in many small arches in the transversal direction of the slab. At the same time, it allows reinforcement in the transversal direction to obtain the outward forces caused by the arches. In the longitudinal directions, pretension wires are placed between the arches. This design offers a slab reinforced in both directions. It is possible to place corrugated tubes in the transversal direction so slabs can be posttensioned transversally. The ends of the slabs are of massive strong concrete, i.e. it is areas of the strong concrete that rest at the supports.

The strong concrete is cast as a plastic mass that makes it easy to cast around moulds for recesses for installations or other specially required shapes. Furthermore, it is possible to fix the slab ends or make the connection continue over a beam. This makes very long spans an option as opposed to traditional simple supported hollow slabs. Furthermore, the combination of light concrete in the bottom and the arch shape gives a very good acoustic performance and a high fire resistance. The flexibility, easily allowing non-regular cuts, and all the other performance advantages are some of the reasons why SL-decks were chosen for the Battery project. Hence, the overall shape of the buildings requires a lot of special elements.

2.4 Cantilevering SL-decks

One of the SL-deck's advantages is that it can be cantilevered with no need of extra structural height or extra beams beneath the cantilevered part. It can be cantilevered in different ways:

- 1) The slab can be placed across a bearing line and project out into the open.
- 2) The bearing line can be a part of the slab by incorporating an internal beam.
- 3) Two slabs can be joined over a bearing line by reinforcement but only as an ordinary reinforcement.

In this case option 2) is chosen as it offers the cantilevering to be handled with the slab without the need of adding extra elements.

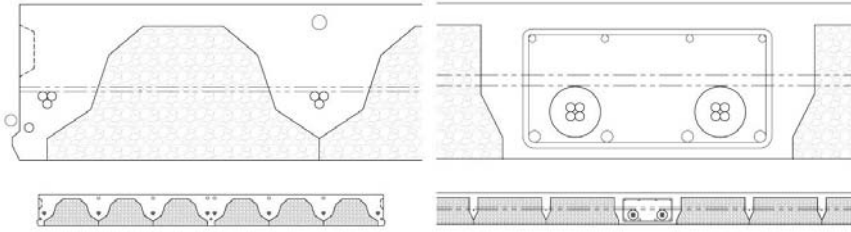


Figure 9+10: Transversal section in SL-deck + Longitudinal section in SL-deck with beam.

The SL-deck is customised to contain a beam by adding extra distance between two rows of lightweight concrete blocks. Hereby, reinforcement for a beam can be placed in the void (Figure 9+10: Transversal section in SL-deck + Longitudinal section in SL-deck with beam). The beam can either be made by ordinary reinforcement or corrugated tubes can be placed for posttension cables or bars. The choice depends on loads and whether more slabs need to be connected. When the deck is cast with the top layer of strong concrete, the beams are integrated in the structure.

As described, the non-cantilevered end of the slab is connected to the crossing slab that it is joined to. The connection is done with overlap but level free. (Figure 11) The connection can be fixed which makes it possible to transfer moment forces. The connection can both be made at ends and on the sides of a slab. In cases where more than one slab is needed between the walls, the connection will support the non-cantilevered end of the slab. Hereby, the slabs will be supported in the same points as if only one slab were placed between the walls.

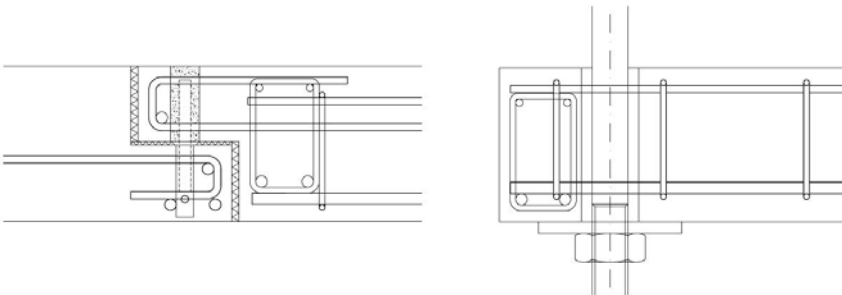


Figure 11+12: Level free connections of SL-deck + Hung connections of SL-deck, Ill. Jakob E. Christensen.

The deck is hung from the walls in the beam part. The solution to hang a SL-deck in a point in the strong concrete is known from another project currently under construction. The solution can be seen at Figure 11+12: Level free connections of SL-deck + Hung connections of SL-deck, Ill. Jakob E. Christensen. Here the slab hung in the solid part at the end of the slab in one point only, but the principle remains the same. In the Battery, instead of one bar, the connection will be made by a number of bolts to distribute the stresses and offer more uniform support to the beam. The connection is possible as the casting of the slab allows adding extra reinforcement in certain areas as previously described.

3. Conclusion

The structural concept for a case building in the Battery project and the application of the SL-deck has been presented. With respect to the overall structure, there may be a possibility for an optimisation of walls with the pearl-chain system, but the presented solution is buildable and further optimisation will require further analyses of how the walls are loaded in uneven load cases. The SL-deck solution is durable, and another project, currently under construction, use details similar to some of the customisations suggested in this paper. The internal beam solution is possible for the spans in the Battery Project and will also be available for connection of slabs with posttensioning, however, the loads on the balcony are large and will constitute the limiting factor for the span.

The paper describes how cost-effective SL-decks offer a more elegant and flexible solution of key problems in the buildings of the Battery compared to solutions using traditional slabs and beams.

4. References

- [1] Hertz K.D., "Super-light concrete with pearl-chains", *Magazine of Concrete Research* 61, No.8. 655-663. Thomas Telford Ltd. October 2009.
- [2] Hertz K.D., "Light-Weight Load-Bearing Structures" (Super-light Structures). Application no. EP 07388085.8. European Patent Office, Munich. November 2007. Application no 61/004278 US Patent and Trademark Office. November 2007. PCT (Patent Cooperation Treaty) Application PCT/EP2008/066013, 21. November 2008. Patent January 2010.
- [3] Hertz K.D., "Light-weight load-bearing structures reinforced by core elements made of segments and a method of casting such structures" (Pearl-Chain Reinforcement). Application no. EP 08160304.5. European Patent Office, Munich. July 2008. Application no 61/080445 US Patent and Trademark Office. July 2008. PCT (Patent Cooperation Treaty) Application PCT/EP2009/052987, 13. March 2009. (Patent pending).
- [4] Hertz K.D., Bagger A., "Super-light structures with pearl-chain reinforcement", *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010, Shanghai*. November 8-12 2010 Shanghai, China.
- [5] Bagger A., Hertz K.D., "Structural behaviour of super-light structures", *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2010, Shanghai*. November 8-12 2010 Shanghai, China.
- [6] Castberg N.A., Hertz K.D., "Design of folded shaped structure with the newly patented concrete structure concept: Super-Light Structures", *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2011, London*. September 20-23 2011 London, England.
- [7] Hertz K.D., Bagger A., "CO₂ emission from Super-light Structures", *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2011, London*. September 20-23 2011 London, England.