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

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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 120.000m^2. 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 CO_2 [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

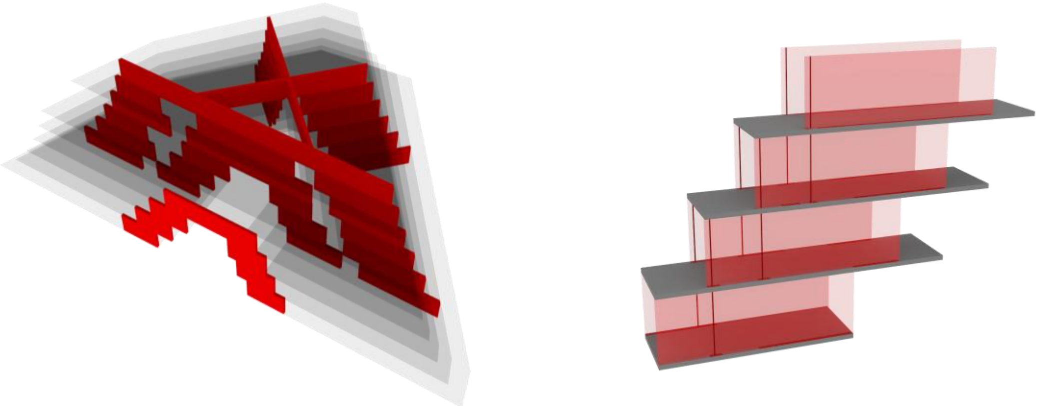


Figure 2+3: Overall structural system and Tension bars stabilising the cantilevering.

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

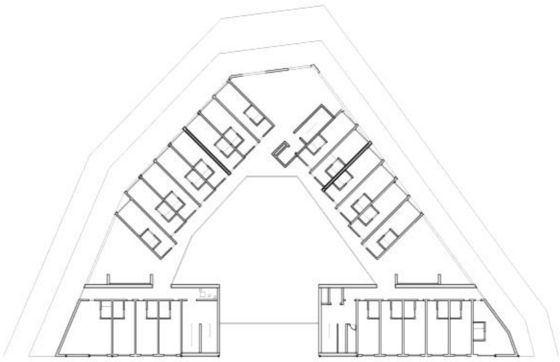
The main structural system will consist of aligned walls to create bearing planes from the top of the atrium to the ground. Due to the different inner and outer shapes, the elements in the bearing planes will all be cantilevered from level to level, narrowing inwards towards the top of the building. 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



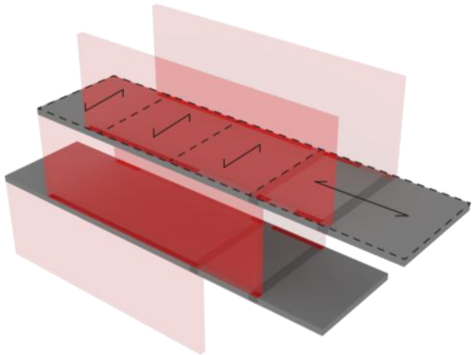


Figure 5+6: Plan + Illustration of directions of span.

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 prestessed 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 slap 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

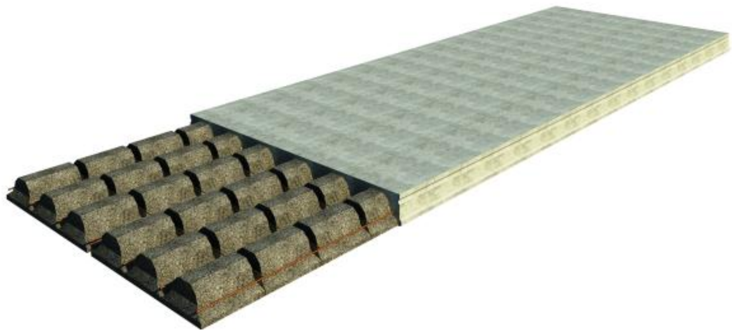


Figure 8: SL-deck illustration by Abeo.

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.

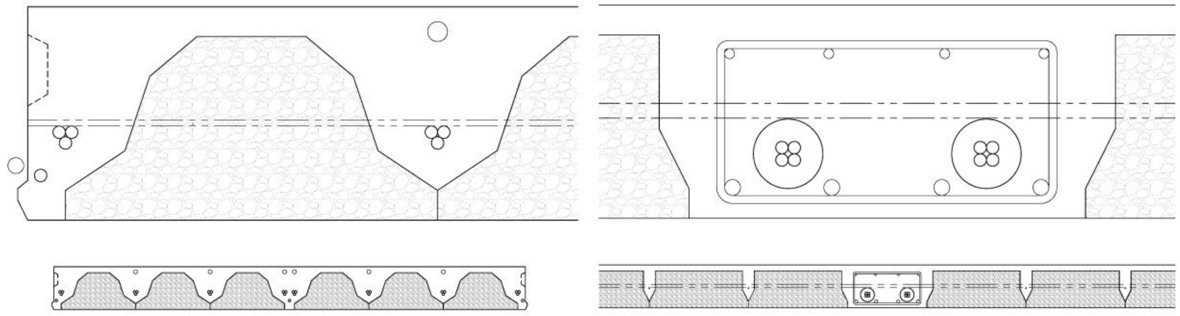


Figure 9+10: Transversal section in SL-deck + Longitudinal section in SL-deck with beam.

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.

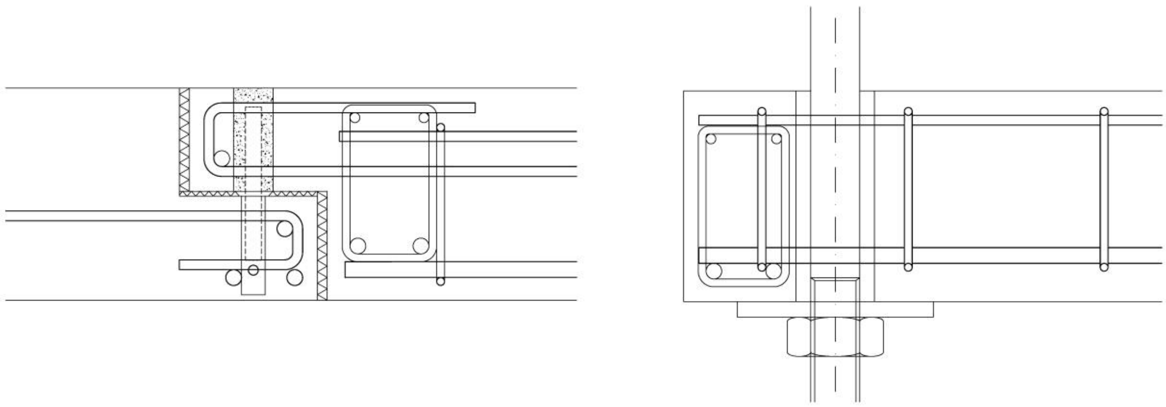


Figure 11+12: Level free connections of SL-deck + Hung connections of SL-deck, Ill. Jakob E. Christensen.

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.

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