STRUCTURE AS ARCHITECTURE

architecture through and by load-bearing structure

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Supervisor: Jens Olsson

CHALMERS

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ABSTRACT

Today, a lot of people see a building’s architectural expression and load-bearing structure as divorced from one another, the latter often hidden away from view. However, this thesis project, Structure as Architecture, makes the claim that this is often to the detriment of the building’s architectural expression and that load-bearing structure is, or at least can be, architecture in and of itself.

Thus, the aim is to showcase this by designing a building with a load-bearing structure that also makes up its architectural expression. Specifically, one where the two elements are so deeply integrated that one cannot be meaningfully removed from the other. In this project, this is called structure as architecture design.

Two designers that have worked in this tradition are Frei Otto and Philippe Block. Frei Otto designed materially efficient and dynamic structures with spatially defining forms. Philippe Block is in some ways the modern way equivalent, working with pure compression masonry structures. It is within this discourse that the project operates.

It was near Frihamnen, Gothenburg, that the opportunity for a building to explore structure as architecture was identified. There, an urban consolidation center would be established, to accommodate the city’s densifying and expansion into Hisingen.

A structure as architecture design was achieved by designing a vaulted building with an anti-funicular form. Not only do anti-funicular forms fulfill the criteria of load-bearing structure and architectural expression being indivisible, but buildings with anti-funicular forms are also typically perceived to be very light and ‘natural’ in appearance, as well as materially efficient. The vault’s structural material was brick masonry, with the bricks carefully arranged to direct the forces in a suitable pattern.

The chosen design method of the project was an iterative process of model-building. Concept models were simple and physical, typically composed of stiffened chains of paperclips. To achieve the necessary level of precision and shell behavior, however, the final model was made digitally.

Key words: structure, vault, brick, models

PREFACE

This booklet has been made as a supplementary work to a design project, a master's thesis project of the MSc. Program "Architecture and Urban Design" at Chalmers University of Technology. The work has been carried out primarily in the spring of 2019, at the Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden. PhD student Jens Olsson served as the supervisor. Professor Morten Lund of Chalmers University of Technology served as the examiner.

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Dennis Wiklund

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For their support throughout this project, there are some people that I would like to extend my thanks to. To start, for the help, technical instructions, and guidance that he provided, I extend my deepest gratitude to my supervisor, Jens Olsson. The discussions and feedback he provided were instrumental to the realization of this project. Also, special mentions go to Project Assistant Emil Adiels, for his advice on the handling of brick material; Ivan Sanchez-Diaz, for his personal interview on logistics; and to Anna Starck, for the information she provided on future Frihamnen. Finally, I am grateful to all others that have offered their time and support, my examiner, Professor Morten Lund, and last, but not least, my family and friends, whom I can't thank enough.

Thanks for all your help and encouragement!

Dennis Wiklund

CONTENT

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BSc – Architecture and Civil Engineering, Chalmers University	**2013 – 2016**
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INTRODUCTION

Background

For a large part of history, going so far back as Vitruvius' Ten Books of Architecture or even the works of Imhotep, the role of architect and engineer was inhabited by the same actor, the master builder. They would serve as the cornerstone of their given building project, being responsible for both the design and construction. However, as history moved on, building projects became increasingly complex and larger in scale. In addition, new technologies were introduced to the building process. Thus, by the time of the nineteenth century, the master builder could no longer maintain their expertise in all their assigned areas and specialization of labor became a necessity. From this fragmentation emerged the modern roles of architect and civil engineer.

From this point on, the two professions and their fields have further diverged from one another. Today, architecture and civil engineering have become related but separate fields. In one way, this specialization has been necessary to meet the challenges thrust upon society by the rapid industrialization and urbanization of the last few centuries. However, some aspects of building design have not kept up.

It could be argued that this separation of architecture and engineering is detrimental to the building process in several ways. For example, it usually provides a less holistic building and more material than needed, as the two professions do not always work synchronously. This project concerns itself with bridging the separation between these two professions.

Illustration 1: Architectural discourse from the illustrated *French Dictionary of Architecture* (1856) by Eugène Viollet-le-Duc.

Purpose

Another consequence of the separation of the roles of architect and civil engineer is that the perception of architecture and civil engineering as separate has emerged, even though, as previously established, this separation is not universal or necessarily desirable. This results in, for example, the common expectation of a building's architectural expression and load-bearing structure as detached from one each other, the latter often purposely obscured. However, this thesis project makes the claim that this separation is often to the detriment of the building's architectural expression as a whole and that the load-bearing structure is, or at least can be, architecture in and of itself.

It is the aim of this project to argue for the virtues of unifying the load-bearing structure and architectural expression in a building project, as well as to serve as a critique of the binary view of structural engineering and architectural design as inherently separate. To do this, a building that exemplifies structure as architecture is to be designed.

Main questions and objectives

The focus of this project is to explore the synthesis of architectural expression and load bearing structure in building design through the design of a building. Some examples of questions to be explored are:

- How can the structural system and architectural expression of a building interplay in a way that that improves the quality of both?
- Why mix the structural system with the architectural expression?
- In what ways can the structural system and architectural expression interplay?
- How do you judge the quality of the two?

Important to note is that project's emphasis lies in the design, both the structural and spatial, and less the building's relation with its function.

The main objective for the structure of the building design is to be 'effective', meaning that the structural elements should help define the building's architectural expression and, in turn, that architectural features should assist its structural integrity. As a part of this, the building's structure should have a clear and appreciable level of materiality, but should also feel light in character, and be effective in its use of material. The project is to be designed through an iterative process of model making.

Delimitations

There are several delimitations put on this project. To start, the structural investigation is not the focus and is mostly limited to approximations. Some analysis of the structural viability should be made, however. For instance, the widths of the spans are to be established as feasible. In addition, the compression and tension in the structure should be shown. The time-plan and construction process are also not developed to a significant degree in this project. Costs are also to be kept to relatively feasible levels but are at the same time not one of the main determining factors in the design evaluation. However, measures should be taken to establish the economic feasibility of the project. Finally, the establishment of a design program and site is not of paramount interest to this project, beyond its feasibility. Therefore, the project adopted a site and program developed by Gothenburg SBK (*Stadsbyggnadskontor*), see the 'Program list' sub-chapter.

Theory

The theory is the material found inside the project's discourse used to answer the question as to 'why?' and to provide understanding. The discourse, for the purposes of this thesis project, refers to the substance and area of study of the project. One could think of it as the intellectual landscape that is to be explored. In this project, the discourse is in building design wherein architecture overlaps with structural engineering.

The literature studied focused on that which inform the methods by which to design buildings that integrate the structure with the architecture. In particular, books or other materials that illustrate how past projects that have achieved the goal of using the load-bearing structure as architecture, or how designers that have worked with that interplay, have succeeded. This includes nature, as principles found in nature that are both functional and visually pleasing have, in a sense, been proven to work, as nature does not do things arbitrarily. Otherwise, special attention was paid to literature which describes the design process of chosen references and their designers. Some examples of literature that has served as research for the project include the following:

- *Frei Otto – a life of research, construction and inspiration* by Irene Meissner and Eberhard Möller
- *Beyond Bending – Reimagining Compression Shells* by Block Research Group (Philippe Block, Tom Van Mele, etc.)
- *Shigeru Ban* by Matilda McQuaid
- *Frei Otto MULTIHALLE* by Georg Vrachliotis

The literature aided in the process of finding inspiration for both the aesthetics and model building methods in the project.

References include past projects that have used their load-bearing structures to be the same as, or at least incorporated in, their architectural expression. Some architects that worked with this sort of design include Oscar Niemeyer, Frei Otto, and Phillipe Block. Especially the latter two have served as inspirations for this project. Some specific references and sources of inspiration are Frei Otto's German Pavilion Expo, Phillipe Block's Armadillo Vault, and the roof of Tiffany's and CO's building, designed by Rafael Guastavino, etc. They have helped forming the design aspects of areas such as the roofing, the supports, the walls, the handling of the light in the building, and more. For example, the spans in Tiffany's and CO's building helped determine the limiting width of the spans in this project.

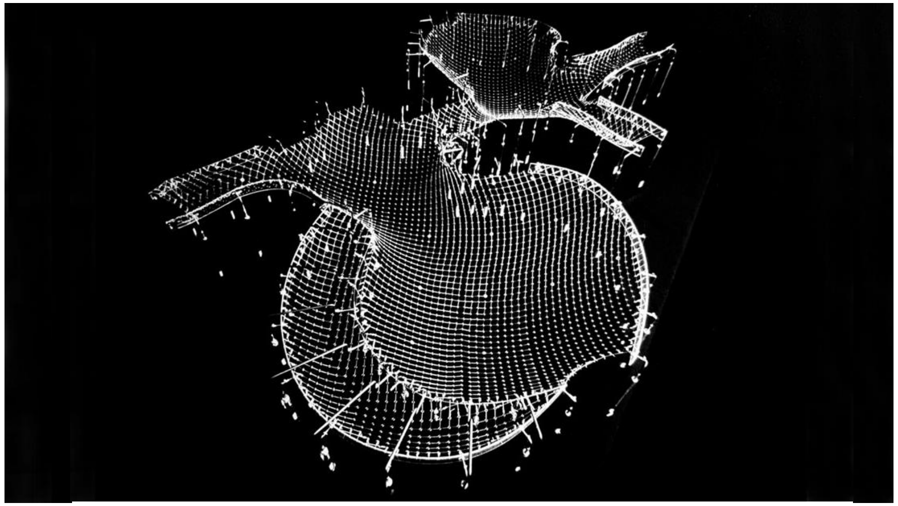


Illustration 2: A chain model of Frei Otto's Mannheim Multihalle, an example of structure as architecture design. (Multihalle Mannheim, 2015).

CONTEXT

Site – Ringön, Gothenburg

In Hisingen, Gothenburg, an opportunity for a structure as architecture designed building was identified. With the city densifying and expanding across the river, the area of Frihamnen will undergo a major expansion in the future. Many more residencies, commercial stores, and offices will be built. As a result, a whole new logistics network will have to be set-up, including an urban consolidation center (UCC) called Älvstadsleveransen. The UCC will be located on the border between Frihamnen and Ringön, against the river. That means that it will occupy prime real estate land that could otherwise have been filled by a potentially high-income residential or office buildings. It will also form a part of Gothenburg's new skyline and be easily visible from the new 'Bridge of Hisingen' (Hisingsbron) bridge. So, it doesn't do for the UCC to be just another anonymous logistics building. This project argues that it will have to visually justify its position's prominent display, a role structure as architecture design could fulfill.

Building function

The building is designed to serve as a UCC for goods and waste in Frihamnen, Gothenburg. A UCC is, for the purposes of this project, a sort of logistics building where trucks carrying goods to be delivered to the Frihamnen area drop of said cargo to be shipped the final distance into Frihamnen on smaller electric vehicles. On their way back, the smaller vehicles also bring waste from Frihamnen to the UCC, from where it will be shipped to a nearby waste treatment center by barge. This logistics flow is to reduce the amount of noise, traffic congestion, and air pollution in the area. In addition, the UCC is to become a community meeting place by providing a useful service. Specifically, a delivery pick-up station. As internet shopping becomes more and more common, such places will also rise in importance.

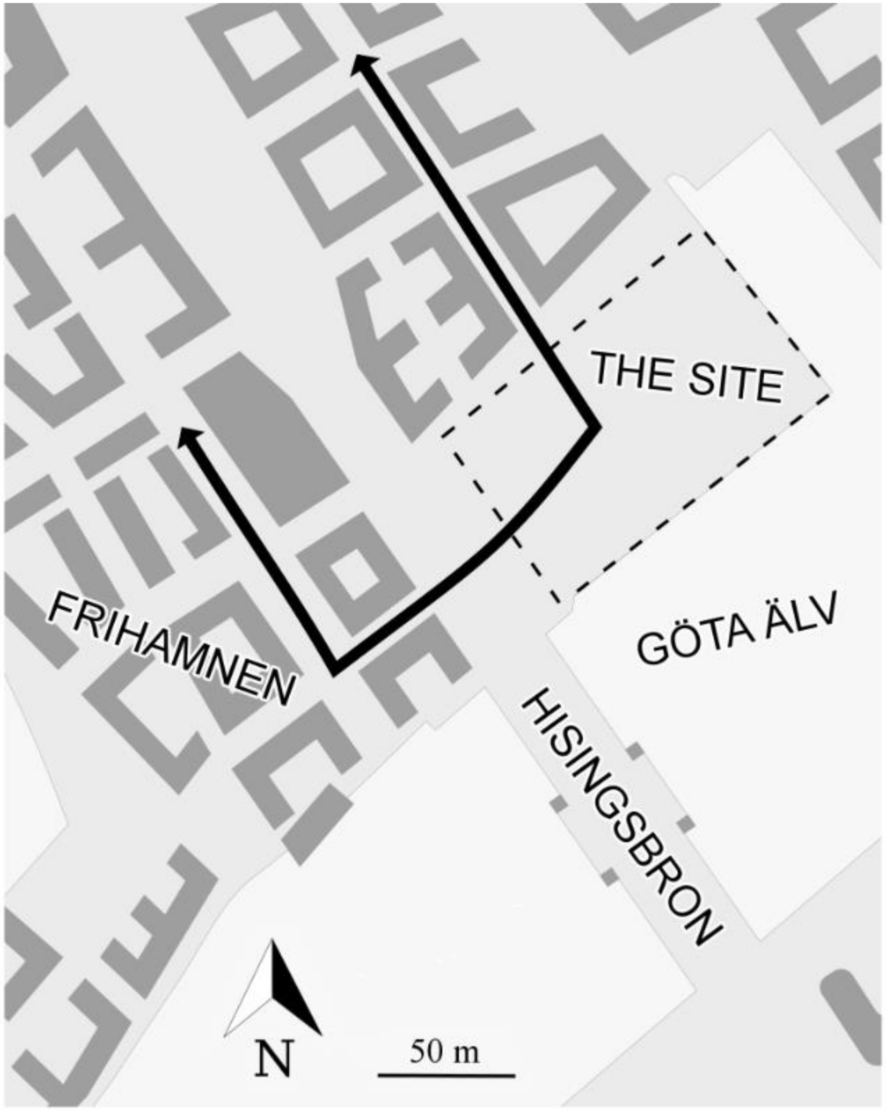


Illustration 3: A map of the site's surrounding area.

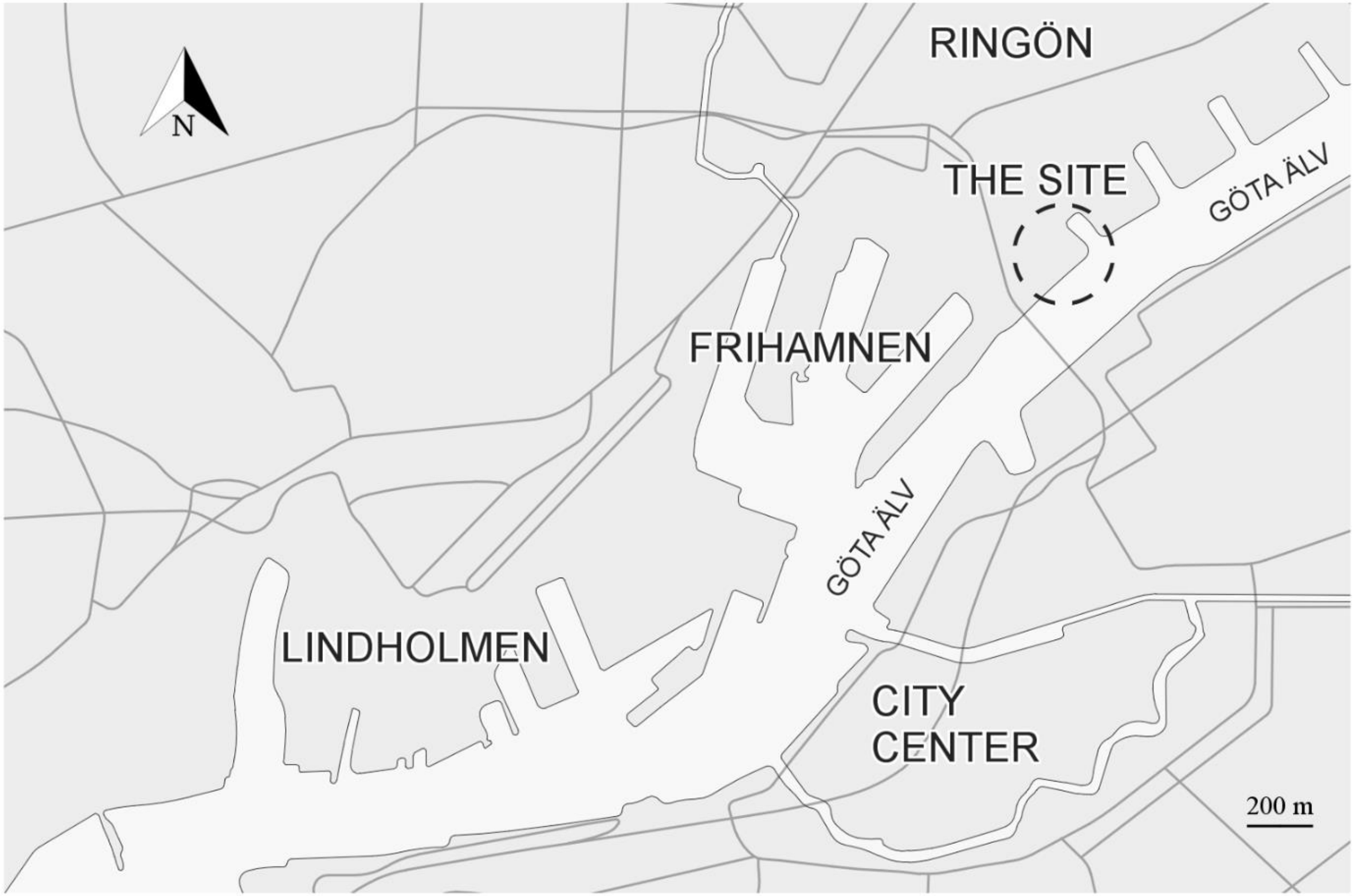


Illustration 4: A map of the site in the context of Gothenburg.

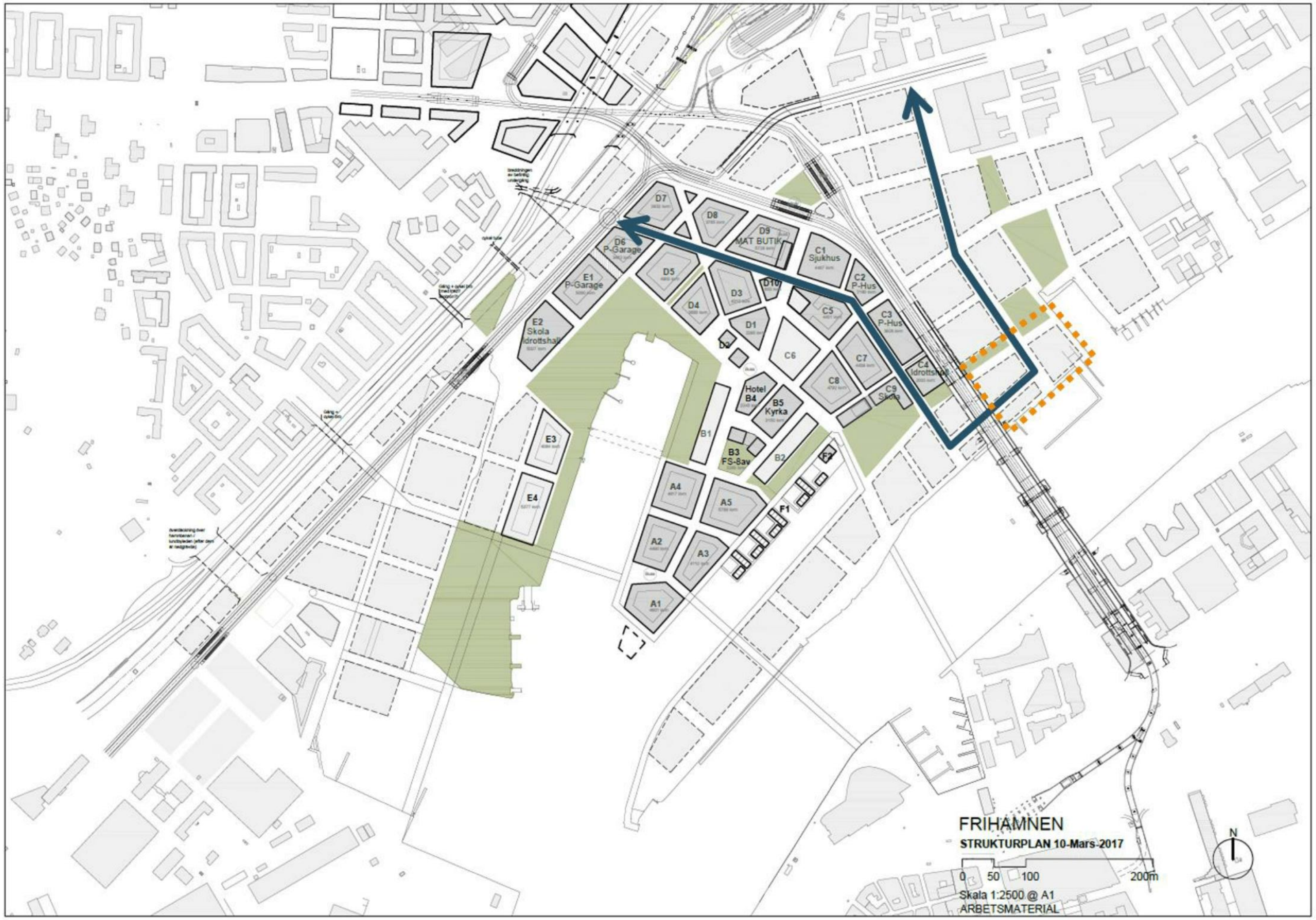


Illustration 5: Map of the Frihamnen and surrounding areas. The site designated for the UCC is inside the dotted orange line. The blue arrows show the direction of the trucks heading to and from the UCC (Program för Frihamnen, 2014).

Urban context

The site of the building is Ringön, Gothenburg, along the northern side of the Göra älv river and east of the road connected to the future Hisingsbron. At present, it is an industrial area, full of old workshops and storages as well as more recently built offices and shops. Most of the older buildings have brick facades. However, the site will be transformed as part of the RiverCity Gothenburg urban development project.

The precise plans have not yet been determined, but proposals have been made of placing 6-14 floor buildings to the west of the site, against the new bridge, and 6-8 floor buildings immediately around the site. In addition, there will be a green corridor going from Frihamnen into the area, just north of the site. On the other side of the road, in Frihamnen, plans have been made (see Illustration 6) of placing city buildings such as parking houses, a sports hall, a school, and a hospital. Further yet into Frihamnen, dense residential housing will be found. With this transformation, new demands emerge, including the transportation of goods and waste in and out of the area. This necessitates the presence of an urban consolidation center in Ringön.

The UCC is located on the border between Frihamnen, the main area for which it is to serve, and Ringön. It is directly connected to Frihamnen by both road and walkway and is easily visible from all approaches. Also, it is situated next to the Hisingsbron bridge, from which it would be visually prominent. It is easily visible from the southern shore of the Göta älv river as well, forming an integral part of the new skyline of Gothenburg. The UCC is enclosed by buildings to its north and south while outlined by waterfronts to the east and south.

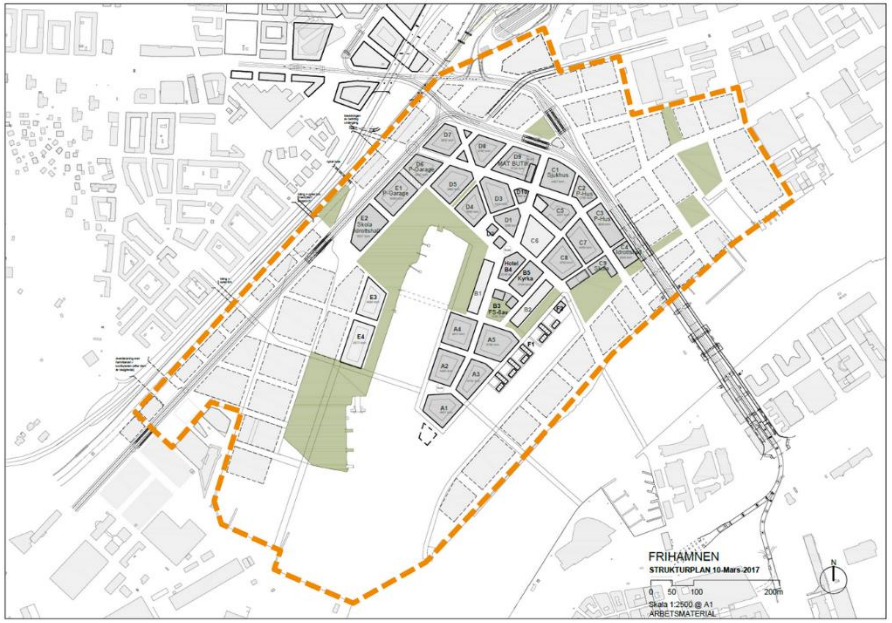


Illustration 6: The area of Frihamnen (Program för Frihamnen, 2014).

Trucks carrying goods into Frihamnen enter from the road in the north-western direction and passes through to the road going south-west, underneath the new Hisingsbron bridge, which will connect the UCC to the city infrastructure. This route will be used for transport to and from the UCC and has to be considered.

Illustration 7: A view of the site, in the context of Göta Älv and Hisingsbron.

Illustration 8: Map of Frihamnen and the surrounding area, with the UCC in red and roughly the area that it is to serve in grey.

Illustration 9: A bird's eye view of the UCC building, as well as the new urban context, from it to the end of Frihamnen.

Illustration 10: The new skyline of Gothenburg, with the Hisingsbron bridge and the UCC building, as seen from the southern side of the Göte Älv river, looking north.

Program list

The program is the list of required items and design goals for the project, specifically those that pertains to the UCC function of the building. It does not, however, include the structure as architecture design goals, as the building is only the narrative example by which to demonstrate them. The program can be split in lists between the required area spaces and the needed capacities. The required areas look as follows:

- Area
    - Footprint
        ca. 4000 m^2 in total
    - Space for 10 containers
        ca. 760 m^2 (ca. 19 x 40 m per container)
    - Space for 12-meter trucks to enter, unload, turn, and leave
        ca. 21.5 x 21.5 meters space
    - Vertical space for the trucks' lifting mechanism
        ca. 8 meters height
    - Space for the storage of goods
        About 510 m^2 area
    - Space for charging stations for the electric vehicles
        ca. 20 m^2

Conversely, the list of additional capacities looks thusly:

- Capacities
    - Possibility for 24-meter trucks to be able to deliver and pick up goods and waste somewhere at the UCC
    - Possibility of loading and unloading goods by river barge

The program was developed by SBK, Gothenburg's City Planning Office, (Program för Frihamnen, 2014) and adopted by this project.

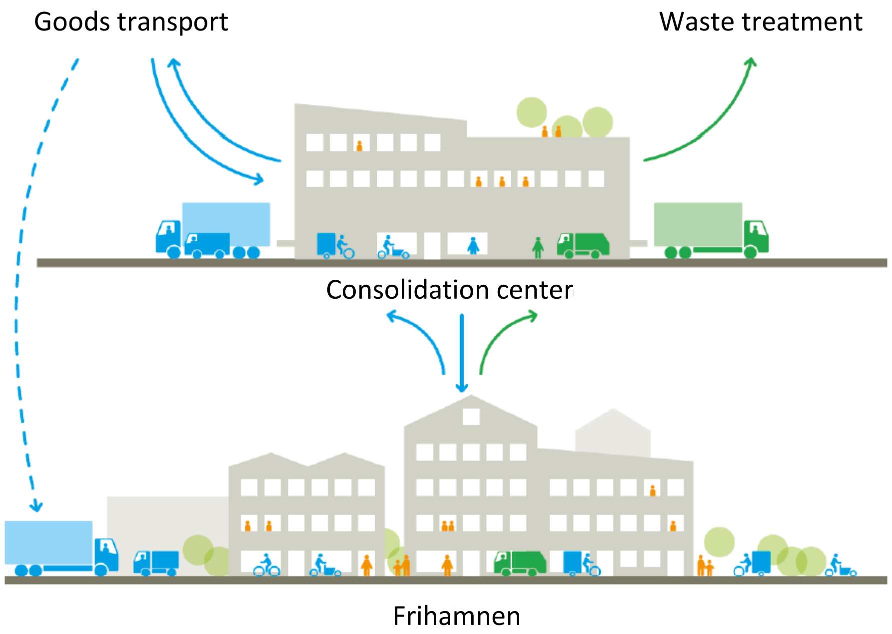


Illustration 11: The relationship between the UCC and Frihamnen (Program för Frihamnen, 2014).

Logistics

The common delivery process of small goods involves suppliers, typically logistics companies, forwarding their own carriers to make individual deliveries from their storages outside dense urban areas to the receivers, like retail shops, in or near the city center. These shipments are a major source of congestion, noise, and air pollution in many cities. This is also how a lot of logistics in Gothenburg function. There have been many attempts to solve the issue. One such solution is a UCC. (Sanchez-Diaz, 2019)

UCCs are 'operational concepts that reduce freight traffic circulating within a target area by fostering consolidation of cargo at a terminal' (Initiative 35, 2019). They were developed once time, and not space or weight, became the primary factor of limitation in logistics. With a UCC, instead of all the delivery trucks from the logistics companies driving all the way to the receivers, the trucks would deliver their goods to the UCC, from where either the receivers would pick up their deliveries or from whence the last stretch of distance is made by smaller electric vehicles that are quieter, cleaner, and take up less space than typical delivery trucks. Thus, UCCs are typically located in or near the fringes of city centers. One example of a UCC in Gothenburg is 'Stadsleveransen', which serves the inner city ('inom Vallgraven'). Other UCCs or UCC-like logistics centers in Gothenburg can be found near the central station and in Lindholmen. Even Johanneberg has a UCC-like delivery hub ('Post- och Transportcentral, med central godsmottagning') that serves the Chalmers campus area. (Sanchez-Diaz, 2019)

Though UCCs address many of the traffic problems associated with the typical logistics arrangement, they also have several problems of their own, especially in terms of economics. Of the many UCCs that have been tested in Europe, relatively few have been economically viable once subsidies are accounted for. (Sanchez-Diaz, 2019)

Those that are successful, however, have a few things in common. For one, they communicate with the receivers. For example, the UCC asks them if they'd like to opt-in in return for a less congested city. The alternative, that they are forced or coerced, makes them less willing to participate. Also, successful UCCs offer services, like the possibility of picking up deliveries on site, to the public. (Sanchez-Diaz, 2019)

It is often difficult to get suppliers involved with UCCs, as many of them are logistics companies and it makes little sense for them to want to cut down on the number of deliveries or delivery trucks, as they are their main source of revenue. Also, they are hesitant to give up on the direct link between them and the receivers, who are their customers. (Sanchez-Diaz, 2019)

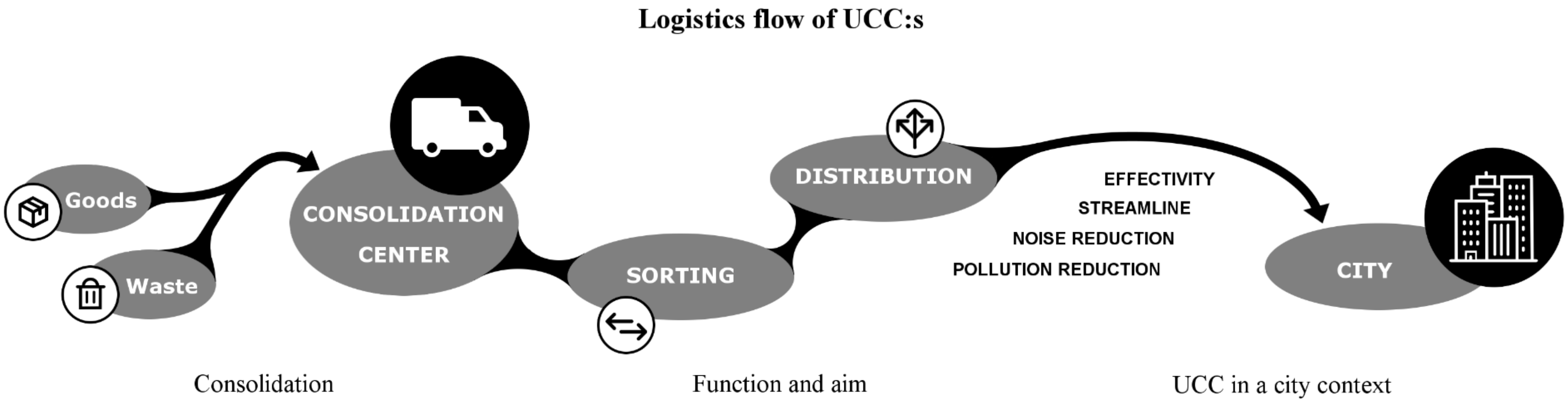


Illustration 12: A basic chart of the general logistic flow of an urban consolidation center.

CONCEPT

Structure as architecture

Structure as architecture is, for the purposes of this thesis project, a vision of design defined by a few principles. To start, the load-bearing structure should be an integral part of the architectural expression. Also, the load bearing structure should, to the point that it is reasonable, be designed to ideally handle the applied loads. Additionally, it should help define the spaces of the building.

A quintessential example of structure as architecture is Frei Otto's German Pavilion. The most striking architectural feature is its dynamic shape, which is only possible due to its structure, composed of a light-weight canopy structure, hanging in tension while supported by columns standing in compression. This sort of structure is very effective, with little 'wasted' material. It also helps to define the spaces underneath and provides a unique visual and spatial experience for the visitor. In short, the load-bearing structure and architectural expression are deeply and seamlessly integrated.

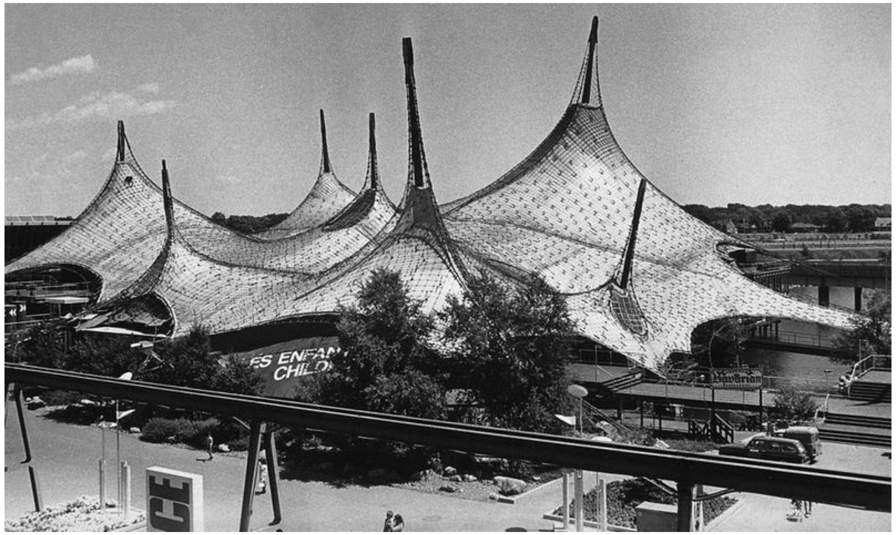


Illustration 13: The German Pavilion Expo by Frei Otto, a seminal inspiration for the project and an example of structure as architecture in practice. (Chousein 2015).

Anti-funicular forms

In this project, the UCC building achieved a structure as architecture design through an anti-funicular form. A funicular, or anti-funicular, structure is a structure that has achieved a state of equilibrium by dynamically entering a shape corresponding to the 'ideal' handling of applied forces. For example, a catenary chain is a 'funicular' form for a uniformly distributed load, but not for any other load distribution. An arch with the same shape as the catenary chain, standing upwards, is its anti-funicular equivalent. For a structure to be stable and 'ideal' in its handling of forces, its form must be funicular in relation to the loading. Mathematically, and graphically, one can derive funicular forms from the funicular polygon or force polygon method, even in three dimensions. In this project, however, physical model-building and digital simulations based on spring behavior were used to find and model funicular forms.

Catenary chains are often seen as synonymous to funicular curves. They have been used by many architects as a tool for design, as they help provide a greater strength to the structural integrity by distributing the weight more effectively. Some examples of architects using catenary chains in their design process are Gaudí and Frei Otto. Typically, this is done by hanging a model composed of some sort of structural element conducive to the behavior of funicular forms, like catenary chains or weighed down strings. This produces the correct funicular shape to form the surfaces that would result in the form with the least amount of stresses required in the structure. It allows one to minimize the size and number of support elements, allowing for more open building plans. Designs with funicular forms are often seen as seeming more natural and often impart a certain level of lightness to the structure. For these reasons, and more, catenary chains were used to make the structure of the physical building-models achieve a funicular form (see 'Physical model building'). Digital models also made use of catenary chains with spring-like behavior in their models (see 'Digital model making').

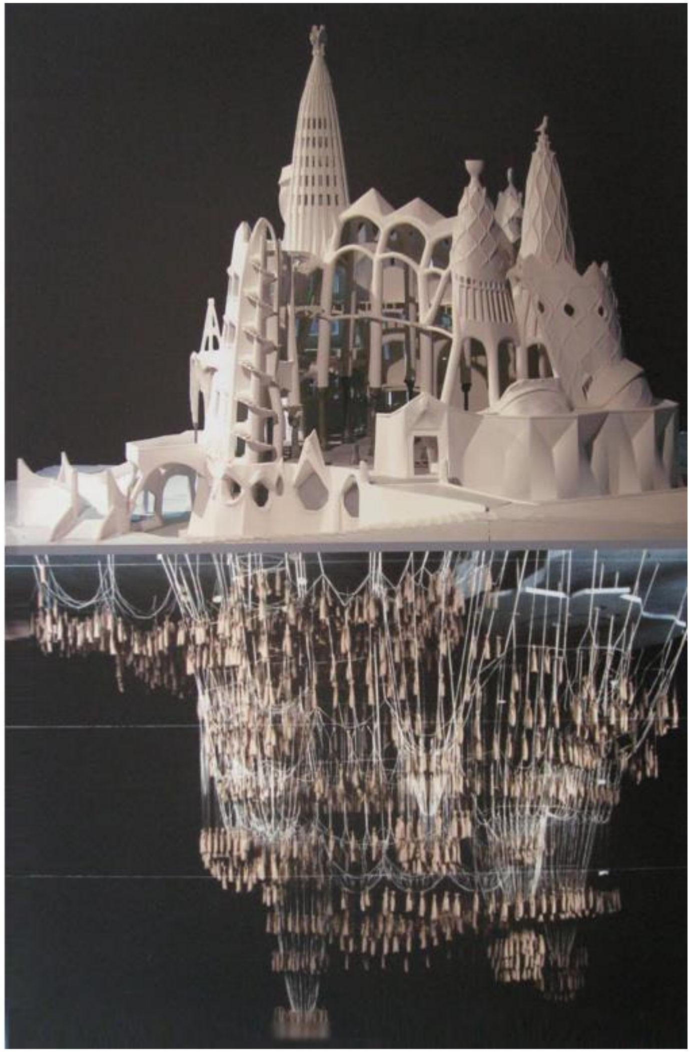


Illustration 14: A recreation of the string model used by Antoni Gaudí to design the Sagrada Familia, an example of an anti-funicular structure in practice.

Materials

In general, a structure as architecture design allows for a more effective use of materials. If the architectural features and the load-bearing structure work in tandem from the start, it leads to a smaller amount of 'superfluous' materials that does not contribute to the building's load-bearing capacity.

For the anti-funicular vault façade, brick and mortar was the chosen material. This was for a few reasons. To start, there is the historical context, as most of the site's present buildings have brick facades. Thus, it would be of a historical value if a similar façade material could be preserved there as part of the UCC, even as the rest of the area was rebuilt as part of the Älvstaden project.

There's also a pre-established tradition of using brick and mortar in vaults—including Gothic churches or works by the aforementioned Philippe Block—that could be tapped into. Bricks are also a generally sympathetic material that imparts a lot of materiality and it has an almost inherent architectural quality to it, as the pattern they form gives a structure a natural form of décor.

Finally, it comes with several structural advantages. For example, as the building is to be located in Gothenburg, ground deformations is an issue, no matter the structural material. However, in a brick vault with an at least semi-elastic mortar, the bricks would just be able to shift slightly, "sliding" inside the mortar instead of cracking under deformation. The thing you have to keep in mind with brick vaults, however, is the direction of the bricks and the pattern they form, as they have implications for the load-bearing structure.

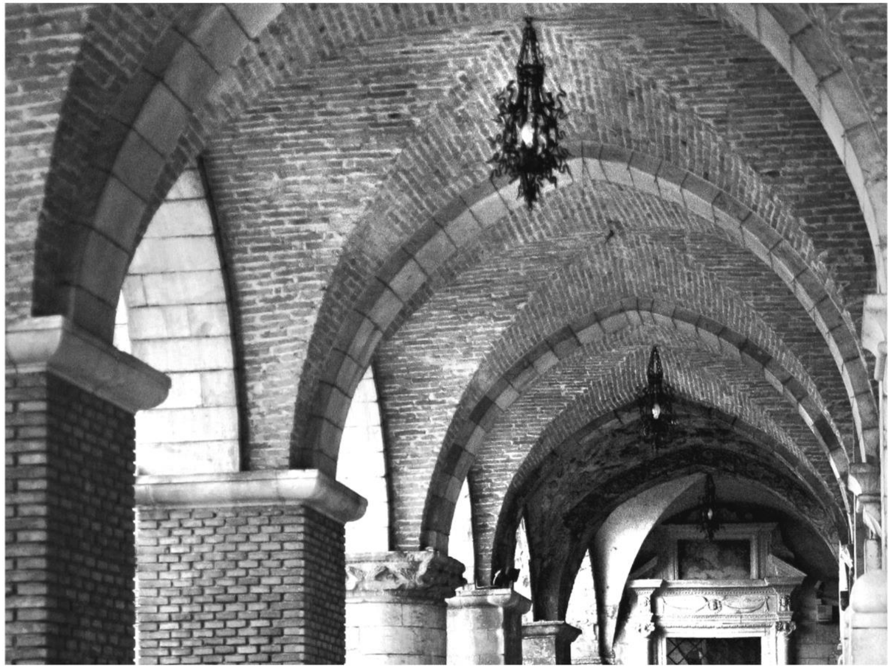


Illustration 15: The new skyline of Gothenburg, with the Hisingsbron bridge and the UCC building, as seen from the southern side of the Göte Älv river, looking north.

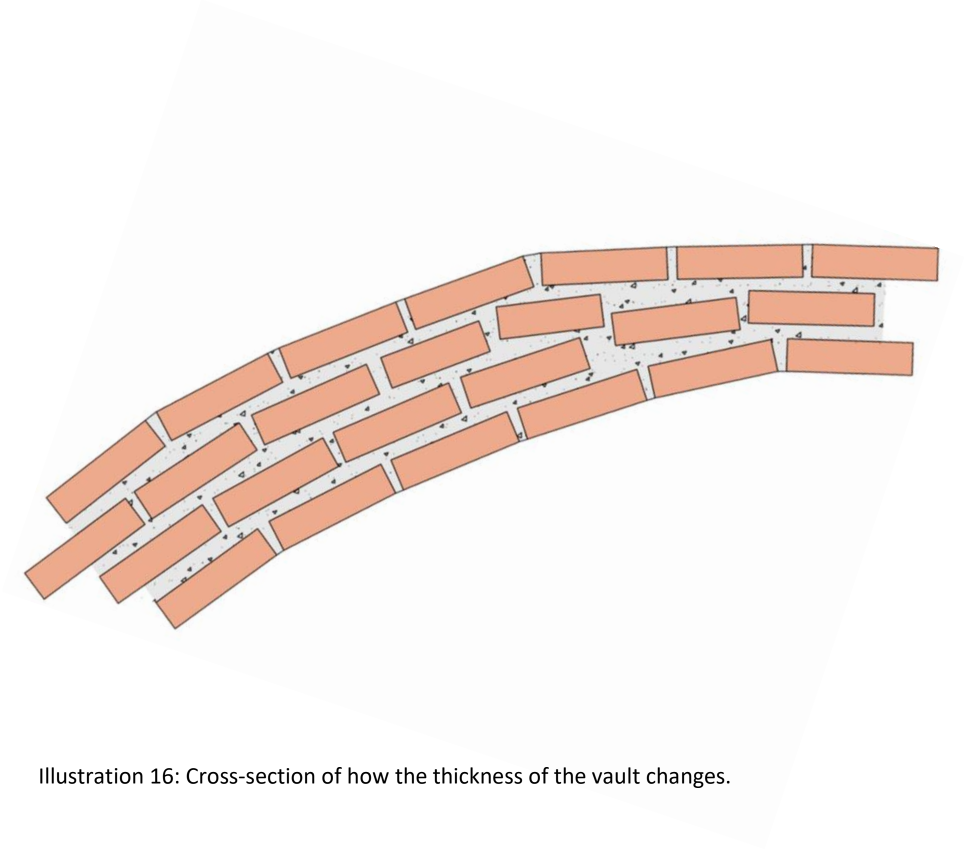


Illustration 16: Cross-section of how the thickness of the vault changes.

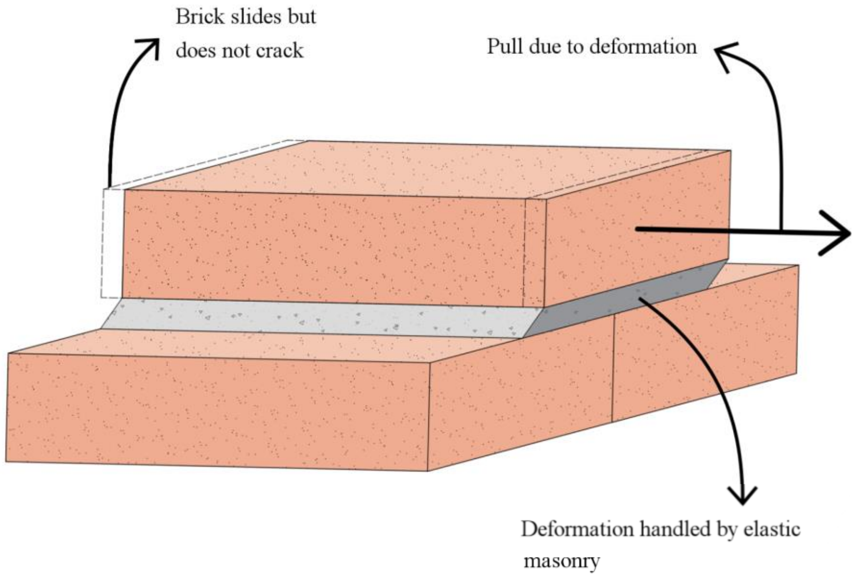


Illustration 17: Illustration of how the brick's masonry handled deformation.

METHODS

If the discourse can be likened to the intellectual landscape to be explored, then the methods would be the tools used to navigate and document that landscape. In other words, if the discourse is the 'what' of what is to be studied, the methods is the 'how'.

For this project, the methods used ranged from reading literature and studying references to drawing sketches and working with models, both digital and physical. An iterative design process was used to arrive at a building design. The first step taken was visiting and documenting the site.

Iterative Process

Armed with the knowledge from studying the literature, the references, and the site, it was possible to make informed design decisions. From there, an iterative design process started. This started with several concept models being made. They were mostly physical but complemented by digital 3D models. The models were evaluated by what consequences each design option had and how they compared to the design criteria. A judgement was then be made as to which models more closely matched the design criteria, what qualities were lacking, and what could be made to improve them. The conclusions were then used to develop a new and better iteration of the models. This was repeated throughout the project up until the final design, the refinement of which was the last step of the iterative design process.

Criteria to judge by:

- Architecture
    - Spatiality possibility to split up spaces, usability, and variety of use,
- Structure
    - Displacement due to applies load and general rigidity

During the early phases of the project, most of the models were physical, but the balance later shifted towards more digital ones, as they were more easily readjusted, more precise, and more shell-like than physical models.

In conjunction with the models, plan and section drawings are also made, typically with each iteration of models. They also help to evaluate the concept ideas they illustrate. Generally, the main limiting factors in the design were the spaces required for the UCC functions, as well as the width of the vault spans, the reasonable load-bearing capacity of the structure, and the geography of the site, not the least of which was the bank of the Göta älv river.

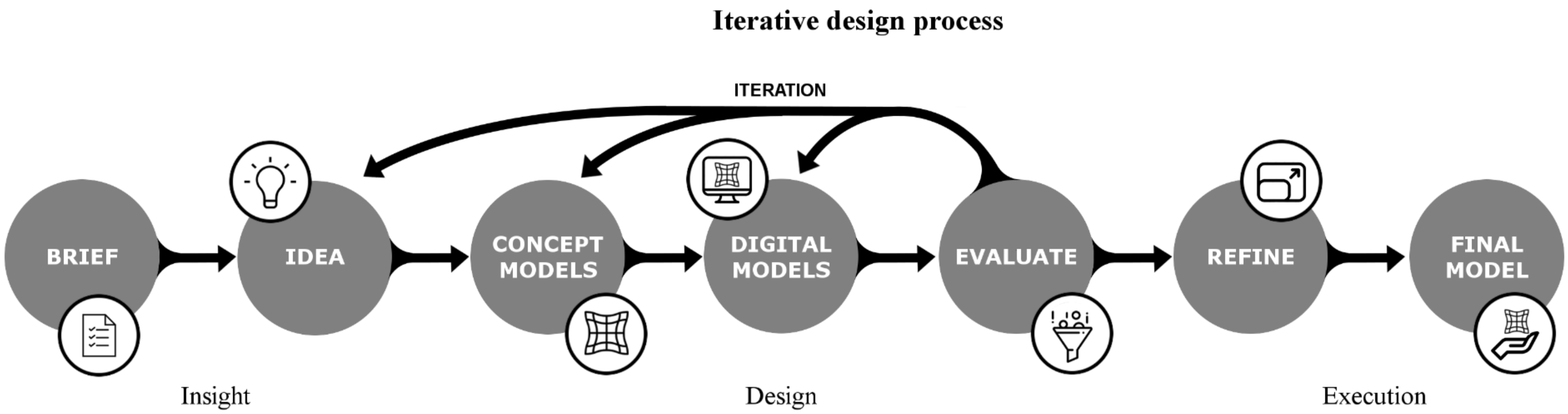


Illustration 18: A basic chart of the flow of the project's iterative process.

Physical model building

One method of model building was the making of physical models. These models were typically of two sorts. The first, and most produced, sort was the concept model. Several concept models were made from catenary chains composed of joined-together paper-clips. The ends of the network of catenary chains were fixed to a base made of cardboard or other similar material.

When hung upside down, the self-weight of the chains made the catenary-chain structure enter a funicular form in accordance with an evenly distributed load. In theory, the forces inside the structure were entirely in tension (apart from the forces inside the base, which, to keep the rest of the structure stable, were in compression). While the catenary chains hung upside down, the structure was glued together using hot glue. Once the glue had solidified, the catenary chains were structurally cohesive and durable. Then, the model was turned 'right-side-up' again. Due to the binding properties provided by the dried glue, the structure of catenary chains could stand on its own. The forces in the structure were now an inversion of what they were before, with the whole catenary chains structure (in theory) entirely in compression and with tension forces inside the base. This provided a relatively strong and efficient structure compared to the amount of materials used. The more chains and the higher up on the structure a load was applied, however, the greater was the load it could carry.

Illustration 19: Left; empty base. Right; anchor hooks.

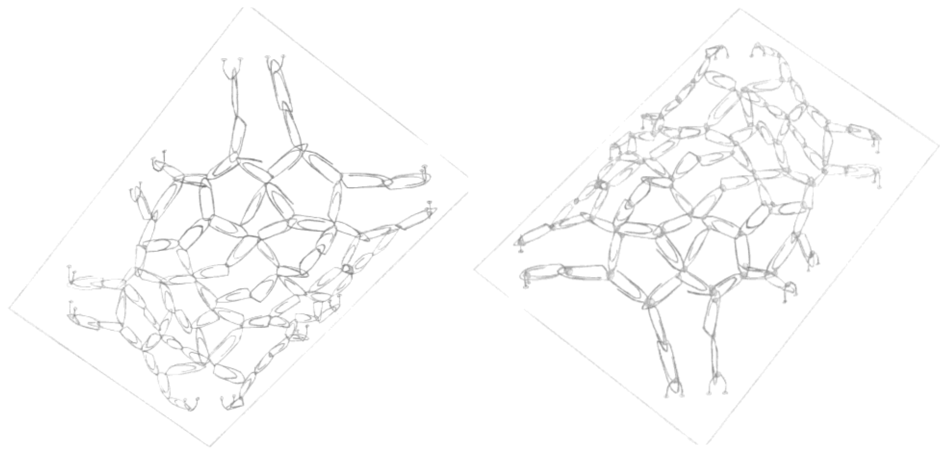


Illustration 20: Left; hot glue melding. Right; rigid paper-clip form.

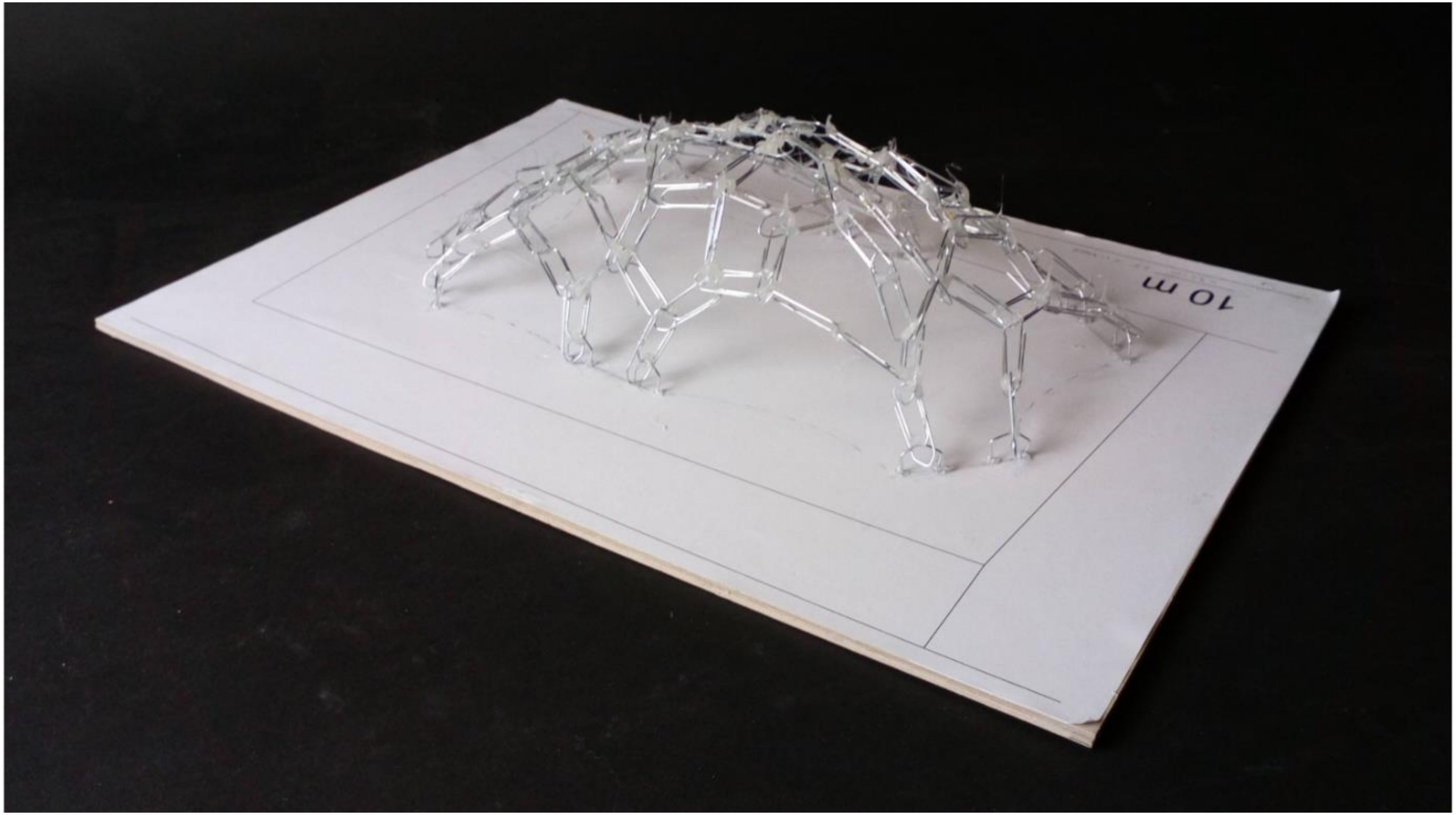


Illustration 21: An example of a simple paper-clip concept model.

The second sort of physical models made was the display models. They were made using more advanced methods, typically involving machines. The model made to illustrate the vault in its urban context, for instance, was made using computer numerical control (CNC) foam cutter, drilling the vault's shape out of a Styrofoam block. The relevant parts of the foam were separated from the larger block and then placed in a vacuum forming machine, where a sheet of plastic is heated up to a moldable temperature and then draped over the Styrofoam model, resulting in a plastic mold of the building's vaulted shape. Holes are made in the model for the vacuum forming machine's suctorial force to reach into the crevices of the model. Afterwards, the parts of the plastic molded form corresponding to the vault is painted white and placed in a model representing its urban context. Other display models showcase individual parts of the building, like its supports and its openings. They were made using a plastic 3D printer.

Illustration 23: 3D-printed model of a column, an internal support.

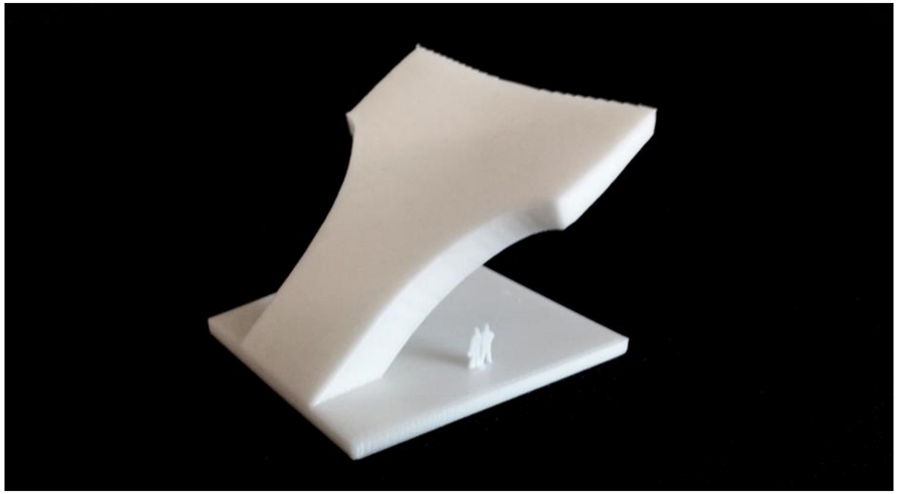


Illustration 22: 3D-printed model of an angled end-support.

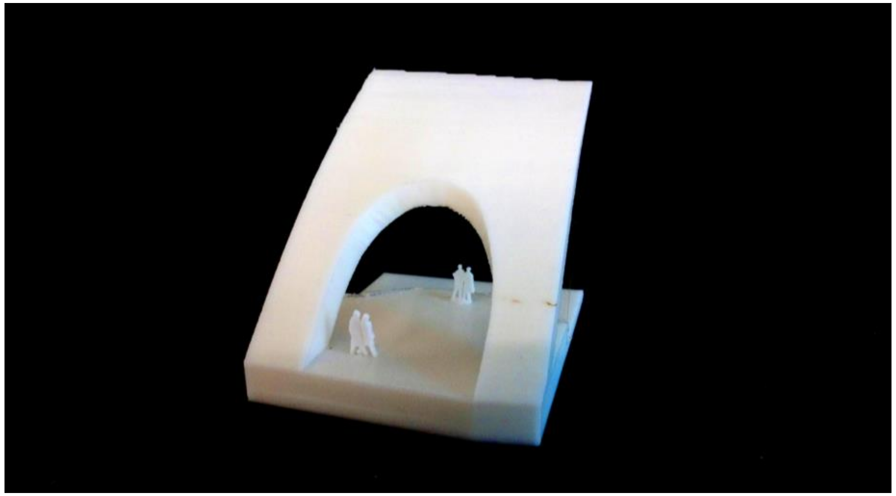


Illustration 24: 3D-printed model of an opening.

Illustration 25: Vacuum-formed plastic model of the vault’s shell.

Illustration 26: A CNC-cut Styrofoam model of the shape of the UCC building.

Illustration 27: The plastic model in a representation of its urban surrounding.

Digital model making

In conjunction with physical models, digital 3D models—both new and recreations of physical ones—were constructed. This was for a few reasons. To start, it allowed for a spontaneous testing of different ideas, as well as the making of slight variations of the same model. For example, two copies of one digital model could be altered easily and quickly to test their behaviors when given different sets of parameters. Also, the digital models, unlike the physical ones, took shear forces into account. The physical concept models could not model shear, which meant that the digital models showed more of a shell behavior than the physical ones.

The digital models were conducted in the Rhinoceros 3D (Rhino) program. Specifically, a script was written using the Grasshopper add-on of Rhino to use a series of manually drawn curves, representing the outer edges of the shell that makes up the façade, to form-find the optimal anti-funicular form.

The process is started by drawing a triangular pattern of curves, roughly in the form of the façade projected on the xy-plane. Special care is taken to make sure that each node not on the edge of that pattern is connected to the same number of curves. This is to make sure that the shell holds a roughly equal amount of stiffness throughout. From there, the curves are split into smaller segments, to make for a finer mesh. Then, the remaining curves are smoothened, and, from those smoothened curves, a mesh is formed.

The edges of that mesh are given a spring-like behavior and it is subjected to a vector force field, representing gravity. Based on that force, the mesh adjusts according to the ideal, anti-funicular form. In addition, the stiffness of the springs inside the mesh and the size of the force can be adjusted, allowing for a spontaneous testing of different scenarios and behaviors.

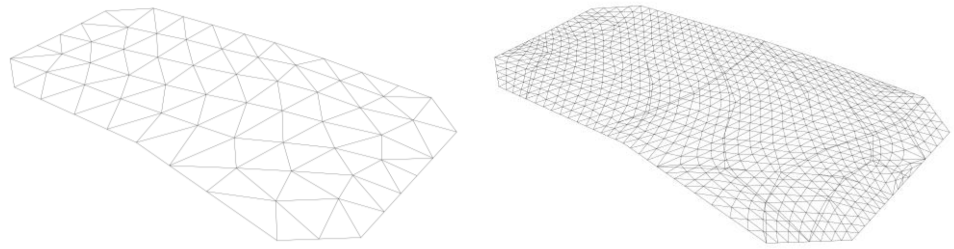


Illustration 28: Left; triangular curve pattern. Right; fine mesh.

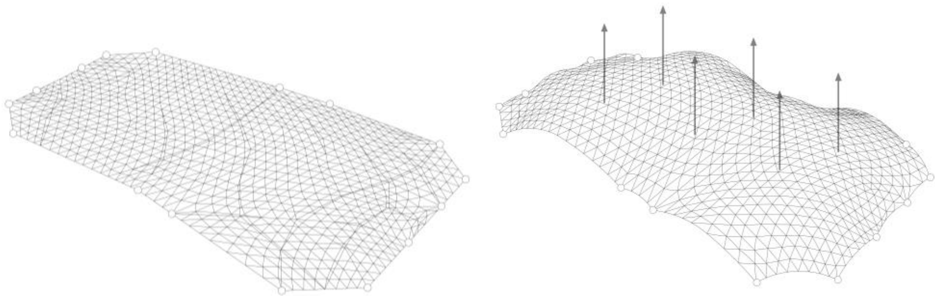


Illustration 29: Left; anchor point assignment. Right; force field application.

Iterations

Iteration 0

The pre-study can be considered 'Iteration 0'. It was conducted as part of both the 'Master's thesis preparation course ARK641' course and the 'Matter, space, structure 3' studio course. During Iteration 0, the main objective was to develop the discourse and the methods of the thesis project. The primary ways by which this was done was by reading literature and cultivating methods of model-building.

Over the course of Iteration 0, several different kinds of materials and methods of model building were explored. Some of the materials tested were plywood, cardboard, steel wires, plastics, chalk, and fabrics. In turn, the methods ranged from assemblage to 3D-printing. One useful method that was to use catenary chains of strung together paper-clips to construct a network hanging in tension from a cardboard base to simulate a funicular form. This method would be maintained in the construction of concept models in future iterations. See the 'Physical model building' sub-chapter for more.

Conversely, discoveries as they pertain to the discourse of the project include literature as well as references of both past projects and relevant designers. The findings are summarized in the 'Context' chapter.

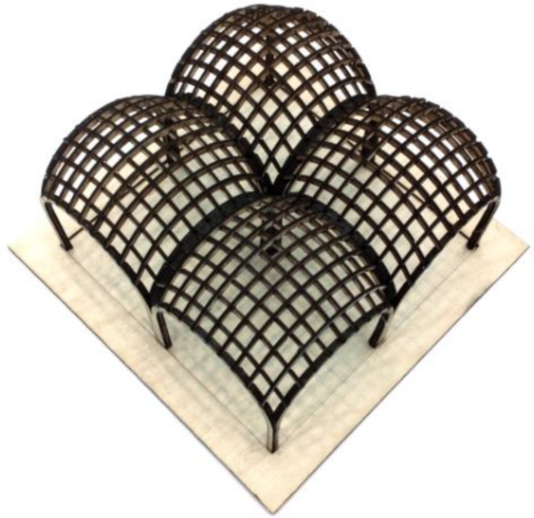


Illustration 30: A test concept model of a vaulted roof.

Illustration 31: A 3D-printed test concept model.

Iteration 1

Time: ca. Jan. 21st – Feb 16th

Iteration 1 was the point at which proper design work started. The first issue addressed was to find a context and a function for the building to be designed. The result of this was the UCC at Frihamnen (see the 'Context' chapter for more). More physical concept models were also made, with the specific site in mind. However, starting from the middle of Iteration 1, the focus shifted more towards design exploration being made in digital models as time went on. More material design decisions, primarily brick masonry, were also made, as was the accompanying research into brick masonry projects as well as designers working with the material, like Dieste, Guastavino, and Philippe Block.

At first, a continuous anti-funicular brick vault constituted the whole load-bearing structure. However, this meant that width of the spans would have to be exceedingly large for the vault to reach the heights needed for the trucks to operate the way that the UCC requires. Thus, a few solutions were developed to address this issue over the course of Iteration 1, alongside general design problem solving.

First, it was decided that there would be a one-meter excavation into the ground in the area where the trucks are to load and unload. It would help to minimize the span of the brick vault and puts the goods that people are to load and unload to and from the trucks on the same elevation level as the trucks' loading area, making the process easier. Thick, vertical walls were also to be placed along the edges of the vault, to help define the spaces underneath and to elevate the anti-funicular vault. It was also decided the building would provide a service area where people could come to pick up or leave deliveries.

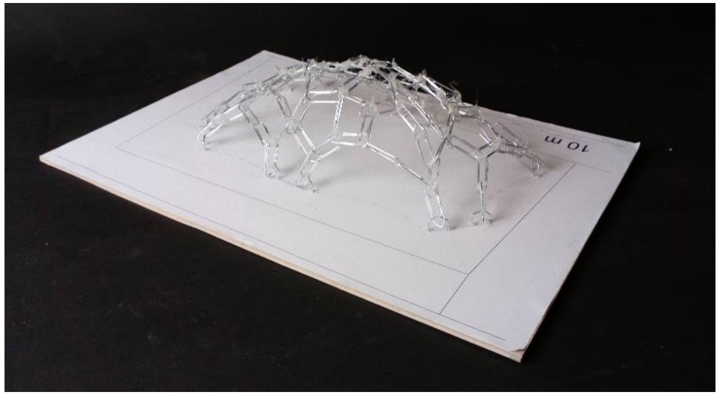


Illustration 32: An example of a simple paper-clip concept model.

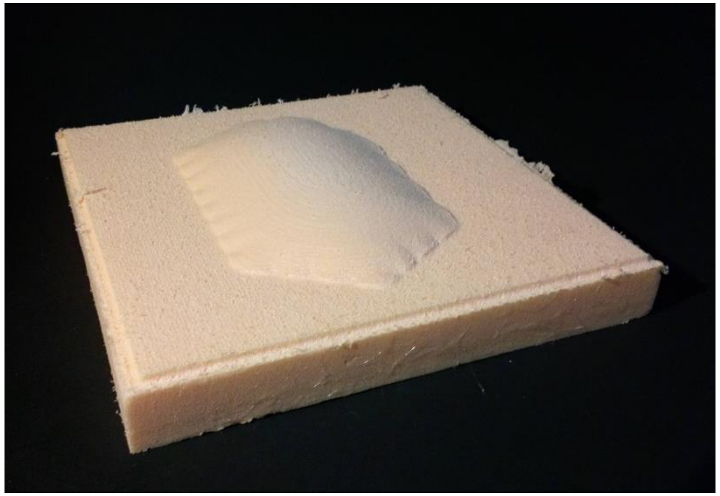


Illustration 33: A cut-out of an early form of the vaulted roof.

Iteration 2

Time: ca. Feb 18th – March 1st

The initial designs made during Iteration 2 had the outer walls supporting the vaulted roof be thick and entirely vertical, in a similar vein as the Stockwell Bus Garage. However, the sharp angle at which the walls met the edges of the vaulted roof would result in an unreasonably concentration of forces. To accommodate this, the walls were put at an angle and split into branched support structures, similar to the supports from Luigi Nervi's Rome Sport's Stadium, to transfer the forces more effectively.

The interior of the building was also altered. To start, the inner supports became a more integrated part of the vaulted structure, as they were made into anchor points, like the edges of the vault. As a result, the shape of the supports widened at the ends and flowed continuously into the vaulted form. This meant that the interior load-bearing structure also helped to define the spaces and the shape of the building, thus reinforcing the ideal of integrating structure with architectural expression.

Additionally, the placements of the inner areas were also changed. To be specific, the placement of the personnel and services areas were switched with that of the goods' loading area. This was both to make it easier to handle goods coming from the long, 24-meter trucks, as they will have to park outside, along the road, and be unloaded outside, next to the interior loading area. The change would also make the UCC service area more visible to and easier for pedestrians walking along the green lane to visit and make use of (for more, see sub-chapter "Flows and function").

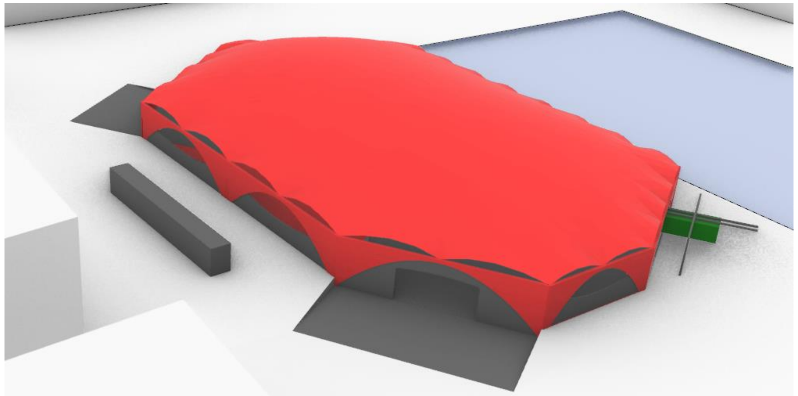


Illustration 34: A digital 3D-model of one version of the building at the start of Iteration 2.

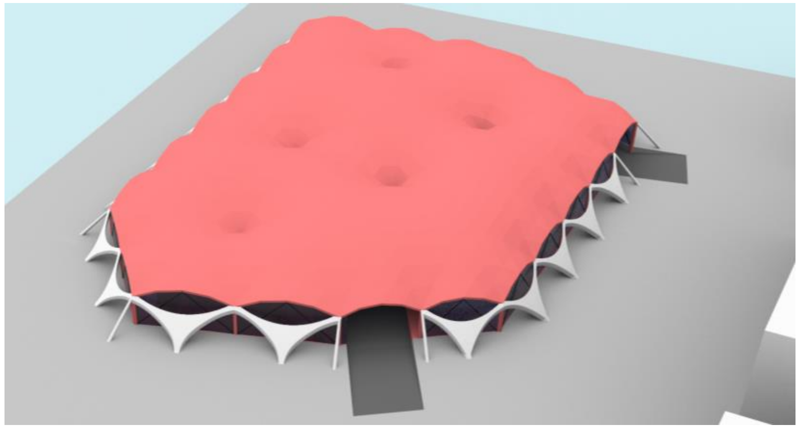


Illustration 35: A simple rendering of one version of the building at the end of Iteration 2.

Iteration 3

Time: ca. March 4th – March 20th

At the start of Iteration 3, a new evaluation of the models was made. It was determined that the current design was too chaotic in terms of combination of materials—ranging from brick masonry to concrete and steel—and what language the structural elements spoke. The way that these elements intersected also resulted in some awkward or complicated connections. In response, several variations of models using different sorts of materials and structural elements, like combinations of concrete and brick, steel and brick, or purely brick masonry, were made and evaluated. Each one had their advantages, but ultimately, the one made primarily of brick was chosen to be further developed.

To this end, the form of the anti-funicular roof and placement of the inner supports were altered to become more symmetric. This served the dual purpose of making the overall impression of the building more uniform and holistic as well as making the structural integrity more feasible, as structure of this kind are typically symmetrical for this reason (Olsson, 2019). Also, the inner supports were adjusted, from a circular to rectangular form—to stand as more of a contrast to the rest of the building—and the connection with the roof was made deliberately and with a natural flow.

Apart from the glass walls, light was also let into the building through semi-transparent bricks in the vaulted roof. Due to the possible complications of having large sections of the structure possess different material properties from the rest, the semi-transparent bricks were scattered throughout the shell in a way similar to that in Félix Candelas' High Life Textile Factor. (Adiels, 2019)

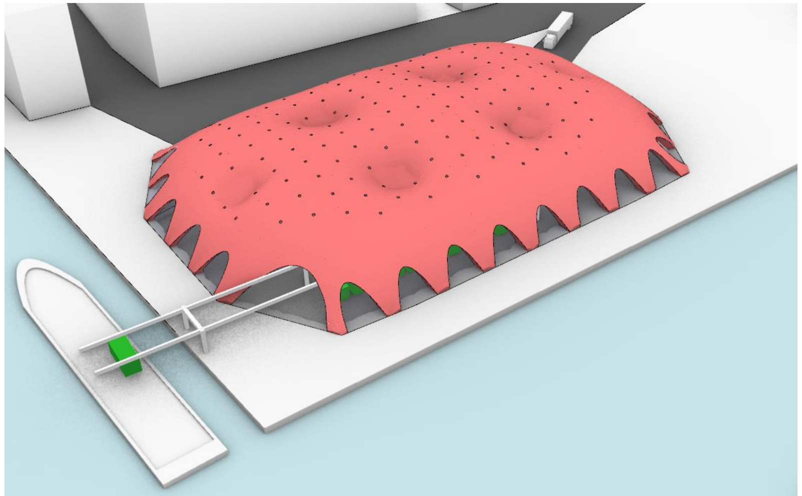


Illustration 36: A simple rendering of one version of the building at the end of Iteration 3.

Iteration 4

Time: ca. March 20th – April 21st

Iteration 4 incorporated much of the feedback given during the Mid-Crit. presentation held in March. To start, the goal of a symmetrical plan was abandoned in favor of a more dynamic shape and a plan that was better catered to the urban context, like the surrounding streets and buildings.

There was also an inclusion of a vertical glass wall just inside the vault, which defined the building's interior space and its controlled environment.

Additionally, the columns' form-finding was improved. The base and general cross-section was changed from a square to hexagonal, allowing for a much smoother surface as well as a form that continuously flows into and integrates with the vaulted roof.

Finally, the nature of the ceiling windows in the roof changed slightly. To start, the distribution of the transparent blocks shifted from being scattered relatively equally throughout the roof to being confined to the areas around the top of the vault, where the shell is the thinnest. This was to minimize the loss of load-bearing capacity and the amount of complications that a change of material in a continuous structure could bring. At the same time, it would still be providing the additional source of daylight and a way to perceive the vault's thinness around the top of the structure.

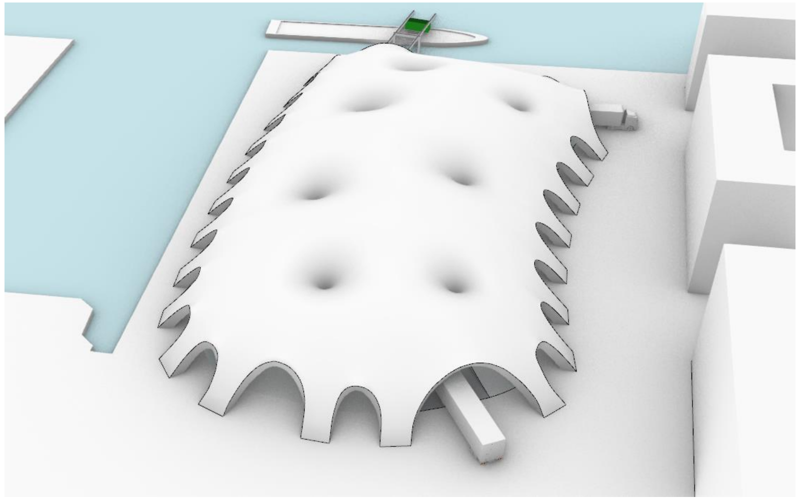


Illustration 37: A digital 3D-model of an iteration 4 building, external.

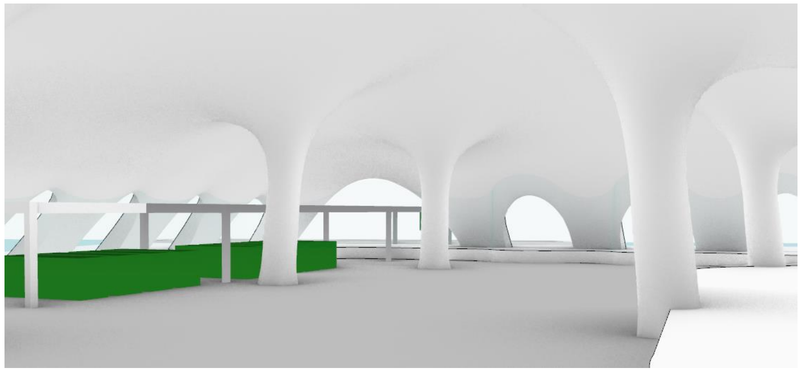


Illustration 38: A digital 3D-model of an iteration 4 building, internal.

Iteration 5

Time: ca. April 21st – May 14th

The sixth and final iteration was less comprehensive in scope than the previous ones and was more about the finishing touches. One of those finishing touches was the implementation of the detail of the meeting between the vertical glass walls and the vaulted roof: a steel frame around glass, tied to the surface of the roof using joint sealer. There was also the inclusion of lookout points to the plan (see the 'Flows and function' Sub-Chapter for more).

A larger change, however, was the abandonment of the ceiling windows. After more deliberation and testing, the resulting conclusion was that it would likely not give the impression of lightness that it was intended to and the additional daylight would not be of paramount importance, as artificial lighting would be necessary in any actual implantation of the design, due to the darker winter months in Gothenburg.

The most distinct and markable addition, though, was the inclusion of the brick texture to the model. The pattern that they formed are of great importance, as they inform the distribution of force paths in the structure. The shell was split into a Voronoi pattern and the direction of the bricks arranged according to the force path direction (see the 'Vaulted roof' Sub-Chapter for more).

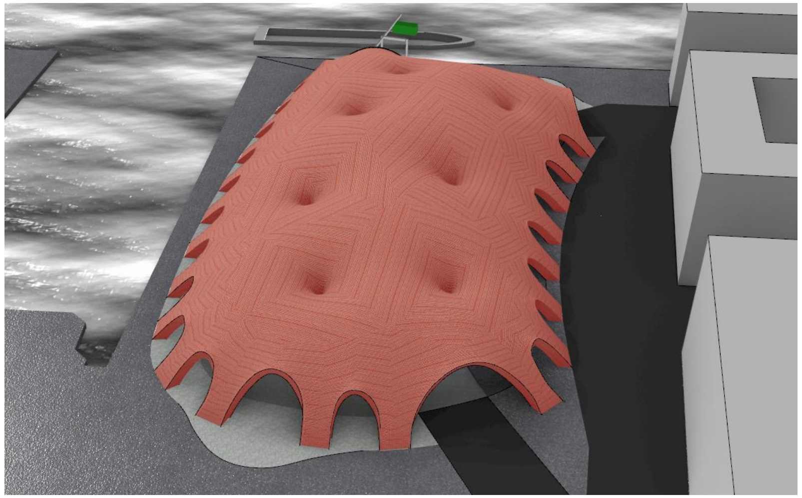


Illustration 39: A digital 3D-model of an iteration 5 building, external.

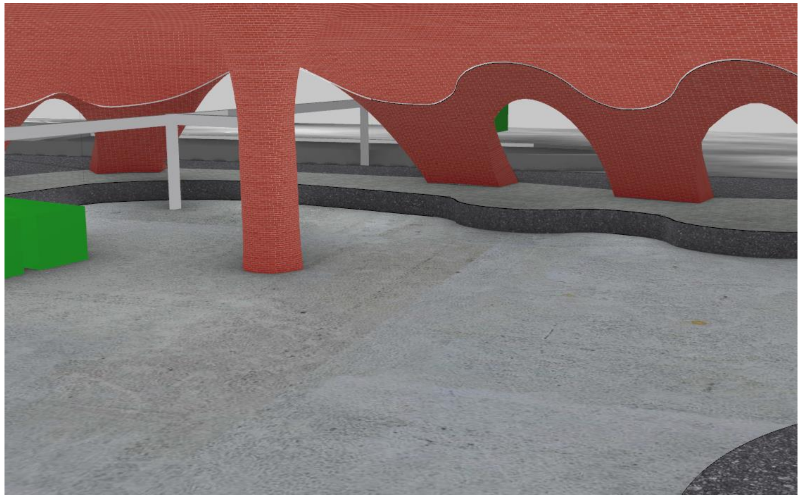


Illustration 40: A digital 3D-model of an iteration 5 building, internal, showcasing the glass walls and lookout points.

DESIGN AND STRUCTURE

Vaulted roof

The main feature of the building's architectural expression is its continuous vaulted shape, with a flowing and wave-like form that extends even so far as the ends of its supports. The supports themselves, with their girths and their heights, stand as monuments inside and around the building and provides it with a sense of weight and materiality. By contrast, the upper sections of the vault are very thin and gives the structure an element of lightness and playfulness. Much of the rest of the building's architectural expression is provided by its material, especially the bricks and the patterns they form on the vaulted roof.

With a building of this size and material, the weight makes self-load the dominant design force and the brick vault can be considered a pure compression structure. Its anti-funicular form ensures this, but for it to work, care has to be taken so that the transition of compression forces between the bricks is near seamless. To be specific, the thrust line—that is, the resultant force of the horizontal thrust and the vertical weight—should be perpendicular to the surface of the brick that it acts on. To achieve this, the arrangement of the bricks is crucial. The aim is for the pattern to facilitate the direction of the forces in the structure down into the foundation as smoothly as possible.

Overall, there are three sorts of directions that make up the arrangement of the brick pattern: horizontal, inclined, and edge bands. The horizontal bricks are placed against the ground—to more smoothly move the forces down into the ground and the foundation—the edge bands are around the edges of the openings—to provide stiffness—and the inclined bricks are in-between the other two.

These arrangements are placed within regions of the vault defined by a Voronoi partition. That is, the vault's brick pattern is partitioned so that the force at any given point is directed towards the support closest to it and the amount of brick carried by the supports are roughly the same as any other of the same kind.

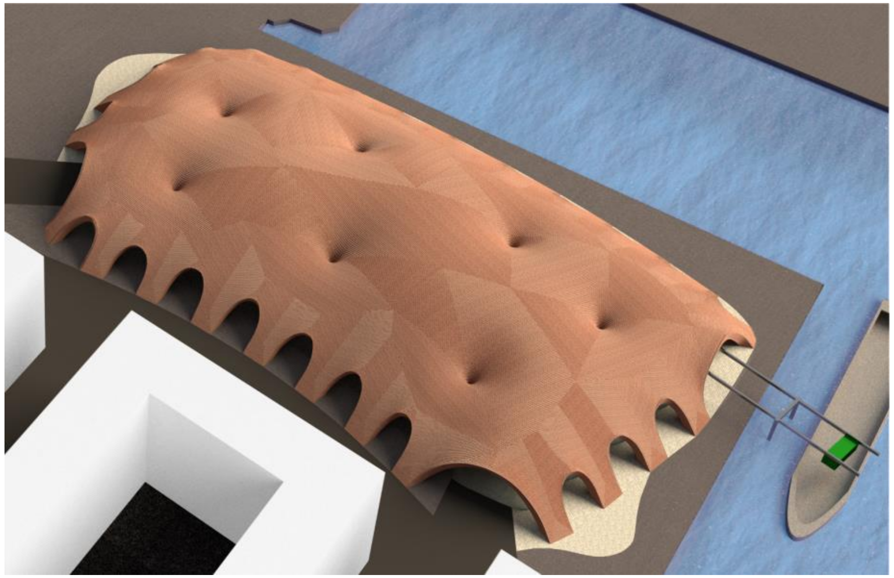


Illustration 41: Aerial view of the UCC's building's exterior.

For example, if a force is applied near the top section of the vault, it may go down into one of the internal supports through a line of horizontal bricks. Alternatively, it could go outwards, though a line of inclined bricks. In that case, it could go down in one of the opening edge band, in which case their stiffness would direct the force towards the ground. Or, it could follow that inclined line of bricks into one of the outer supports, in which case it would, at some point, collide with an inverse line of bricks, carrying a force going the other direction.

There, the horizontal components of those forces would cancel each other out and the result would be a thrust line going down the center of the support. Further down, that thrust line would carry over into a region of horizontal bricks, from which it would land into the ground. At that point, one could consider the vertical component of the force to push down into the ground and the horizontal component to project outwards. In either case, this is handled by the foundation of the building.

Illustration 42: A view of the interior of the building.

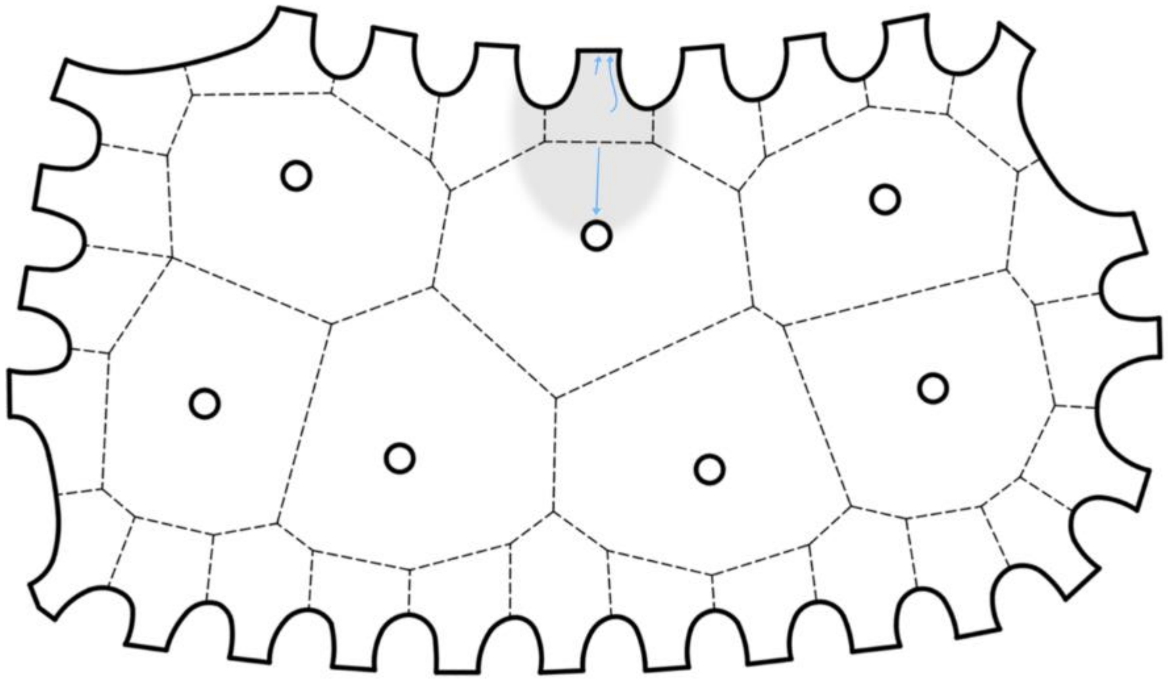


Illustration 43: Illustration of the Voronoi partition used to determine the directions of the vault.

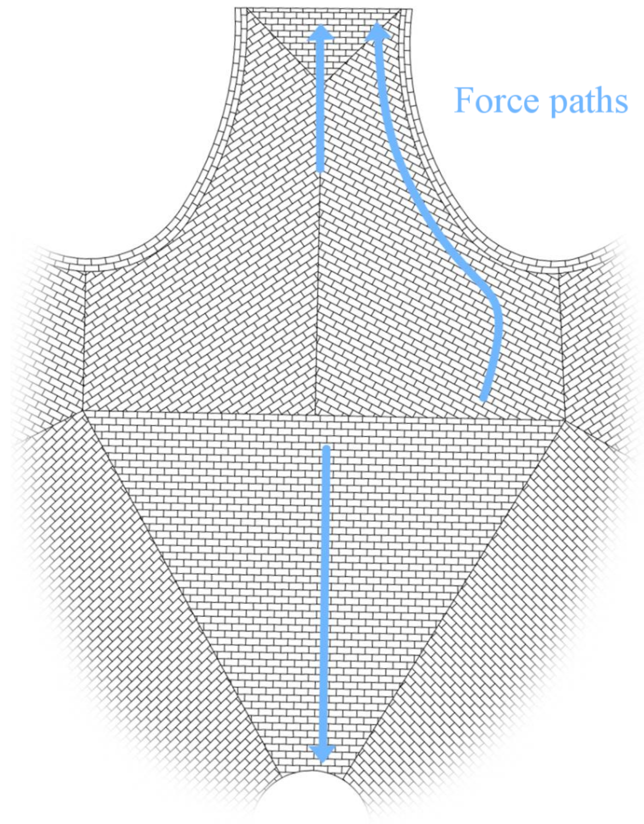


Illustration 44: The direction of the force paths in a segment of the vault's Voronoi partition.

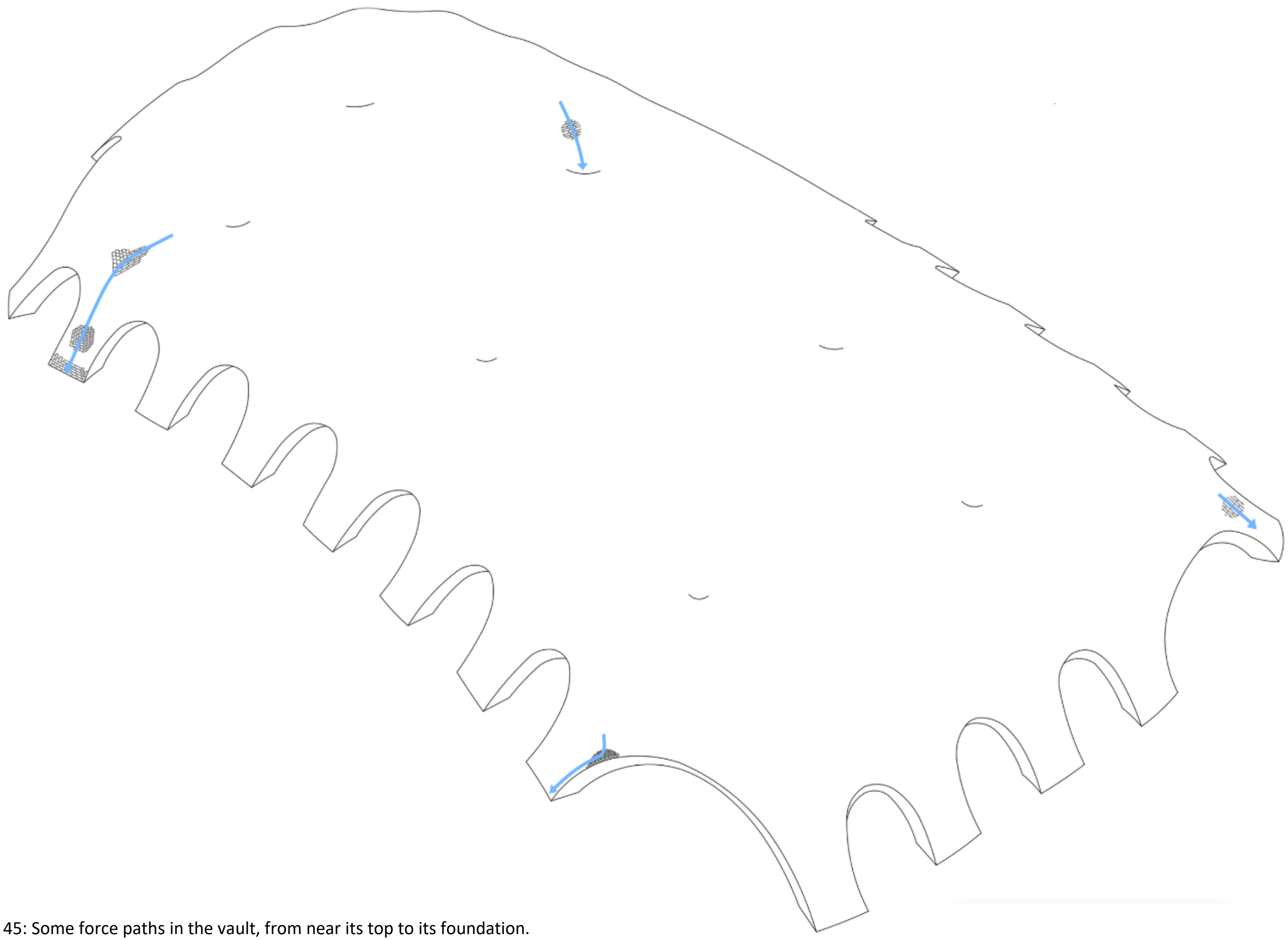


Illustration 45: Some force paths in the vault, from near its top to its foundation.

Illustration 46: Bricks placed horizontally against the ground. Horizontal bricks from the top of the vault lead down to the foundation through the columns.

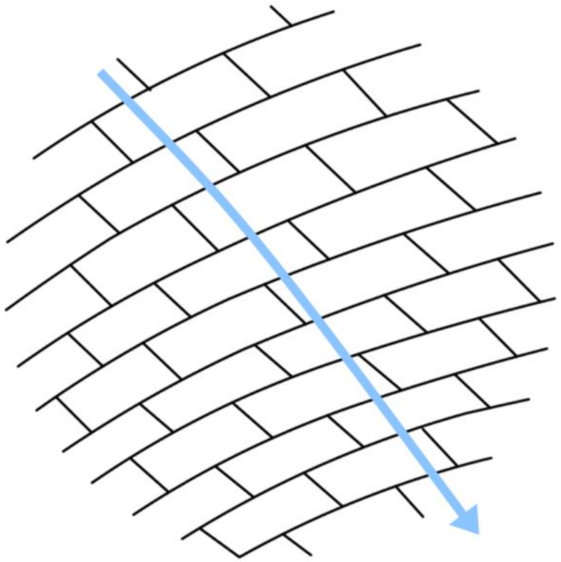
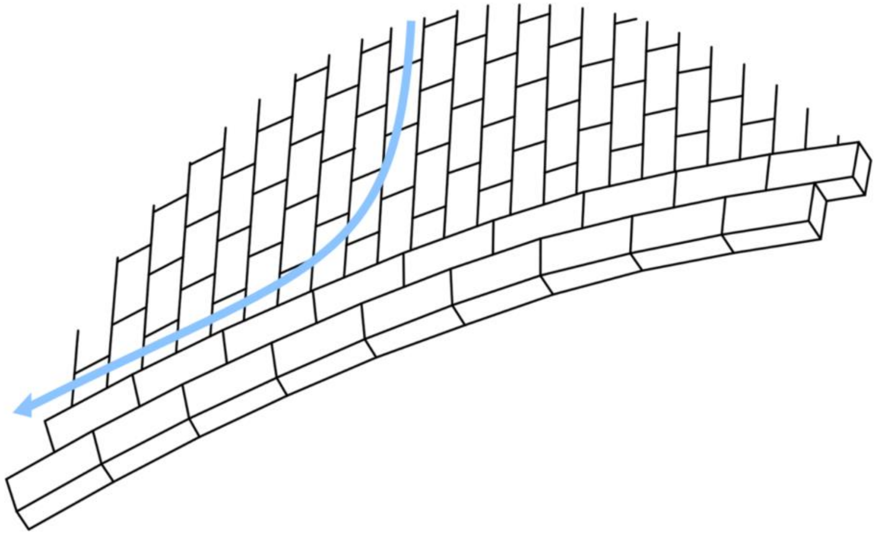


Illustration 47: The stiffened edges guide compression forces down into the ground. The open edges—that is, the edges around the openings—are stiffened by several layers of bricks placed along the edges.



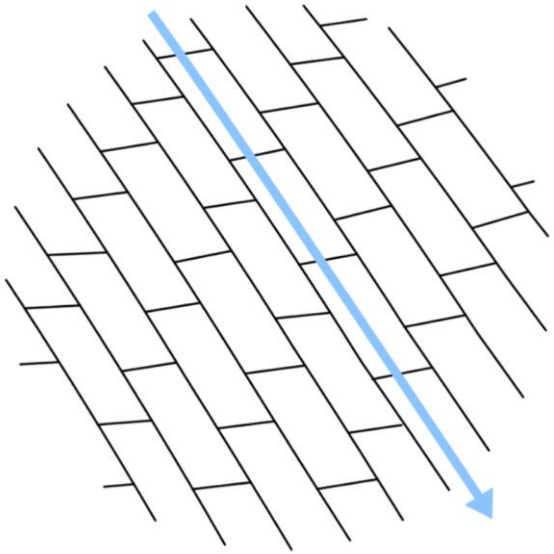


Illustration 48: From the top of the vault’s brick structure to the outer supports, the bricks are arranged with an inclined angle. The direction is mirrored around the middle of the support, to direct the forces down into the ground. They direct the forces along the axis.

Illustration 49: When subjected to a load, the forces in a portion of inclined bricks are carried along the axis until the inclined bricks collide with another set of inverse inclined bricks. The horizontal forces cancel each other out and the resulting thrust travels down the intersection.

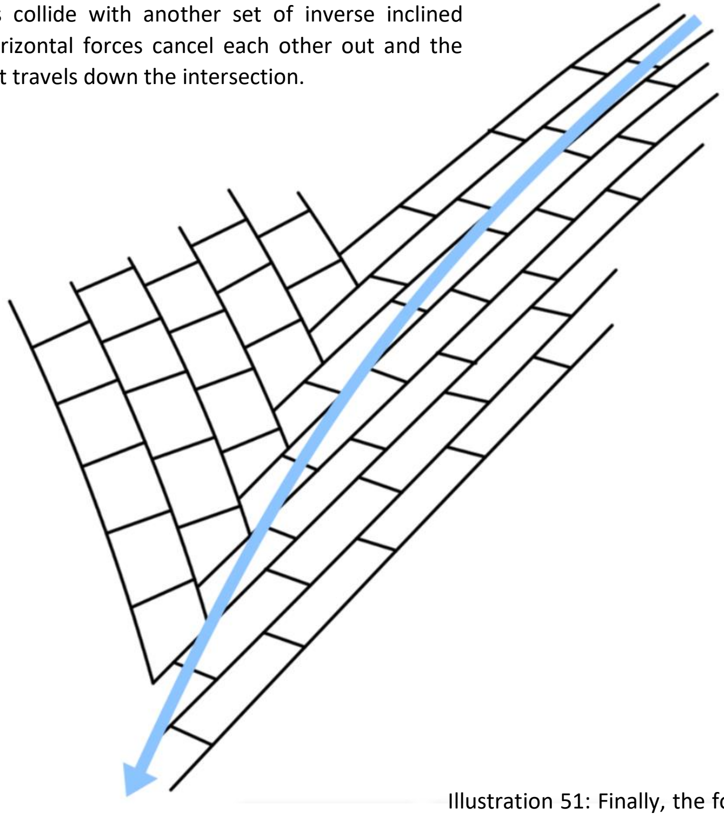
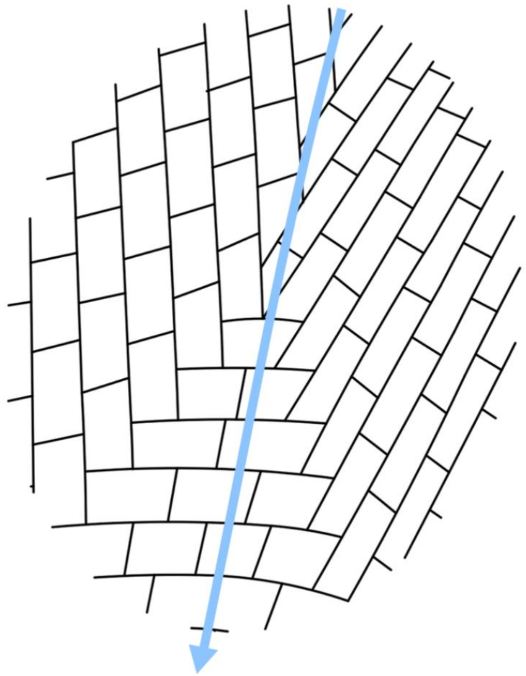


Illustration 50: When nearing the end of a support, the thrust from the inclined bricks moves into a set of bricks lined horizontally against the ground. The arrangement of the bricks ensure that this transition is seamless.



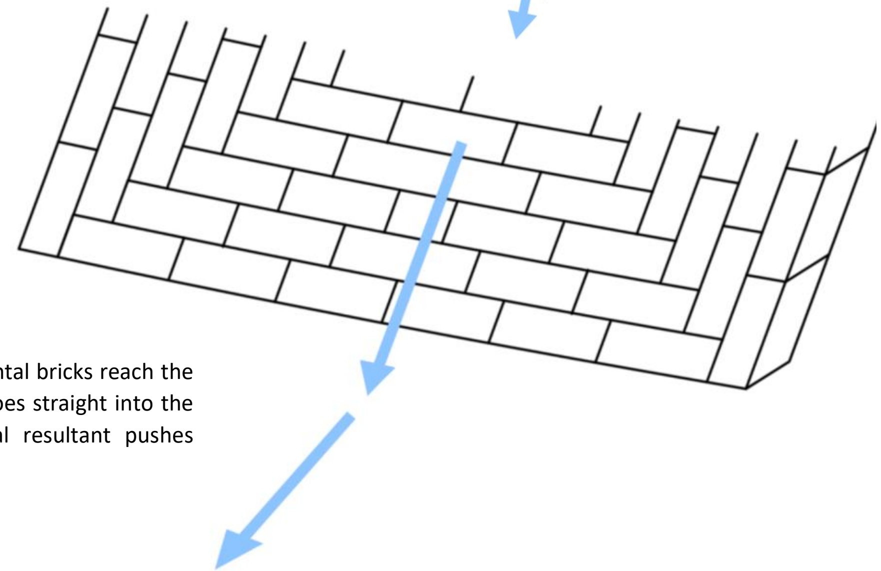
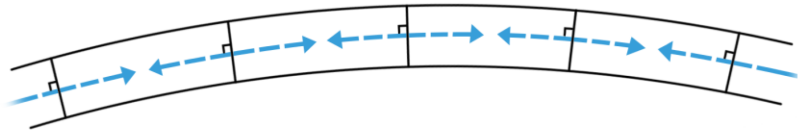


Illustration 51: Finally, the force in the horizontal bricks reach the ground. The vertical resultant of the thrust goes straight into the ground, pushing downwards. The horizontal resultant pushes outwards and is handled by the foundation.

Illustration 52: The circular force at a given horizontal cross-section of the vault, perpendicular to the surface of the bricks.



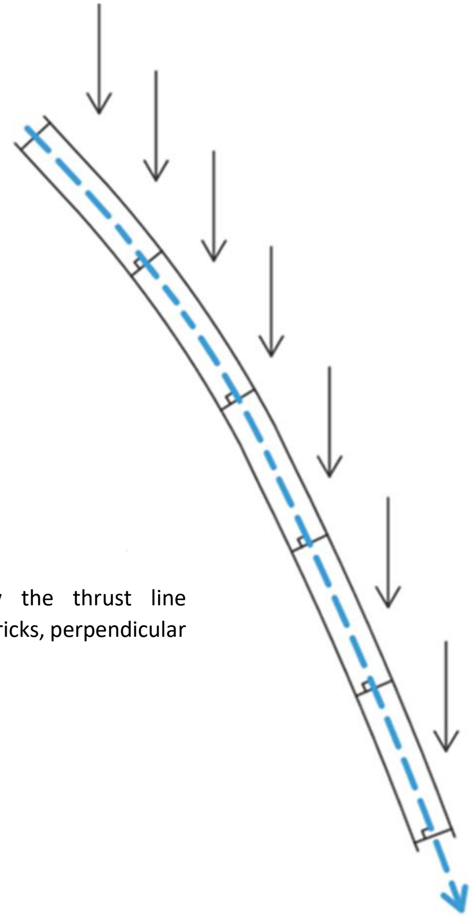


Illustration 53: How the thrust line transitions between bricks, perpendicular to the surface.

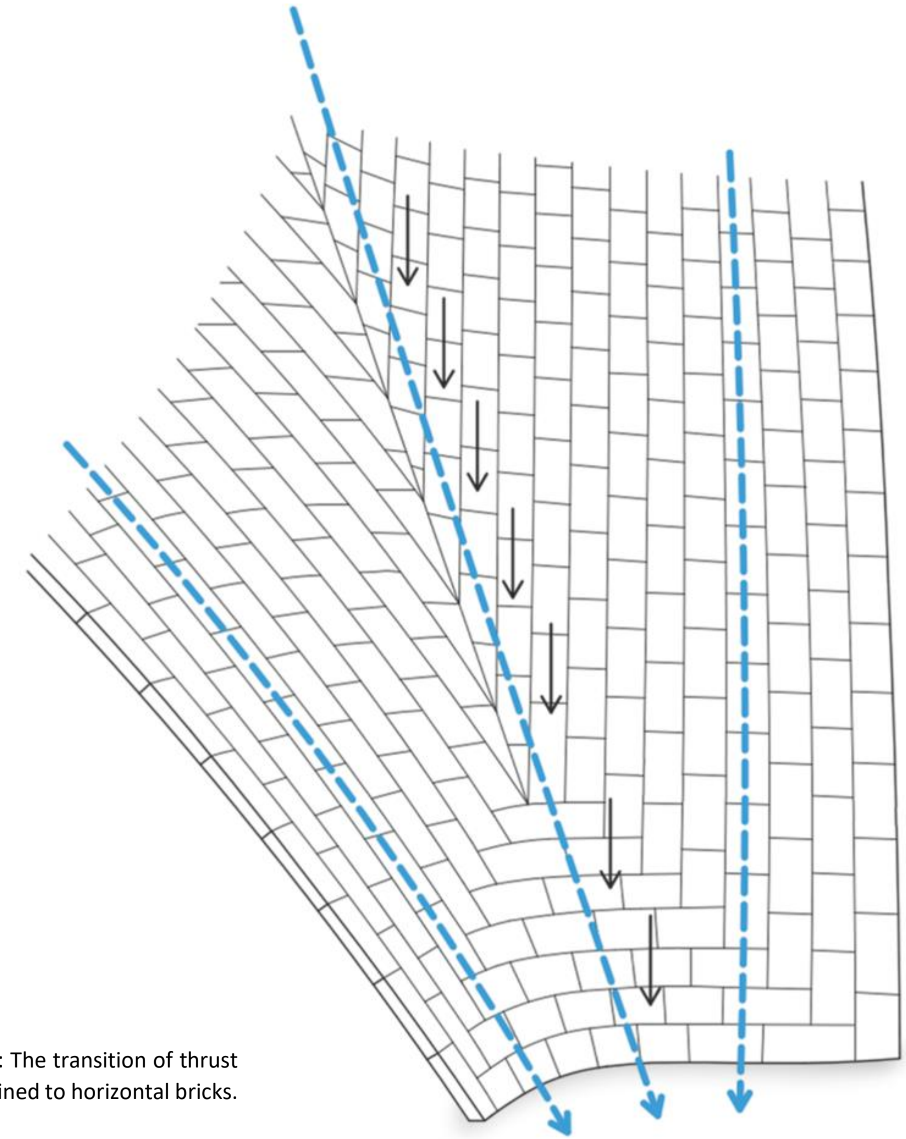
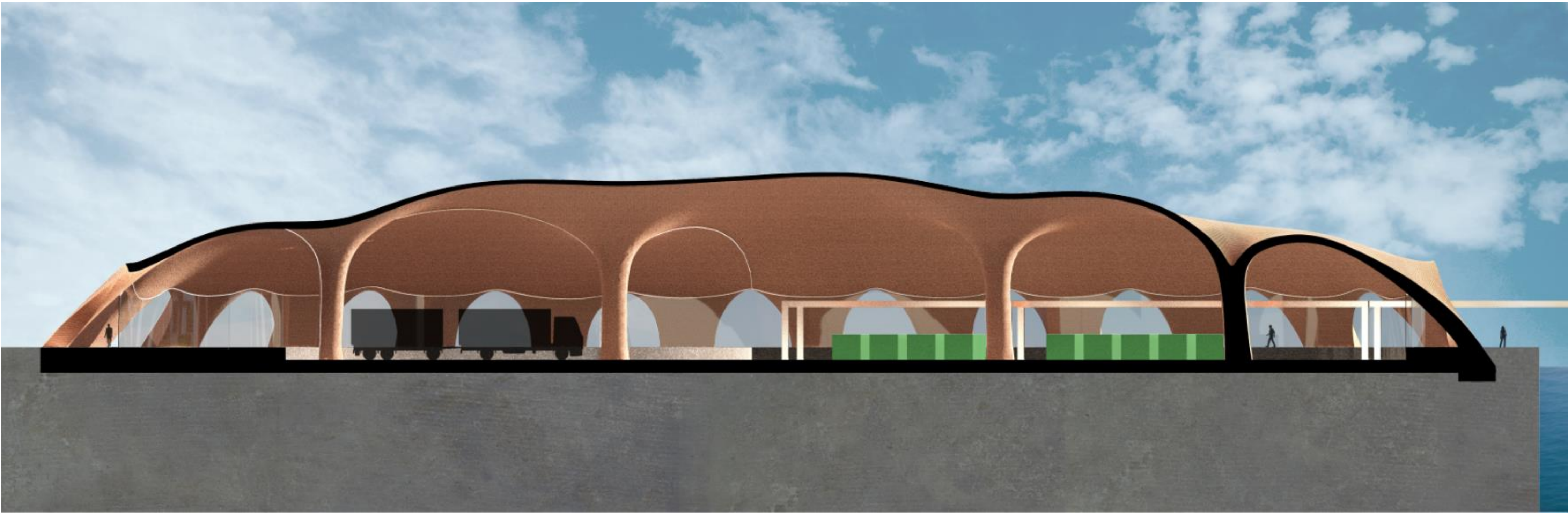


Illustration 54: The transition of thrust lines from inclined to horizontal bricks.

Illustration 55: Long section of the UCC building.



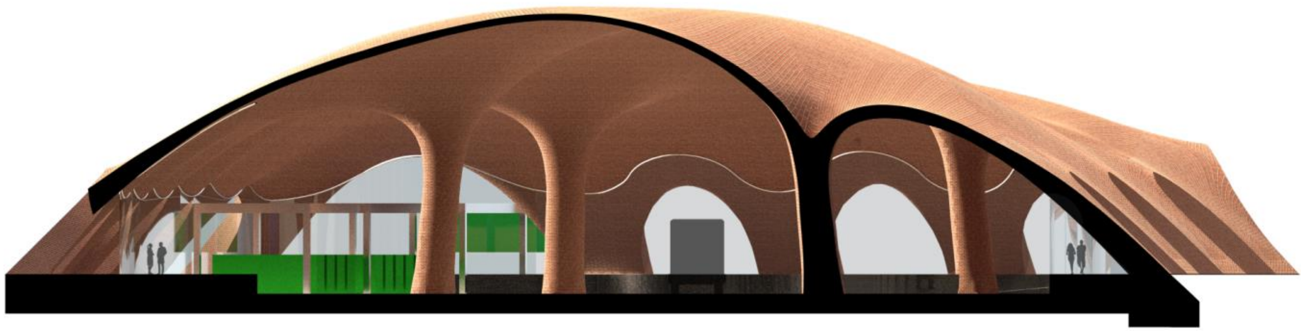


Illustration 56: Short section of the UCC.

Flows and function

The flows, meaning the general movement paths, inside and around the building can be divided in two categories: people and goods. The former can be further divided between workers of and visitors to the UCC. Workers would be split between the goods area, where they would handle the loading and unloading of goods coming to and from the UCC, and the service area, where they would manage the personal delivery service in the UCC. Visitors, meanwhile, would typically walk through a green lane, either coming from the Frihamnen area to the west or walking towards it, from the east, just north on the building, from which they would see and enter the entrance to the delivery service area. There, they would conduct their business before leaving through the same entrance.

Goods, however, pass through the building on its way to the Frihamnen area. 12-meter-long trucks carrying goods heading for Frihamnen come from the road's northern direction, turns from the main road and into the UCC. This is in contrast to the occasional 24-meter truck, which parks along the road, outside the building. In either case, the trucks park by the goods area, where the goods they carry are unloaded. Then, the 12-meter trucks exit through the other side of the building and moves onto the main road again. All trucks then pass beneath the Hisingsbron bridge and turns back north from hence they came. The goods left, however, are picked up by smaller electric vehicles and driven to its final destination in Frihamnen. On the way back, the same electric vehicles pick up waste from the area to the UCC. In the UCC, the waste is put into containers that, when filled, is lifted by machinery from the ground and hoisted onto a barge that is parked on the waterside to the south of the building. The barge then transports that waste to a nearby waste management facility.

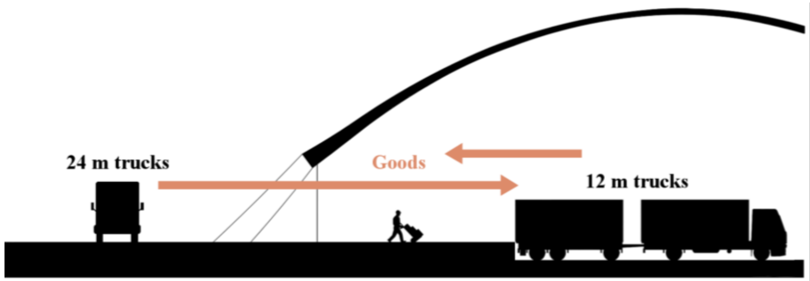


Illustration 57: A section of the loading area of the UCC.

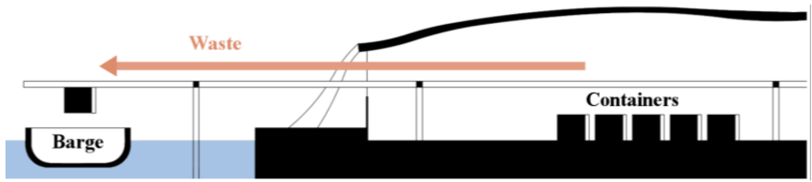


Illustration 58: A section illustrating the loading and unloading of containers, waterside.

These flows, defined by the building's function, influenced its design, especially the plan. For example, one markable design feature inside the building is the plan's change of elevation. This is to accommodate the function of the building, by separating people from trucks driving through it. It also helps workers to load and unload goods as well as to manage the height requirements demanded by the trucks. In addition to its internal composition, the trucks' movements also defined the building's relationship with its surrounding area.

As a UCC, a sort of logistics building, it is inherently tied to its urban context, not just its placement in relation to the city or to the Frihamnen area. The function also provides the restraints that motivate the shape of the building's plan, its relationship to the river, the surrounding buildings, and the road network. For example, just the fact that trucks come from the road in the northern direction and passing through to the west defines the placement of the entrance and the exit as well as the elongated plan. Similarly, the plan's slight curvature is a consequence both of the building's one-directional nature—with the trucks only entering though one side and only exiting out the other—as well as its need to occasionally accommodate much larger trucks which park just outside the loading area, along the space defined by the building's curvature.

The movements of pedestrians are directed using a walkway around the building, defined by a change in material from the surrounding cityscape. It generally follows the surrounding arcade but extends out at places to invite pedestrians into the walkway and the building.

What all this shows is the practical aspect of structure as architecture design. That this building has been designed for a real context with an actual function and program showcases the viability of this approach, even in a dense urban setting.

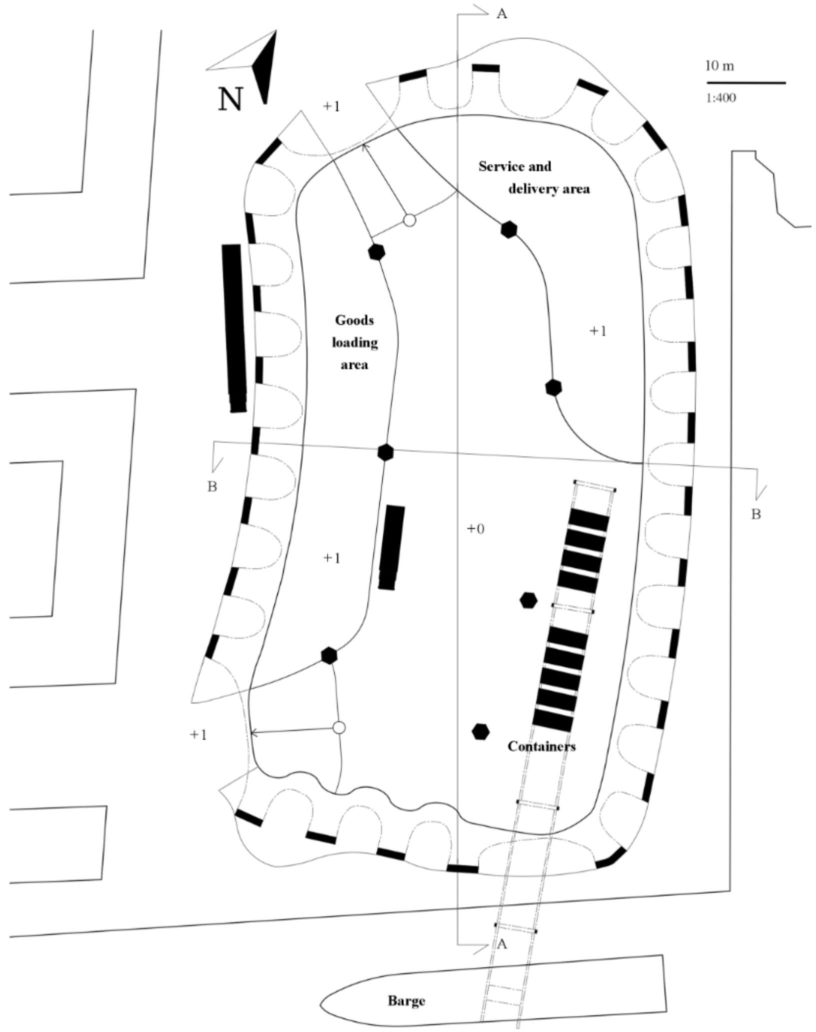


Illustration 59: A building plan of the UCC.

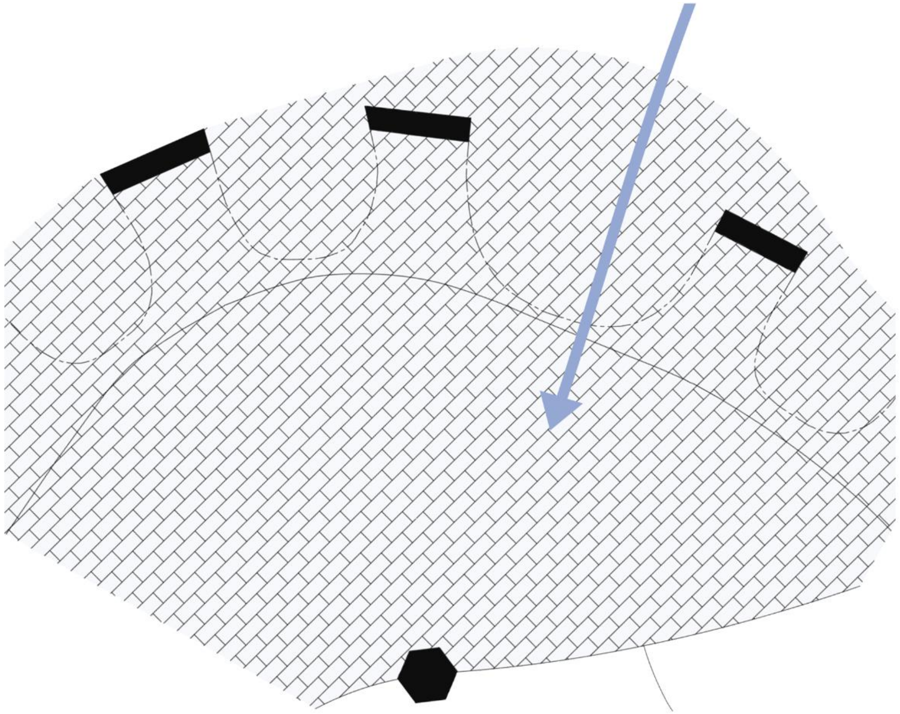


Illustration 60: Example of a visitor's path of entrance into the service and delivery area.

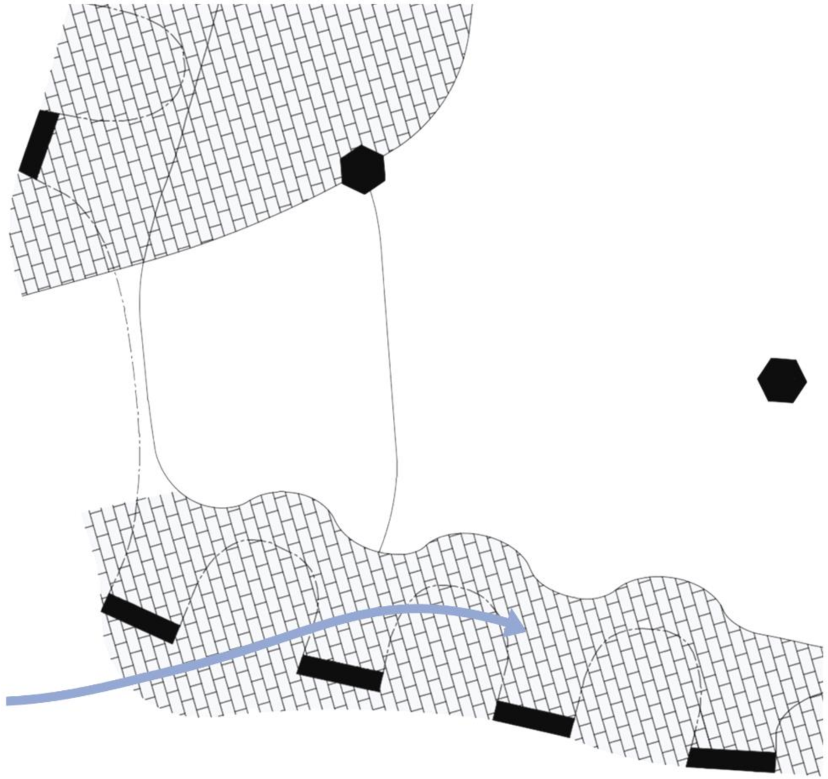


Illustration 61: Example of a visitor's path of entrance into the walkway.

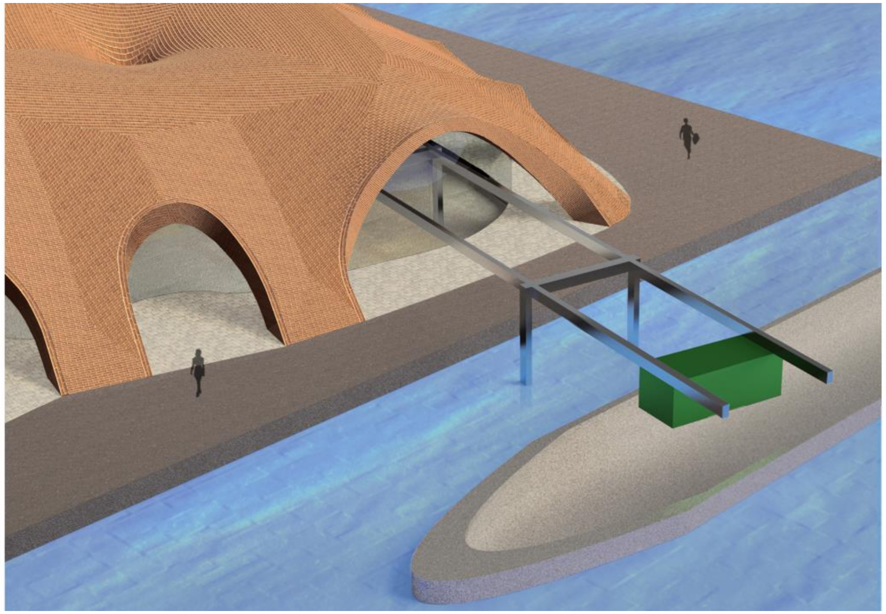


Illustration 62: View of the UCC’s barge loading.


Illustration 63: Street view, including the exit and the surrounding buildings.

Illustration 64: Entrance of the Service and delivery area.

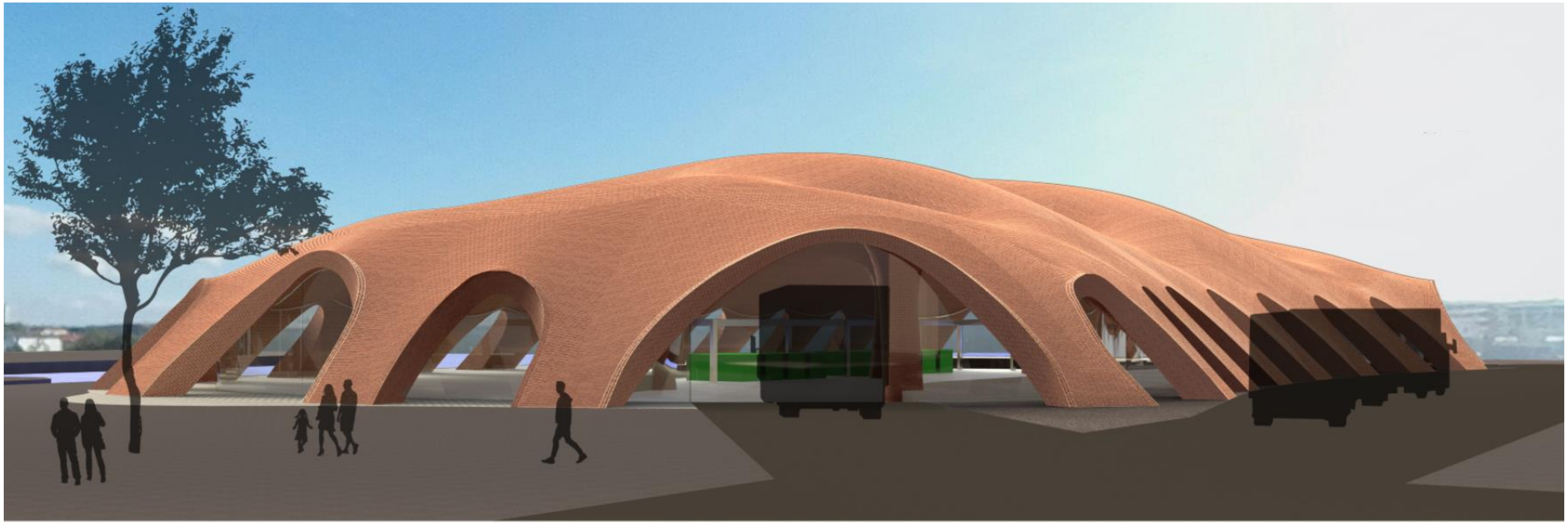


Illustration 65: Truck entrance and the exterior of the UCC building.

Foundation

The foundation is a thick slab of reinforced concrete and it fulfills several structural functions. To start, as the horizontal thrust pushes the edges of the vault outwards, the reinforced concrete handles the tension forces in between, keeping the structure together. Similarly, the generously sized slab helps to counteract the weight of the vault. With this heavy a structure, the vertical force is quite large, especially for the muddy ground in Gothenburg. So, by having a large slab with hollow sections that take up space otherwise occupied by ground soil, Archimedes' principle is used to provide a buoyant force to counteract this weight. The hollow cores also function as a space to hold wiring, air ducts, and other technical systems, so that they wouldn't have to be installed where they might break the continuation of the vault's brick pattern.

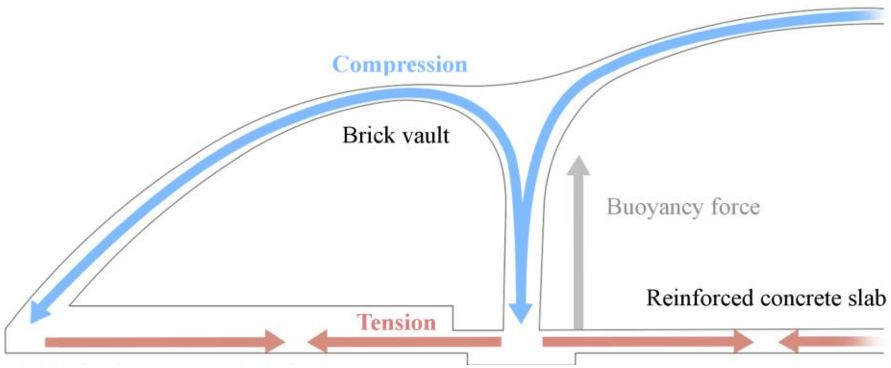


Illustration 66: Principle of tension and compression in the structure.

Finally, the slab helps to resist deformation issues. If, for example, one part of the building was to submerge slightly deeper than the rest due to some unevenness in the ground, then the stiff slab would ensure that the structure overall remains plane and that the placements of the supports are the same relative to each other, even if the structure as a whole moves slightly. This way, the foundation and the brick mortar help to reinforce each other to ensure that there are no issues of deformation in the building.

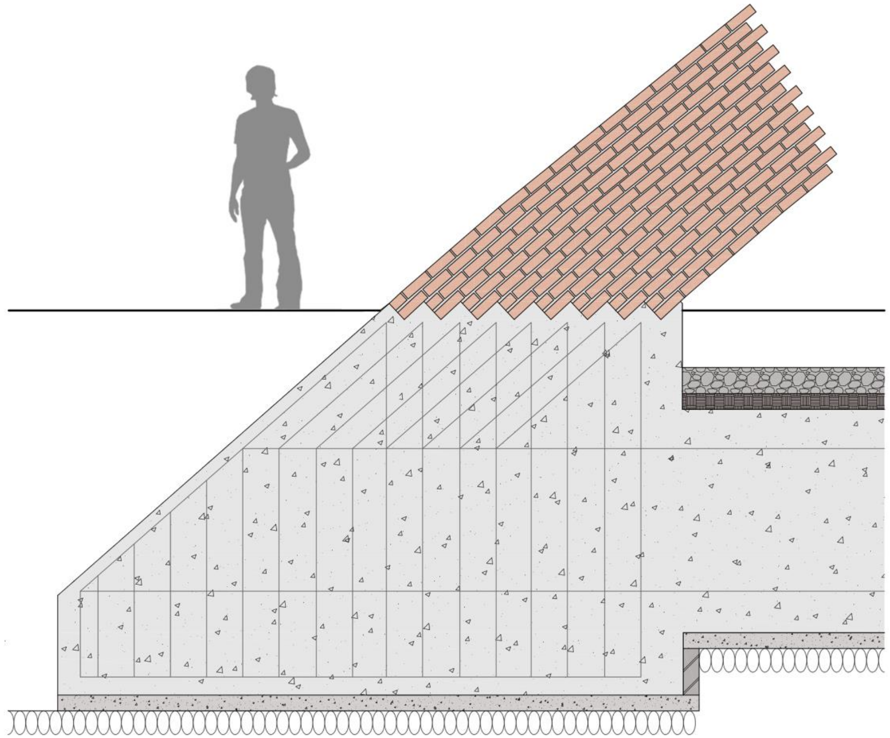


Illustration 67: Detail of the vaulted brick shell meeting the reinforced concrete slab.

Supports

There are two categories of supports in the building, internal and external supports. The internal supports are one of the main architectural features inside the building, standing as monoliths throughout the plan. From their base, they diverge and their cross-section expands as they approach the top and seamlessly flow into the vaulted roof. The internal supports are evenly distributed underneath the vaulted roof and ensure that the span of the vault does not exceed 25 meters, the reasonable limits of Guastavino vault based on examples such as the roofs of the St. Lawrence Basilica and the Tiffany and CO's New York City building.

They also help to break up the internal spaces and handle the drainage of rainwater in the vault. The way that they diverge towards the end and seamlessly flow into the vaulted roof also demonstrates the project's themes of structure as architecture design.

The outer supports meet the edges of the vaulted roof at an angle that makes it easy for the forces to transfer to the ground. They are shaped to have rounded edges, in a smooth and dynamic way that connects it to the vaulted roof itself. However, they also provide a contrast to the vault in other ways; for instance, they are thicker and of different material and color. Aesthetically, they are inspired by Luigi Nervi's Roman Sports Stadium.

The outer supports are placed evenly throughout the ends of the vault, framing the openings that provide its source of daylight and transparency. They are relatively thick at the base, to accommodate for the concentration of forces, but the thickness quickly narrows the closer their cross-sections approach the top of the vault. This hints at the thinness of the upper levels of the vault, and the accompanying elegance and material efficiency. The thickness increases again as the vault's cross-section approaches the inner supports.

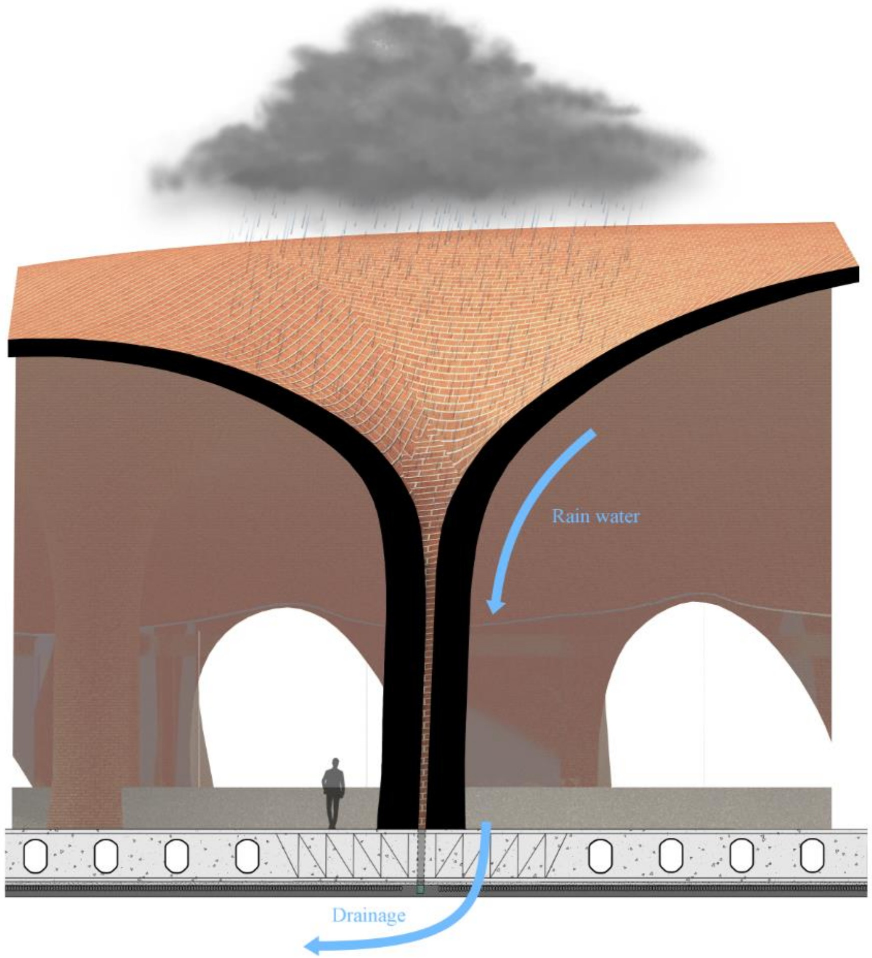


Illustration 68: Section of support column, showing handling of rain water as well as the meeting with the slab.

Spaces

The resulting vault structure has a dynamic form that is both flowing and organic in shape, yet rhythmic in composition, lending it a sense of balance. The shape itself also creates a variety of spaces that are both stimulating and out of the ordinary. For example, the space between the vertical glass walls and the outer supports form a natural corridor that shield against both rain and wind when walking beside the building. It also functions as an arcade that provides the opportunity to take a scenic walk around the building, where one can both look out onto the river or peer at the activity inside. There are even some designated lookout points by the riverside specifically for this, where people can stand and observe the logistics flow inside the building and gain a greater insight into how their goods are handled.

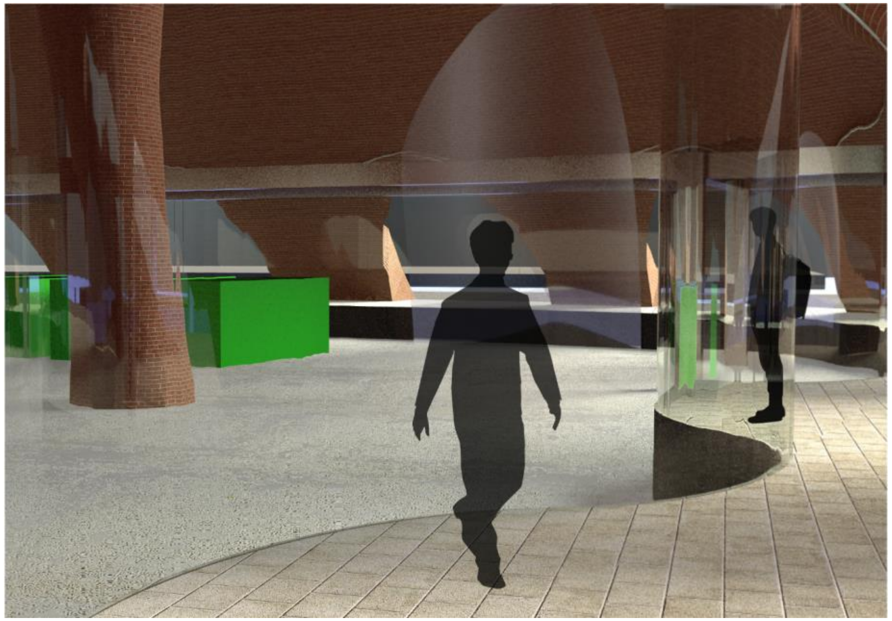


Illustration 69: The lookout points, a place made for visitors to stand and peek in to witness the structure or activities inside the building.

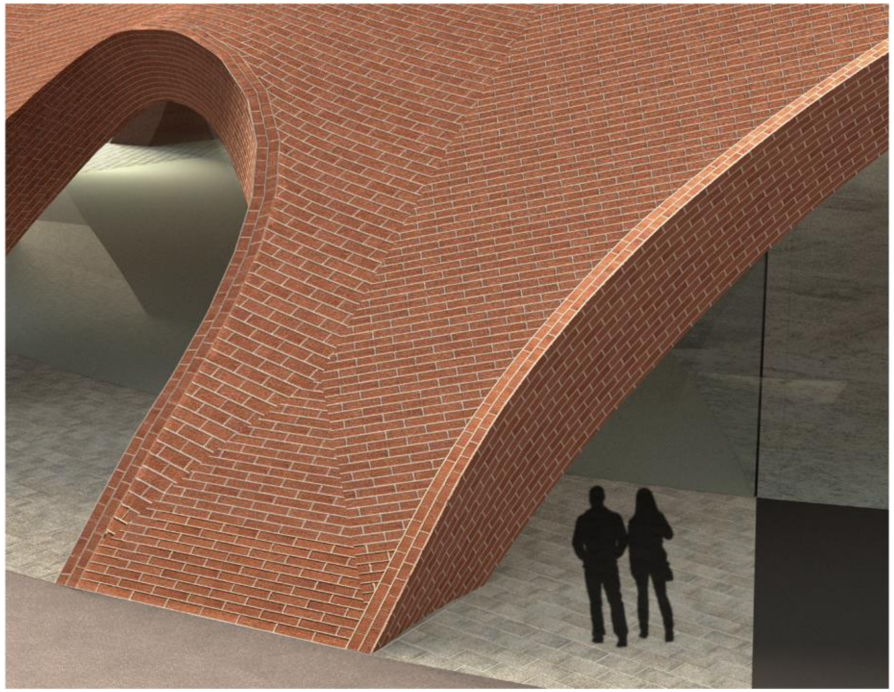
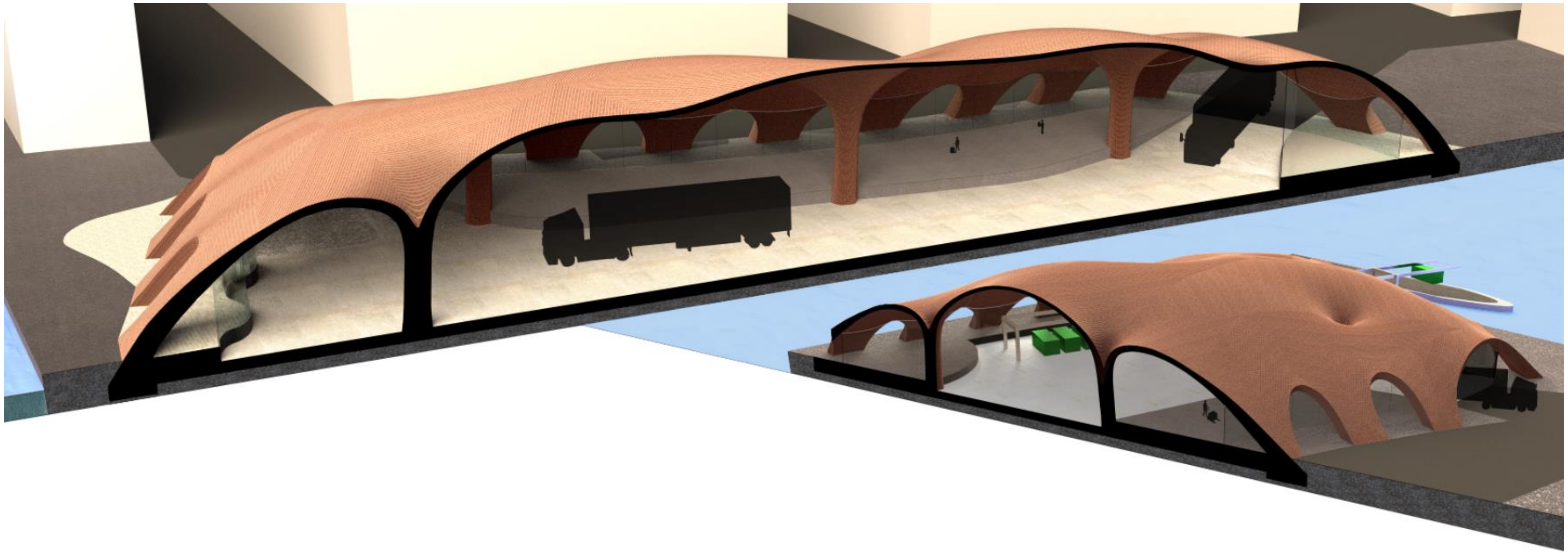


Illustration 70: Inclined end support.

Illustration 71: Long cross-section (top) and short cross-section (bottom) of the UCC.



Light

As some people will be regularly working inside the UCC, and some of the building will be used to host delivery services aimed towards the public, it is important to create an indoor environment that can be controlled and altered according to needs. Thus, the requirement for an enclosed space. However, it would also be in the interest of the public if they could witness the handling of their goods and waste, so that they could feel a deeper connection with the logistical flows that serve them.

To serve both ends, large parts of both the external and internal walls are composed of glass elements. This serves a dual purpose. To start, it lets a large amount of natural daylight into the building, making the UCC a more agreeable working environment. In addition, the prevalence of glass walls reinforces the desired impression of lightness to the structure, a design goal defined at the outset of the project.

Illustration 73: Glass wall of the Elbphilharmonie, Hamburg, that speaks the same visual language as the UCC’s glass walls.

Illustration 72: Exterior of the Maya Somaiya Library, with glass walls.

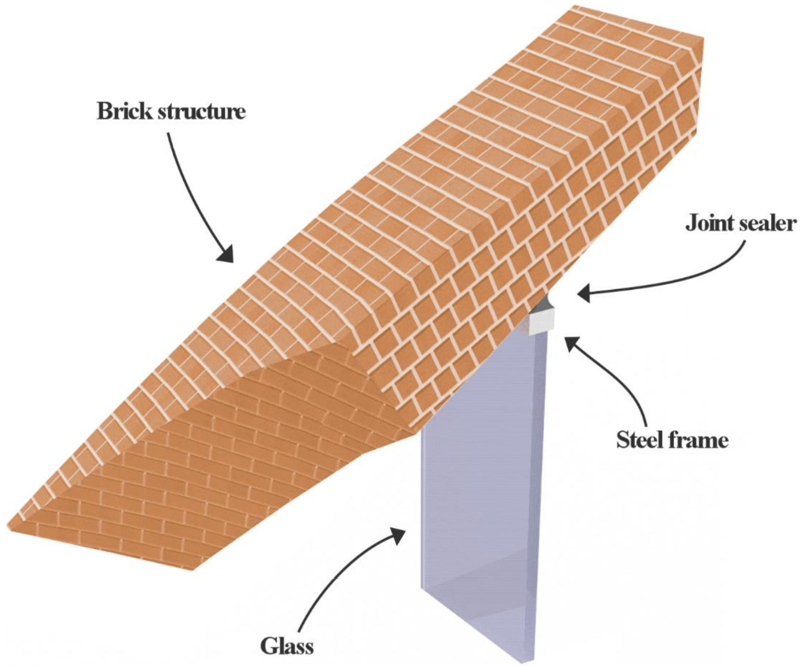


Illustration 74: Detail of the brick vault meeting the glass wall.

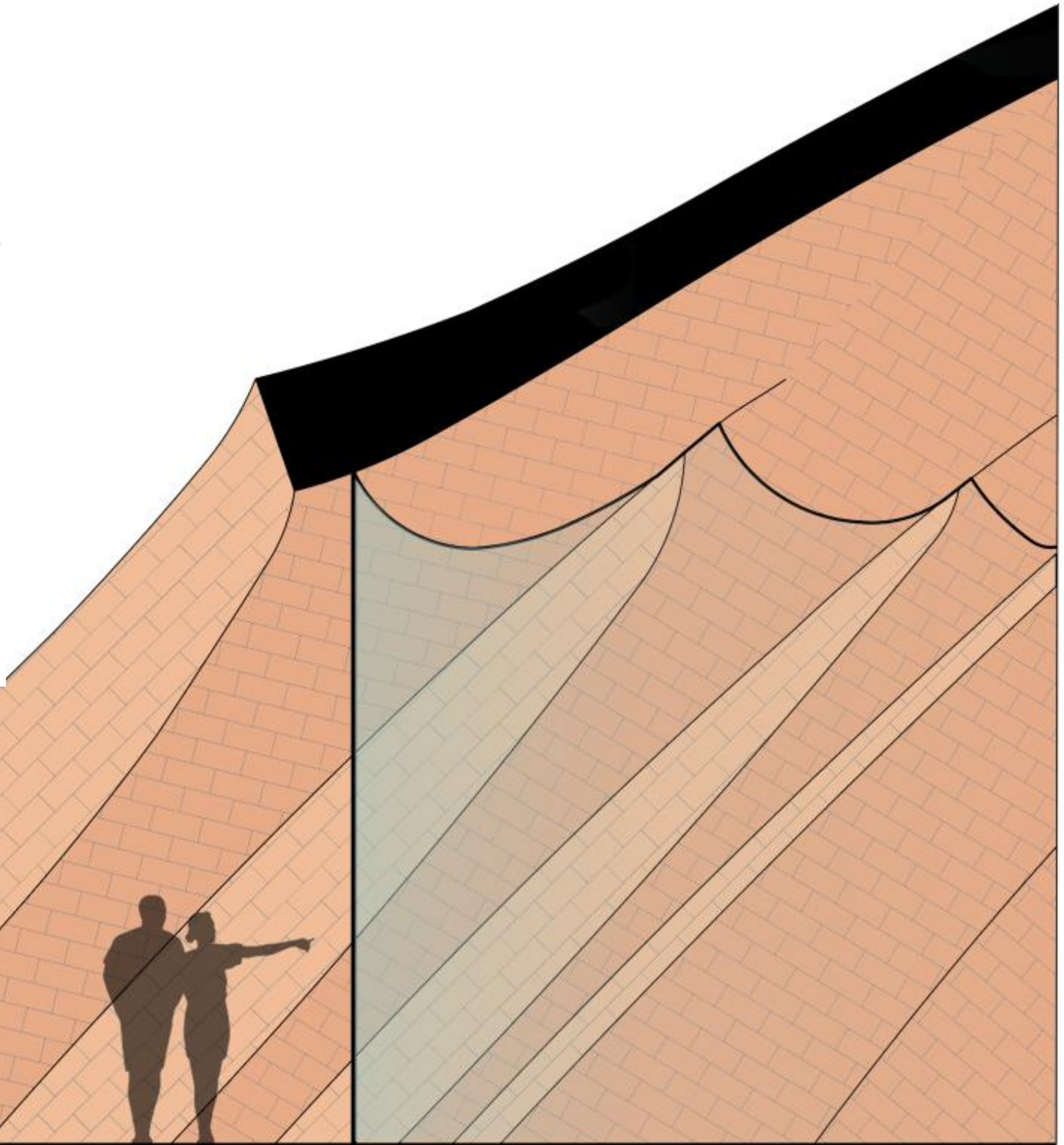


Illustration 75: A cross-section of the 'natural' walkway between the outer supports and inner glass wall.

CONCLUSIONS AND DISCUSSION

So, in conclusion, by building upon designs like Frei Otto's and Philippe Block's and by using an iterative design method, an actually proposed building was designed using the structure as architecture approach. The result was a brick vault with an anti-funicular form: a design where the load-bearing structure and the architectural expression can't be meaningfully separated from one another. Since the building's architectural features and load-bearing structure worked in tandem from the start, the use of materials was also effective. Not only that, but the spaces created by the form of the vault are compelling and cannot be easily replicated by more traditional methods of design. Neither can its dynamic shape, which would be easily visible for anyone using the new Hisingsbron bridge and would be a significant piece in Gothenburg's future skyline. Thus, the project achieved its aims of bridging the gap between structure and architecture and to demonstrate through building design that a load-bearing structure can be architecture in and of itself.

This demonstration is important for several reasons. To start, the fusing of architects and engineers could lead to more holistic building projects. This is not without complications, however. As was experienced in this project, one of the foremost challenges lied in the design process and methods by which to arrive at a design in which the load-bearing structure also serves as a pleasing architectural expression. It was challenging in the sense that any important decisions would have to be motivated from both an architectural and engineering aspect.

Also, a structure as architecture design approach could be a way of managing resources in the future. Since, as previously mentioned, when the load-bearing structure and architectural expression complement each other from the start, there is more efficient use of material. This principle could be used to lessen the toll of urbanization on natural resources in the future.

This serves as the answer to the focus question "Why mix the structural system with the architectural expression?". Also, an example of "How can the structural system and architectural expression of a building interplay in a way that that improves the quality of both?" and "In what ways can the structural system and architectural expression interplay?" is the anti-funicular form used in this project, as it unites structure with form in a visually pleasing yet structurally and materially efficient way. Finally, as to "How do you judge the quality of the two?", it comes down to a case-by-case basis. The key, however, is to strive for a design where the two aspects of architecture and load-bearing structure reinforce each other. For example, by using a form, like an anti-funicular vault, where the two are inseparable and also by choosing an aesthetically agreeable yet structurally sound material, like brick masonry was in this project.

To reflect on this project in retrospect, there are some things that could maybe be improved upon had the process been redone from the start or progressed further. For example, the layers inside the brick vault that makes its interior an indoor environment. The project could have been served by the investigation and addressing of potential brick masonry issues, such as leakages like those found in the Nya Krematoriet by Johan Celsing in Skogskyrkogården, Stockholm, or freezing damages. Another subject that could have been investigated further is the foundation.

If time had allowed, an investigation of the possibility to use point foundation—piles at the vault's points of contact against the ground, with tension wires in-between to handle horizontal loads—could potentially have been beneficial. Finally, the brick arrangement could maybe have been improved further. For instance, by making the change in directions smoother. A way to do this could have been to, instead of working from the top of the vault and then arrange the brick pattern 'downwards', to start from the ends of the support—the most 'sensitive' part of the structure, exposed to the highest concentration of forces—and arrange the brick pattern 'upwards' and handle the potentially challenging meetings in the brick pattern there instead.

COLLABORATORS

A list of some collaborators, people who may lend their knowledge and expertise to assist in the making of the project, from within Chalmers and the industry at large:

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