

# Force material form – transferring historical construction concepts into contemporary architectural design

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**ABSTRACT:** Considering the rich and complex construction history a history of ideas and concepts, improvisations and attempts, lots of inspiring facets can be made accessible for contemporary designers. A new teaching concept is therefore proposed pursuing the problem of structural form from three different directions: material properties, experimentation, and scientific concepts. The students translate the concepts of historical constructions studied in-depth into a contemporary context and develop new formal and constructional solutions by combining key features of historic examples with contemporary possibilities and conditions.

## 1 INTRODUCTION

Courses for both architects and structural engineers on the history of building construction commonly consist of mainstream examples in order to give a chronological overview of the achievements and milestones of different periods. These examples are mostly presented as case studies and function as a well-graded comparison of technological steps within the idea of progress in engineering science and building design. However, this view neglects the unique circumstances, requirements and inventions inherently attached to these examples. They also lack a differentiation of general attitudes leading to miscellaneous strategies and approaches.

A different teaching concept is therefore proposed pursuing the problem of structural form from three different directions: Developing out of

1. the use of building materials by complying with their inherent properties and characteristics
2. the theoretical and practical experimentation as well as analyzing principles and phenomena in nature
3. the scientific understanding of structures, which cultivates systemic descriptions of complex matter by establishing general principles

In doing so, it will be evident, which concepts of force flow are basically possible – both for structural analysis and design – and which of them found their way into building practice. In this context it will be an interesting finding to see that there are always many different correct structural solution for a given problem.

The changes in perceiving and understanding the problem of architectural and structural form are traced back by investigating the relationship of inner force flow, materialization of form, construction detail and design idea.

To make construction history more accessible but moreover usable for designers it appears reasonable to consider construction history a history of ideas and concepts, improvisations and attempts. Thereby specific problems seem to be recurrent and of fundamental nature and that there is a long tradition of constructional ideas. Actually it becomes obvious that the histories of structural theory and construction history show two very different paths.

In order to make use of the many rich concepts of building history, students are asked to translate the concepts of closely reviewed historical constructions into a contemporary context and develop new formal and constructional solutions by combining key features of historic examples with contemporary possibilities and conditions. They could also be used to demonstrate a very different understanding and conception of the relationship of form and force flow in architecture and engineering.

## 2 BASIC APPROACHES TO GAIN KNOWLEDGE

For the better understanding of how the three different approaches gain knowledge it is interesting to compare directly how findings are produced (figure 1). Knowing the material properties and their peculiarities is the only way to use materials in a sophisticated manner. Due to the various characteristics of natural materials – their microstructure – and the possibility or necessity to use them for many very different purposes it is necessary to collect the experiences made with them. This obviously applied to both successful and failed attempts. These insights are all together a larger body of acquired knowledge.

Experiments are in principle experiences but they are targeted at a specific question. Thus experimental (empirical) knowledge is an enforced answer and also forms inductively a law arisen from regularity of a phenomenon.

Scientific approaches, here coming from the mechanics, aim to formulate a universal law valid for a given scope. Afterwards several conclusions are deduced from it in order to formulate answers to many different problems. Because these theories possess a conceptual directive and develop knowledge from the general to the specific they provide a macrostructure to the solution of a problem.

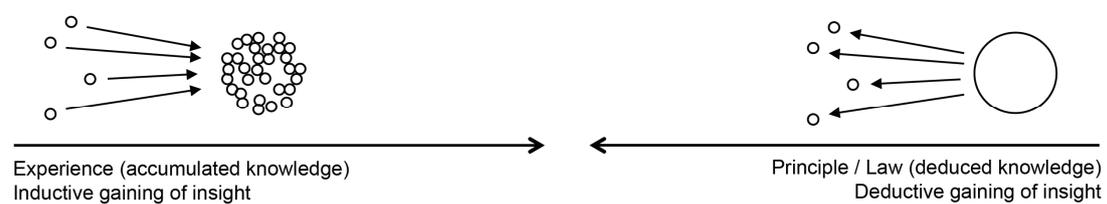


Figure 1. Abstract comparison of inductive and deductive knowledge production

## 3 MATERIAL CHARACTERISTICS AS A DESIGN BASIS

### 3.1 *Microstructure*

Deriving construction principles from the inherent properties of building materials means to understand the material's strengths or weaknesses, which are a result of the material's specific inner structure, i.e. its microstructure. This microstructure also gives evidence whether this strength is directional or not. Natural building materials, e.g. timber or stone, are heterogeneous, and if their heterogeneity is directional, as it is at least for timber, then they also possess anisotropy. Heterogeneity mostly leads to greater dimensions of the structural components because it is harder to ensure the soundness of the continuous material and the reliability of load path and force transmission. For the natural stone this means – together with its limited capacity of transferring tension forces – a considerable increase of dimensions for the respective material use. This can also be comprehended by studying natural stonewalls of great height or if single pieces, which have to withstand larger spans.

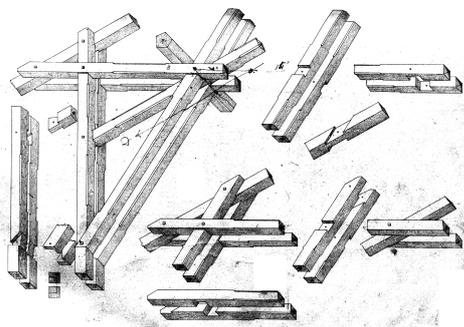


Figure 2. Overlay emerging from the necessity of continuous members (Moller 1833)

The anisotropy of timber leads to great importance how to arrange pieces according to the anticipated load direction. Since it has a much greater strength in its longitudinal direction due to its internal fiber structure timber was often used to form framework structures. The relation between microstructure and structural form or layout can thus be directly demonstrated.

### 3.2 Connections

Equally important to this relationship is the dependency of the type of the structural members' connection joints from the material strength and the microstructure. For timber pieces the transferred forces always needs to be directed into the member's longitudinal direction, which is why often complex connection details arise creating large geometrical-ly complicated surface areas of the joints. In order to reduce complexity timber designs always sought to reduce tensile connections. Furthermore, framework members were often arranged spatially in several layers letting them run continuously to produce a smaller number of connections, which also provided a higher stiffness (Figure 2). This characteristic form of interweaving bars generates a subtle timber inherent articulation of space. These kinds of timber-based approaches also serve as distinguished ways to achieve framework layouts very much different from contemporary industrial types, which bring all members together in one single plane. Considering contemporary manufacturing processes these types of timber construction techniques could easily be applied.

The consideration of stone connections leads to the question of how important joints are for the entity of stone elements forming something like a wall. A comparison of the stone microstructure and the joints of stones within a wall could help to understand the necessity of an orientation of both the inner structure of the material (alignment of elements) and the joints (alignment of cutting line) in respect to the anticipated load direction.

### 3.3 Industrialization of building materials

The production and use of industrially fabricated materials in large quantities like iron by the end of the 18<sup>th</sup> century, or together with concrete (reinforced concrete) by the end of the 19<sup>th</sup> century, fundamentally changed the way construction members were used and connected. In this context, the microstructure was restructured because industrial manufacturing processes lead to more homogeneous materials. Both iron and reinforced concrete "naturally" possess greater strength but also a greater certainty of material quality. For these reasons they can be used in smaller dimensions and connections are much more simple. Because iron members are much smaller in size and connections can be reduced to relatively small points even iron sheets are added to provide a discrete element for the members to meet. Only from this introduction sheets are used in building construction and soon also even to simplify timber connections. The dependencies of the resulting member layout to connection requirements as well as member dimensions can be seen in figure 3, where typical timber and iron roof structures are displayed.

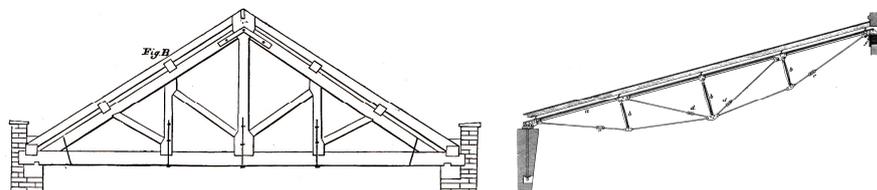


Figure 3. Conditions of member connection and resulting overall layout and shape

The reinforcement of stone structures like walls and pillars go back to the Romans who used iron clamps to interlock adjoining stones. When iron became readily available in the 19<sup>th</sup> century it was also extensively used to enhance stone constructions, which allowed the dramatic deduction of their dimensions. For some of these constructions iron even became the actual load bearing structure as it can be seen in figure 4. These examples are important to understand the early interpretation and use of reinforced concrete, when it was partly not perceived as a linear substitute of a beam but a closely connected entity of stone segments held in place by iron reinforcement.

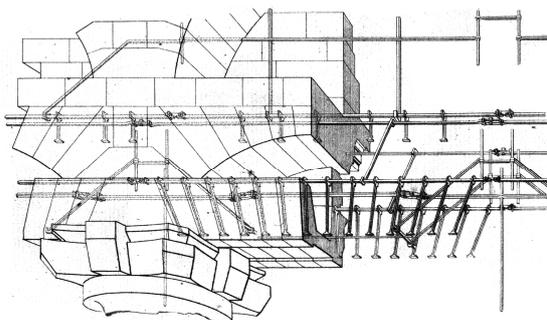


Figure 4. Iron loadbearing structure and connected stones (Rondelet 1817)

### 3.4 Formal appropriateness of material use

“New materials” initially evoke “old uses” of materials. During their early decades both iron and reinforced concrete are only surrogates and are “modeled” according to a traditional understanding of construction. By tracing the roads of development and important construction examples not only the progressive (but definitely not straight) way towards a formally appropriate use of materials can be shown but also many other possible alternatives. The development of a material use is often pushed by an idea of efficiency but also by considering manufacturing processes. Concrete, for instance, is cast continuously into any formwork and is, by nature, not linearly shaped but best used as continuous planar structural elements. Figure 5 shows two examples of this development from its early use as surrogate of linear timber or iron beams to thin shells. Because criteria for form development of material change and the latest (mostly considered best developed solution) is often a favorite option to designers, older episodes of a material use can reveal remarkably smart and expressive ways of construction.



Figure 5. Warehouse in Strassburg, 1899, and Market hall in Frankfurt, 1927

### 3.5 Decrease of constructional conditions

Every material used for construction requires its unique way how and in which form components can be formed and connected. Looking at the specific properties of a material and what arises therefrom in terms of form and connection requirements coming from nature and arriving at industrial materials reveals a loss of conditions for the emergence of constructions. Connections become stronger and smaller at the same timer; for reinforced concrete there are theoretically no natural joints but only one firmly bound entity. Figure 6 shows the characteristic standard types of connections of traditional timber, classic iron, and early reinforced concrete in comparison.

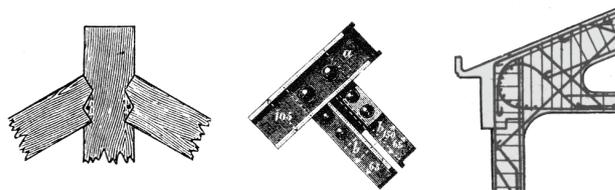


Figure 6. Characteristic standard type of connection of timber, iron, and reinforced concrete

To understand the formal connections and developments between materials it might prove helpful to arrange their appearance and specify their internal structure graphically. Figure 7 gives a very radical description of these correlations. Here, the abovementioned aspects, i.e. microstructure, its homogenization, combinations, and decrease of conditions can be followed.

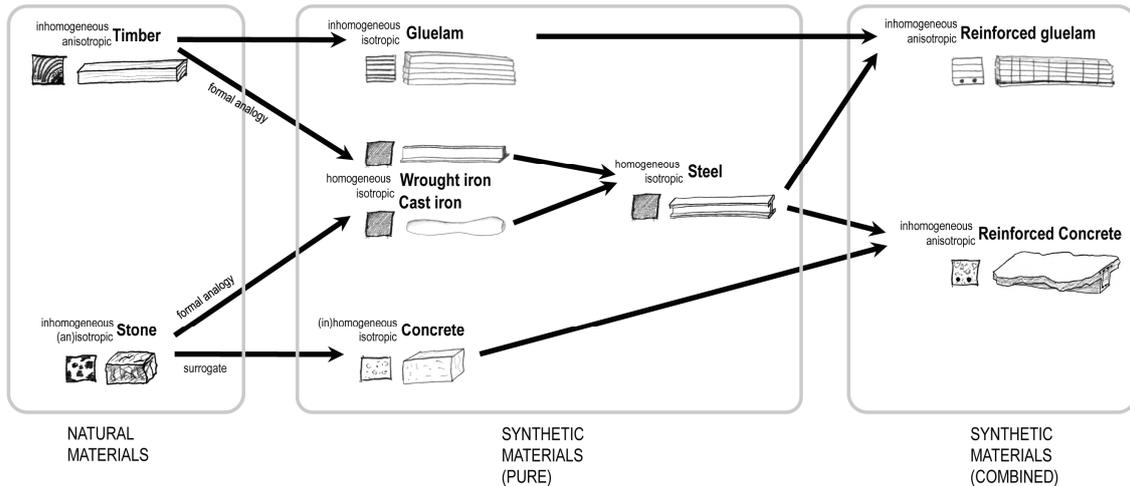


Figure 7. Logic of formal and constructive relations between materials

#### 4 EXPERIMENTATION AND THE IMITATION OF NATURAL PHENOMENA

The long tradition of experimentation in building history covers the testing of new materials or materials in a innovative way but also the determination of principles like the formation of structural form under certain conditions, e.g. geometry or loads. Since Galileo Galilei such systematic approaches are regularly carried out in order to articulate specific questions about general phenomena in mechanics but also often to find authentication for purely theoretically derived principles. There are many “modern” examples of an empirical form finding process, which can be used to illustrate the necessity to moderate material boundaries, fabrication requirements, geometrical conditions, or formal demands. One popular case is the development of the Britannia Bridge designed by Robert Stephenson in 1850 altered from suspension to beam bridge and developed specifically in detail to accommodate the high compression forces with means of iron sheet construction.

One major aspect of studying the possibilities of empiricism is the analysis of natural phenomena and their imitation. This helps to understand both the natural efficiency dealing with common physical problems and new ways of approaching new design possibilities. A very comprehensive approach has been undertaken by the Scottish mathematician and biologist D’Arcy Thompson (D’Arcy 1917), who studied amongst other things the shape and structure of many animals’ skeletons. Figure 8 shows two examples of this study, which revealed the distribution of bones and their specific shape according to their presumed load. The comparison of these “natural load-bearing structures” also displays the effect of scale when looking at gravity issues comparing the ratio of total weight and the weight portion of all bones: mouse 8% vs. human 18%. Following these basic observations it is much easier to explain the disproportional performance of two different beams of the same dimension and relative load but different length.

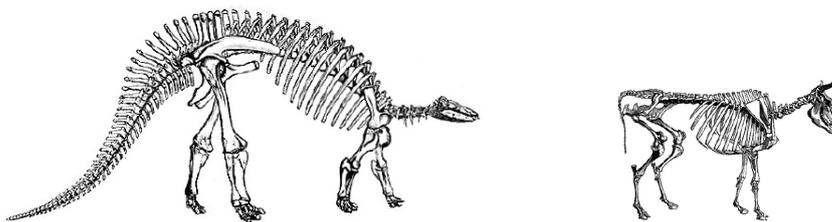


Figure 8. D’Arcy Thompson on the relation of load and the skeleton structure

One can also derive construction principles directly from nature as Frei Otto practised it. This can lead to specific arrangements of structural elements and their connections, which is not logically derived from the use of a certain material. Figure 9 shows one of Frei Otto’s experimental construction principles inspired from in-depth studies of cell structures.

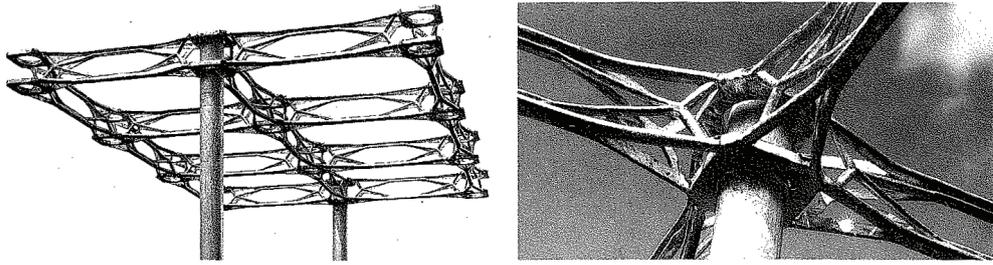


Figure 9. Study for a girder grid by Frei Otto, 1965 (Barthel 1990)

Prominent examples of structural forms derived “naturally” are the hanging models from Antoni Gaudi, Frei Otto, or Heinz Isler. These designers applied a method developed at the early 19<sup>th</sup> century. They obtained a direct form response by using a tensile structure representing a certain compression structure, e.g. vault or shell, in reverse and which was adjusted according to the original geometrical boundary conditions. Figure 10 shows a concrete shell developed by Swiss engineer Heinz Isler in 1968 and one of his many hanging models.

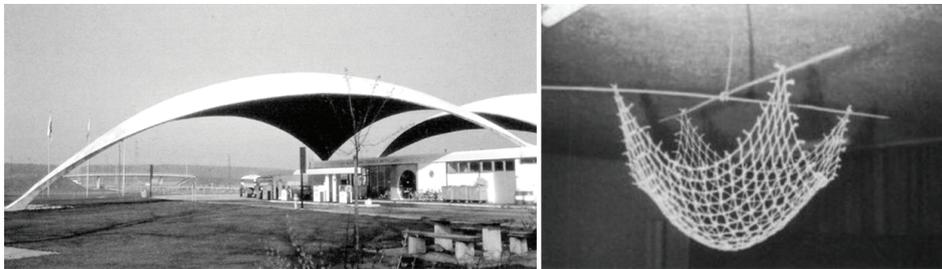


Figure 10. Rest stop in Deitingen, Switzerland, 1968 by Heinz Isler and the hanging model

## 5 RATIONALITY AND SCIENTIFIC CONCEPTS AS DESIGN DRIVERS

Concept based approaches found their way into design and building practice at the beginning of 19<sup>th</sup> century. This general paradigmatic change in dealing with technical problems goes back to the reorganization and institutionalization of engineering education. These approaches are characterized by the systematic description of boundary conditions and requirements, which lead to a direct and formalized response, but do not have to be non-ambiguous and explicit.

A very rich period of development and innovation is the bridge building culture in North America during the first half of the 19<sup>th</sup> century. After many imported structural concepts from Europe were found too complicated or expensive to build many (often self-made) designers developed their own concepts. There is a remarkable amount of bridge construction patents registered at that time, which have also been studied by European engineers and builders. The best known and most illustrative is Karl Culmann’s report on his journey in 1850-1852 (Culmann 1851).

One major problem to the new infrastructure of the expanding railway system in Europe and North America was the new phenomenon of very high moving loads caused by the heavy trains running across the (often large span) bridges. The structural concepts developed therefore are very different in Europe and North America at that time due to different design cultures; whereas in Europe a distinct academic engineering culture was established in North America a culture of pragmatism was predominant.

For the problem of the moving trainloads the American self-taught engineer Wendel Bollman developed a solution, which can be described as an overlay of a hanging pair of cables for all possible locations. This overlay is a systematic approach resulting in a rational design, but it does not seek to form an integral system; it is rather a sum of many equally important systems. Figure 11 shows Bollman’s design and a typical American timber bridge of the early 19<sup>th</sup> century with a similar approach by strutting all posts additionally from each abutment.

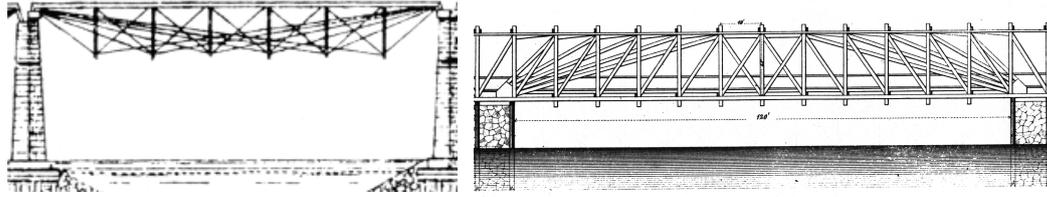


Figure 11. Iron bridge by Wendel Bollman, 1868, and typical American timber bridge, early 19<sup>th</sup> century

There is a similar design approach from Albert Fink, a German engineer, who received a professional training and worked later in the United States. He also developed a system, which consists of several minor systems providing support for different locations of the load. But instead of supporting each of these individual systems directly from the abutments the supporting mechanisms are interlocked; the load transfer is organized hierarchically towards the center of the span and from there to the ends. This at first sight looks very complicated or even playful but it is effective inasmuch as it always centers the moving load to eventually arrive at the highest hierarchical level in the center of the span. Figure 12 shows this concept and a timber bridge with a similar approach documented by Andrea Palladio (Palladio 1570).

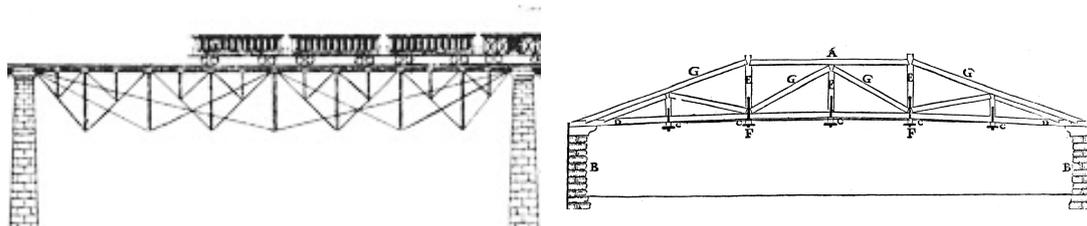


Figure 12. Iron bridge by Albert Fink, 1859, timber bridge over the River Cismone, 16<sup>th</sup> century

Also in Europe many concepts of truss layouts have been developed at that time. One important work is the theory developed by Johann W. Schwedler in 1851. In his derivation of an optimal truss configuration seeking equal dimensions in the chords and minimal stress in the diagonals under moving loads Schwedler arrives at the theoretical form given in figure 13. The comparison of integral and overlaid systems can be enriching to a formal design spectrum and should be considered for a broader use of design approaches.

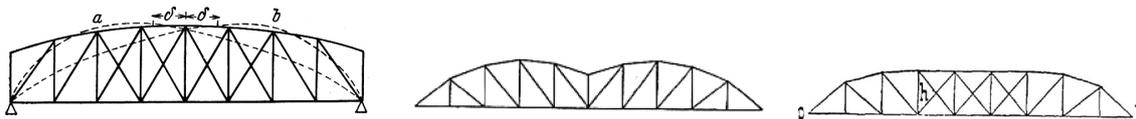


Figure 13. Development of an optimal truss beam for moving loads, Johann W. Schwedler, 1851

## 6 TRANSFERRING HISTORICAL CONCEPTS INTO CONTEMPORARY DESIGN

During a period of eight weeks the students of the course shall develop their own design concepts basing on historical inventions, construction principles, or experimental studies they studied in depth. To do so they can enhance a construction principle with new technical means, study the role of materials within construction principles, or develop small projects from formal criteria of structural principles in order to transform historical but valuable ideas into contemporary architectural design. It is important to note that the results presented by the students are still conceptual; the aim is to generate new applications of original design or construction inventions by cultivating an intellectual discussion of basic concepts and their dependencies both formally and technically. Figures 14 and 15 show two examples of student projects.



Figure 14. Study of interlinked hanging chains and application for a x-mas illumination concept

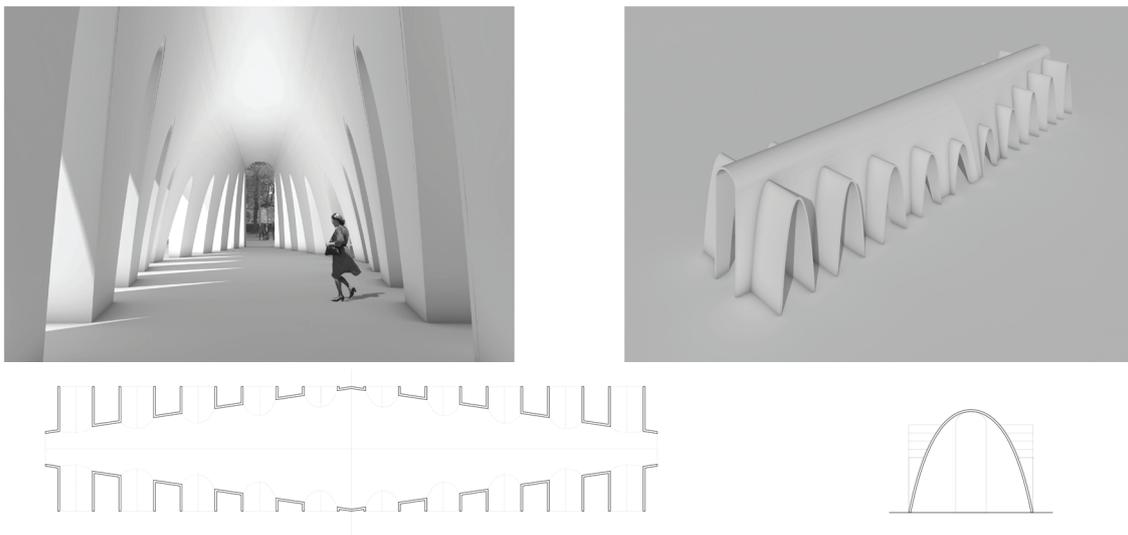


Figure 15. Intersected concrete shells varying inclination in combination with crossing vaults

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