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CONCEPTUAL DESIGN OF STRUCTURES AS A MEETING POINT BETWEEN ARCHITECTURE AND ENGINEERING. THE FORMALIZATION OF STRUCTURAL INTUITION AND ITS USE AS A DESIGN AND TEACHING TOOL

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For my wife Nataliya

and our kids Sofia, Daniele, and Miriam

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The path that has led me to completing this thesis has been long and full of relationships that have made this project a success. Therefore, there are many people that I want to thank, without them this project would not have seen the light of day.

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INDEX

ABSTRACT

Structural creativity is the combination of three inseparable elements. The first element is the ability to conceive a structure that optimally solves all the structural issues related to equilibrium, stability, resistance, stiffness, ductility, and durability. The second element is the creation of the spaces and volumes required by each architectural project. The third element is the optimization of all the other architectural requirements such as illumination, aeration, and aesthetics. Therefore, the conception of a structure is a creative process, as it means the creation of a new object from a series of external conditions set by the architectural project. However, this creativity is not as free as artistic creativity, as it requires in-depth knowledge of the fundamental structural principles. Hence, this type of creativity, unlike that of art, does not exclusively rely on personal talent, but people can be trained and taught in it.

The main goal of this work is the formalization of structural creativity, revealing the structural principles on which it is based, in order to transform it into a design tool available to architectural and structural designers. This project is based on four premises. The importance of a common language between architects and engineers and the existence of teaching methods that favor collaboration make up the first premise. After identifying the reasons why the separation between architecture and engineering occurred, some teaching approaches that have been experimented with since the 1980s in different European and North American universities are presented, with the aim of promoting a rapprochement between the two professions. The advantages of using graphic statics and graphic methods to favor the collaboration of architects and engineers is the second premise. Graphic statics has a fundamental role in the creation of structural creativity. In order to overcome the limitations that have led to graphic statics being abandoned in favor of analytical statics, i.e., the laboriousness of graphic constructions and the iterative nature of the process of researching the natural shape of the loads, an original formulation of the Cremona-Maxwell method in matrix form is presented. This formulation enables graphic statics to be used for form-finding purposes. The importance of the history of constructions and of structural engineering and the lack of research and courses on these subjects in engineering faculty curricula are the third premise. After defining the characteristic of this hybrid discipline, which integrates historiographic methods with technical engineering methods, two original examples of research on the history of structures are presented. The first of these examples is the importance of the Palace of Ctesiphon in the history of structural engineering, and the

second is the work of the Swiss engineer Henry Lossier. The advantages of collaboration between architects and engineers based on the structural conception is the fourth premise. The analysis and presentation of two specific projects, the Volta school in Basel, by the architects Miller and Maranta and the engineer Jürg Conzett, and the retirement home in Giornico, by the architects Baserga and Mozzetti and the engineers Pedrazzini Guidotti, show how collaboration between architects and engineers from the early stages of design encourages structural creativity.

In order to formalize structural creativity, the objective, measurable, and therefore, formalizable aspects of this creativity must be identified. These aspects come from the fact that all structures need to be safe and efficient. This need for safety and efficiency limits, and also drives, structural creativity. There are many aspects that an engineer must consider to guarantee structural safety and efficiency: balance, structural typology, shape, mechanical properties of materials, geometry of the elements, position of supports, etc. All these aspects and the variety of solutions available that meet safety and efficiency requirements are the essence of structural creativity. After highlighting the role of intuition and experience in the conception of a creative structure, the formalization of three technical aspects on which structural creativity depends have been developed: equilibrium, the position and type of the supports, and the form. These technical aspects are illustrated by presenting and analyzing buildings that exemplify each of these three aspects. The APG Golf Club in Luque, Paraguay, by the architect Javier Corvalán, has been analyzed to show the role of equilibrium in the formation of structural intuition. The roof of the Ascona lido by the architect Livio Vacchini has been chosen to show the role of the type and position of the supports. In order to show the role of form in the creation of structural intuition, the structural solution chosen by Livio Vacchini for the roof of the gymnasium in Losone, a grid of prestressed reinforced concrete beams, has been compared to other possible structural solutions involving the use of shape resistant structures and vector resistant structures. Finally, the role of context – geographical, economic, political, and of tradition – in the creation of structural intuition has been analyzed, by presenting an original piece of research on promoting the diffusion of timber buildings in the Swiss region of Ticino, as a result of the enhancement of local building traditions.

If structural intuition can be formalized, it can also be taught. Therefore, some teaching experiments carried out at the Mendrisio Academy of Architecture, Switzerland, on the teaching of structural design, are presented. These experiments are based on research on the formalization of structural intuition, as well as on the results of some questionnaires specifically prepared and given to architecture students and professional architects to investigate the level of interest that architects have in structural issues and the state of the relationship between architects and engineers. The purpose of the experiments is also to show the advantages of fruitful collaboration between architects and engineers.

RESUMEN

La creatividad estructural es la combinación de tres elementos inseparables. El primer elemento es la capacidad de concebir una estructura que resuelva de manera óptima todos los problemas estructurales relacionados con el equilibrio, la estabilidad, la resistencia, la rigidez, la ductilidad y la durabilidad. El segundo elemento es la creación de los espacios y volúmenes que requiere cada proyecto arquitectónico. El tercer elemento es la optimización de todos los demás requisitos arquitectónicos como la iluminación, la aireación y la estética. Por lo tanto, la concepción de una estructura es un proceso creativo, ya que implica la creación de un nuevo objeto a partir de una serie de condiciones externas establecidas por el proyecto arquitectónico. Sin embargo, esta creatividad no es tan libre como la creatividad artística, ya que requiere un conocimiento profundo de los principios estructurales fundamentales. Este tipo de creatividad, a diferencia de la del arte, no se basa exclusivamente en el talento personal, y se debe formar y enseñar.

El objetivo principal de este trabajo es la formalización de la creatividad estructural, revelando los principios estructurales en los que se basa, para transformarla en una herramienta de diseño disponible para los diseñadores arquitectónicos y estructurales. Este proyecto se basa en cuatro premisas. La importancia de un lenguaje común entre arquitectos e ingenieros y la existencia de métodos de enseñanza que favorezcan la colaboración constituyen la primera premisa. Tras identificar las razones por las que se produjo la separación entre arquitectura e ingeniería, se presentan algunos enfoques didácticos que se han experimentado desde la década de 1980 en diferentes universidades europeas y norteamericanas, con el objetivo de promover un acercamiento entre las profesiones. Las ventajas de utilizar la estática gráfica y los métodos gráficos para favorecer la colaboración entre arquitectos e ingenieros constituyen la segunda premisa. La estática gráfica tiene un papel fundamental en la creación de la creatividad estructural. Para superar las limitaciones que han llevado al abandono de la estática gráfica en favor de la estática analítica, es decir, la laboriosidad de las construcciones gráficas y la iteratividad del proceso de búsqueda de la forma natural de las cargas, se presenta una formulación original del método de Cremona-Maxwell en forma matricial. Esta formulación permite que la estática gráfica se utilice con fines de búsqueda de formas. La importancia de la historia de las construcciones y de la ingeniería estructural y la falta de investigación y de cursos sobre estos temas en los planes de estudio de las facultades de ingeniería son la tercera premisa. Tras definir

las características de esta disciplina híbrida, que integra métodos historiográficos con métodos técnicos de ingeniería, se presentan dos ejemplos originales de investigación sobre la historia de las estructuras. El primero de estos ejemplos es la importancia del Palacio de Ctesifonte en la historia de la ingeniería estructural, y el segundo es la obra del ingeniero suizo Henry Lossier. Las ventajas de una colaboración entre arquitectos e ingenieros basada en la concepción estructural es la cuarta premisa. El análisis y la presentación de dos proyectos concretos, la escuela Volta de Basilea, de los arquitectos Miller y Maranta y el ingeniero Jürg Conzett, y la residencia de ancianos de Giornico, de los arquitectos Baserga y Mozzetti y los ingenieros Pedrazzini Guidotti, muestran cómo la colaboración entre arquitectos e ingenieros desde las primeras etapas del diseño fomenta la creatividad estructural.

Para formalizar la creatividad estructural es necesario identificar los aspectos objetivos, medibles y, por tanto, formalizables de esta creatividad. Estos aspectos provienen de la necesidad de que todas las estructuras sean seguras y eficientes. Esta necesidad de seguridad y eficiencia limita, y también impulsa, la creatividad estructural. Son muchos los aspectos que un ingeniero debe tener en cuenta para garantizar la seguridad y la eficiencia estructural: el equilibrio, la tipología estructural, la forma, las propiedades mecánicas de los materiales, la geometría de los elementos, la posición de los apoyos, etc. Todos estos aspectos y la variedad de soluciones disponibles que cumplen con la seguridad y la eficiencia son la esencia de la creatividad estructural. Tras destacar el papel de la intuición y de la experiencia en la concepción de una estructura creativa, se ha desarrollado la formalización de tres aspectos técnicos de los que depende la creatividad estructural: el equilibrio, la posición y el tipo de soportes, y la forma, a través de la presentación y análisis de edificios que ejemplifican cada uno de estos tres aspectos. Se ha analizado el Club de Golf APG en Luque, Paraguay, del arquitecto Javier Corvalán, para mostrar el papel del equilibrio en la formación de la intuición estructural. El techo del Lido de Ascona del arquitecto Livio Vacchini ha sido elegido para mostrar el papel del tipo y la posición de los soportes. Para mostrar el papel de la forma en la formación de la intuición estructural, la solución estructural elegida por Livio Vacchini para el techo del gimnasio de Losone, una retícula de vigas de hormigón armado pretensado, ha sido comparada con otras posibles soluciones estructurales que implican el uso de estructuras resistentes por forma y por resistencia vectorial. Finalmente, se analiza el papel del contexto -geográfico, económico, político y de la tradición- en la formación de la intuición estructural, presentando una investigación original sobre la promoción de la difusión de los edificios de madera en la región suiza de Ticino, a través de la valorización de las tradiciones locales de construcción.

Si la intuición estructural se puede formalizar, se puede también enseñar. Por lo tanto, se presentan algunos experimentos didácticos realizados en la Academia de Arquitectura de Mendrisio, Suiza, sobre la enseñanza del diseño estructural. Estos experimentos se basan en la investigación sobre la formalización de la intuición estructural, así como en los resultados de unos cuestionarios preparados específicamente y entregados a estudiantes de arquitectura y arquitectos profesionales para investigar el nivel de interés que tienen los arquitectos en cuestiones estructurales y el estado de las relaciones entre arquitectos e ingenieros. El propósito de los experimentos es también mostrar las ventajas de una colaboración fructífera entre arquitectos e ingenieros.

INTRODUCTION

Structural creativity is the combination of three inseparable elements. The first element is the ability to conceive a structure that optimally solves all the structural issues related to equilibrium, stability, resistance, stiffness, ductility, and durability. The second element is the creation of the spaces and volumes required by each architectural project. The third element is the optimization of all the other architectural requirements such as illumination, aeration, and aesthetics. Therefore, the conception of a structure is a creative process, as it means the creation of a new object from a series of external conditions imposed by the architectural project. However, this creativity is not as free as artistic creativity, as it requires in-depth knowledge of the fundamental structural principles.

Therefore, this type of creativity, unlike that of art, does not exclusively rely on personal talent, but people can be trained and taught in it.

The main goal of this work is the formalization of structural creativity, revealing the structural principles on which it is based, in order to transform it into a design tool available to architectural and structural designers. This project is based on four premises, which are presented in chapter 1

Only after the industrial revolution did the figures of the architect and engineer, originally united in the role of the master builder, begin to separate and specialize and, because of their specializations, speak different languages. The architects speak a creative one, the engineers speak an analytical one, and this difference in language hinders collaboration. This communication problem is well known, and many professionals and scholars, especially since the end the twentieth century, have thought about how to overcome it, proposing, especially at the university level, innovative teaching methods which, by focusing on the creative aspect of structural design, favor collaboration between architects and engineers. The importance of a common language and the existence of teaching methods that favor collaboration are the first premise on which this work is based, presented in section 1.1.

All the teaching methods that focus on the creative aspect of structural design use graphic statics, rather than analytical statics, as it allows a visual link between the structural form and the forces that generate it to be maintained. Graphic methods, which for centuries before the advent of computers were the main design tools for engineers, favor structural creativity and collaboration between architects and engineers. These methods also maintain the precision and scientific rigor of analytical methods. The advantages of using graphic statics and graphic methods are the second premise on which this work is based, presented in section 1.2.

In addition to the language differences, there is another major difference in the education of architects and engineers. When designing, architects usually reflect on the history of their discipline, find historical references, focus their work on established techniques and styles, and reflect on the evolution of architecture to make hypotheses on possible future scenarios. In contrast, engineers do not have this type of historical backgrounds, as the curricula of structural engineering departments are focused on analytical and technical aspects. However, it is possible to identify particularly prosperous historical moments in the development of structural engineering, in which different historical, geographical, technical, and political contingencies, have led to the creation of buildings of significant architectural value. This value mainly comes from their structures, and these buildings are often given the name of the engineers who designed them. In the field of reinforced concrete, think for example of the heyday of Italian structural engineering, between 1930 and 1970, with the works of Pier Luigi Nervi, Riccardo Morandi, Sergio Musmeci, Silvano Zorzi, and Aldo Favini. In the field of steel structures, think of the 1889 Exposition Universelle in Paris, whose aim was to show the world the potential of steel, and which left us one of the most famous and symbolic buildings in the world, the Eiffel Tower. Then think of other examples: the Gothic cathedrals, with their vaults, the Roman arched bridges, the traditional Japanese houses and temples, the first skyscrapers and large-span suspension bridges. We can also consider the rediscovery of timber as a building material and its development with glue-laminated timber and digital design. There are many historical moments characterized by specific types of structures, materials, and construction techniques. However, many of these types of structures are isolated cases that have not left a legacy to future generations. An example of this is 20th century Italian structural engineering. In order to avoid this fate, these structures need to be studied from historical and engineering perspectives, which can show the historical and technical contingencies that favored their development, as well as the lessons they can bring to today's designers. The importance of history, and, in particular, the lack of research and courses on this subject in engineering faculty curricula is the third premise on which this work is based, presented in section 1.3.

The creative aspect of structural design, structural conception, is often ignored by architects, who do not consider structure as an integral part of architecture, seeing it only as a tool that enables their project to "stand up". It is thought to be just a phase that comes after architectural projects, which architects do not deal with directly, and which is delegated to engineers. But, surprisingly, it is also ignored by engineers, who mainly deal with the analytical phase of structural design, that of calculation, in both their training and professional careers. Nevertheless, there are numerous examples of buildings in which structure generates architecture, and it allows the spaces and volumes required by the architectural project to be built in a creative way. In some cases, buildings of this type are conceived thanks to the extraordinary skills of an individual designer, architect or engineer, and in other cases, these buildings are the result of collaboration between architects and engineers. And, if we admit that structure is part of architecture, structural conception, that is, the creative part of structural design, can be the meeting point between architects and engineers and a common educational topic. Structural conception is an architectural design tool, and the advantages of collaboration between architects and engineers based on the structural conception, is the fourth premise of this work, as presented in section 1.4.

Once the premises have been defined, chapter 2 deals with the objective of this work, that is, the formalization of structural creativity. But how is it possible to formalize something creative? What are the objective, measurable, and therefore, formalizable aspects of this creativity? In order to answer these questions, the requirements that every structure should fulfill must be considered. Besides creating the spaces required by the architectural project, a structure must also be safe and efficient. And it is this need for safety and efficiency that limits, and also drives, structural creativity. However, before dealing with safety and efficiency, for a structure to be conceived creatively, the different structural typologies that can be used to solve a specific spatial / volumetric need must be known. Think, for example, of the design of the roof of a gym. What is the best structural typology to use? There is no one answer to this question. A roof can be a reinforced concrete slab, a ribbed slab, a funicular structure, etc., and each of these solutions has advantages, disadvantages, dimensional limits, and different aesthetic results. Once a structural system has been chosen, the first condition that it must satisfy is the equilibrium for any force or combination of forces that have a direction equal to those of the forces and actions that will act on the structure (vertical actions - from gravitational loads; horizontal forces from wind and earthquakes). But, when there is a system of forces, it is possible to design different structural systems that fulfill the conditions of equilibrium. And since there is not only one solution, structural creativity can come into play. Section 2.1 deals with the theme of equilibrium as a creative design tool.

The safety and efficiency of the structure must be guaranteed once a structural system has been chosen and its equilibrium verified. A structure is safe when, for each reasonably foreseeable load condition, the maximum stress in all the structural elements is lower than the resistance of the materials of which these elements are made. A structure is efficient when, for each reasonably foreseeable load condition, the maximum deformations are contained within defined limits, in order to not compromise the purpose for which the structure is built. By choosing the materials, the resistance with which the maximum stresses in the structural elements must be compared is defined. When the loads acting on the structure are also defined, the only parameters on which it is possible to act are the maximum stresses (axial action, shear and bending moment) in the structural elements, their geometry, and their stiffness. The position and type of constraints affect the magnitude of the stresses. For example, it is possible to reduce the bending moment in a beam by reducing its span, moving the constraints closer, or by fixing its ends. So, the constraints can be used as a creative design tool and this topic is treated in section 2.2.

The choice of structural typology, in particular of the shape of the structure, has an effect on the type of stress. Considering the previous example, if the roof of a gym is made by using a funicular structure, the main stress is the axial action so the strength and stiffness of the structure mainly depend on the area of the structural elements. If, on the other hand, a ribbed slab is chosen, the main stresses in the structural elements are those of shear and bending moment, and the strength and stiffness of the structure mainly depend on the moment of inertia of the structural elements. Once the structural type and the constraints, and therefore the type and magnitude of the stresses, have been defined, it is possible to improve the safety and efficiency of a structure by acting on the geometry of the sections. These actions take place specifically on the area, to increase resistance, and on the moment of inertia, to increase stiffness. So, the shape of the structure and the geometry of the sections are design tools that can be used to form the structural creativity. This topic is looked at in section 2.3.

Finally, there are other aspects that limit and, therefore, guide structural choices. For example, the availability of a certain material, the accessibility of the construction site, a local building tradition, and political and legislative choices. All these aspects, which the term "context" encompasses, help to form structural creativity, and can be used as design tools. This topic is dealt with in section 2.4.

If structural creativity can be formalized, showing the parameters on which it depends, then students can be trained and educated in this creativity. And, given that conceiving a structure is a task that belongs to both architects and engineers, the first step towards fostering collaboration is to include training on structural conception in the curricula of engineering and architecture schools. Chapter 3 presents the results of some teaching experiments carried out at the Mendrisio Academy of Architecture, Switzerland, for developing the structural creativity of architecture students.

1. PREMISES

The idea of this project came from some observations on structural creativity. These observations were then organized into four premises on which this work is based, and they are presented in the following sections.

OBSERVATION 1

Before the first industrial revolution, the architect and the engineer were not separate figures. The "master builder" was an architect, engineer, and builder. Modern structural theories did not exist at this time, and constructions were made by following rules based on experience, trial and error, and static intuition, which played a major role. However, even without structural theories, the master builders were able to build impressive constructions such as the Gothic cathedrals, whose architectural quality (spaces / volume, light, aesthetics) and the static challenges that they overcame (height, covered spans, domes, openings, buttresses) are impressive. Structure is an integral part of the architecture of these constructions, it is responsible for the creation of spaces, and it remains visible and contributes to the aesthetics. Some of the static problems in these constructions were solved creatively by using aesthetic solutions. For example, spires provide a concentrated load at specific points where the load needs to be diverted. In the graphic analysis of the loads on the section of St. Martin’s church in Landshut, carried out by E. Zorn for his PhD dissertation in 1933, the loads of every part of the structure contributes to the deviation of the thrust lines and, therefore, to the general equilibrium of the structure (figure 1.1).

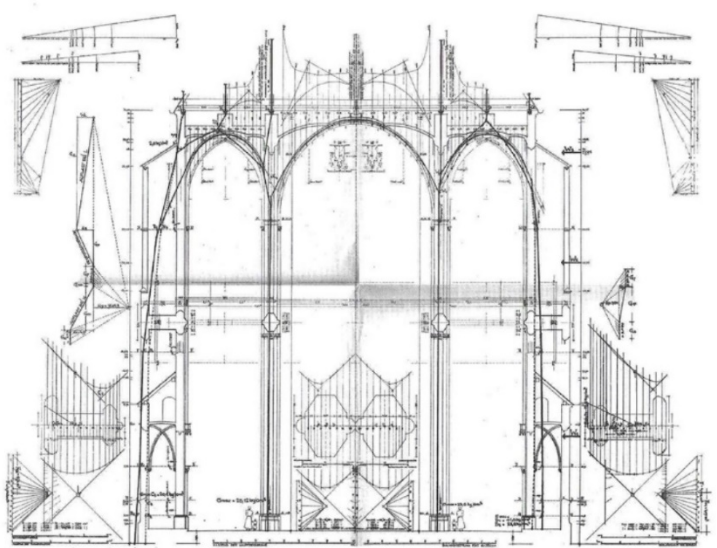


Figure 1.1. Thrust line analysis of the section of St. Martin’s chuch in Landshut. Source of the image: E. Allen, W. Zelewski, Form and Forces, Wiley, p. 225

OBSERVATION 2

The use of concrete as a construction material was at its height in the middle of the 20th century. Several buildings from this period are examples of how structure plays an important role and constitutes the architectural space itself. In this period, the figures of the architect and the engineer had already separated, and the structural creativity of the engineers usually stood out in the creation of these buildings, but sometimes the architects also showed highly developed structural sensitivity. In both cases, the designers had in-depth knowledge of the material, which was used in an optimized way, and the architectural choices were characterized by profound static honesty. The main protagonists of this phase are Pier Luigi Nervi, Riccardo Morandi, Eduardo Torroja, Félix Candela, Oscar Niemeyer, Heinz Isler, Frei Otto, Sergio Musmeci, Robert Maillart. One of the most important examples of this type of building is the hall in Mannheim designed by Frei Otto (figure 1.2).

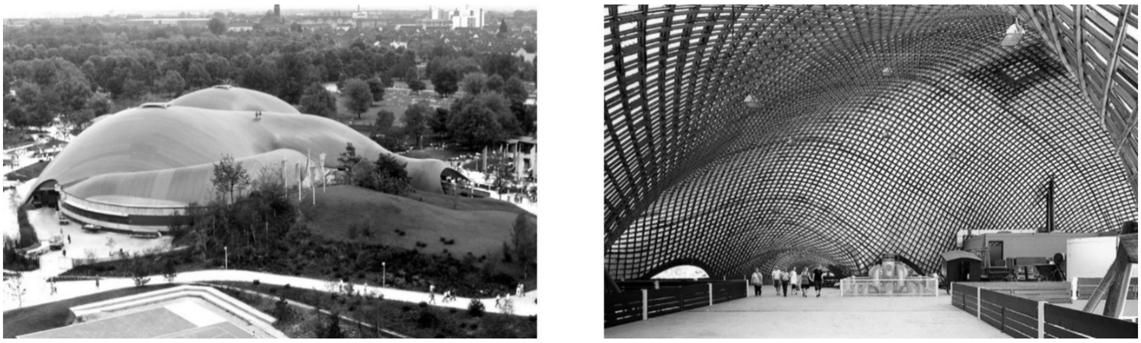


Figure 1.2. Hall in Mannheim, Frei Otto, 1975 (source Archive Frei Otto)

OBSERVATION 3

the free form architectural current of the total freedom of design and the domain of architecture over structure has developed over the last 40 years. This has resulted in buildings in which the structures had to be adapted to the architectural requirements without any connections to the static requirements, such as the Guggenheim museum in Bilbao (figure 1.3, left) and the national stadium in Beijing. In contrast, there have also been examples of buildings in which structure and architecture are in harmony. These types of buildings are usually the result of collaboration between an architect and an engineer, who often form a strong partnership. Some examples of these architect/engineer partnerships, which have collaborated and still collaborate today, are Kristian Kerez and Joseph Schwartz (Leutschenbach school – figure 1.3 right, apartment building on Fosterstrasse, house with one wall, etc). Toyo Ito and Matsuro Sasaki (Media

Library in Sendai, Kakamigahara Crematorium, etc.); Nicola Baserga and Pedrazzini Guidotti engineers (gym in Chiasso, Casa Minghetti-Rossi, etc.), Shigeru Ban and Blumer Lehman (Yeoju Golf Club South Korea, Tamedia office building, Zurich, etc.), Miller and Maranta architects and Jurg Conzett (Volta Schulhaus Basel, Markthalle Aarau, etc.).

Figure 1.3. Gugennheim museum, Bilbao, arch. F. Gehry, 1997 (left, photo paratusgroup.com); Leutschenbach school, Zurich, arch. C. Kerez, eng. J. Schwartz, 2009 (right, photo leonardo finotti)

OBSERVATION 4

The projects belonging to the groups mentioned in the first three observations all use graphic statics, the use of which has a great advantage over analytical statics. When graphic statics is used, the link between form and forces remains clear, and the precision of analytical statics is maintained. Since Karl Culmann's 1866 treatise (Culmann, 1866), graphic statics was studied and taught in the main European polytechnic schools, however, it has been totally supplanted by analytical statics since graphic statics has some weaknesses: i) the graphic constructions needed for solving some problems can be particularly time-consuming and ii) it is difficult to apply graphical analysis to three-dimensional problems; this can only be achieved with the construction of complicated physical models (for example, Antoni Gaudì’s models for the Sagrada Familia – figure 1.4 left, and Frei Otto's model for the design of the Munich stadium – figure 1.4 right). Analytical statics, based on solving systems of equations, enables faster and simpler solutions to be found, especially with the help of computers. However, the awareness of the link between forces and form has almost completely disappeared. This has resulted in some structural types, such as beams, frames, and plates, taking precedents because they are easier to solve with analytical statics. This has happened at the expense of other structural typologies, such as arches, cables, vaults, and shells, which are easier to design with graphic statics.

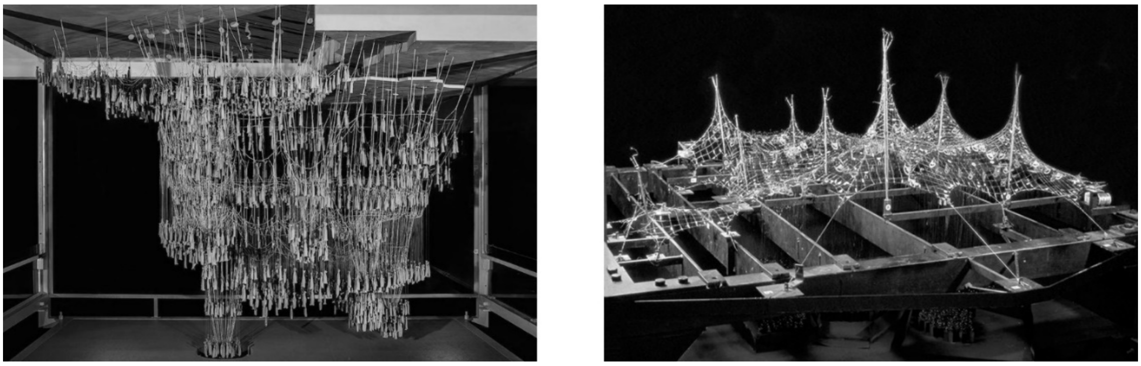


Figure 1.4. Model of the Sagrada Familia by Antoni Gaudì (left, photo blog.sagradafamilia.org); model of the Munich stadium by Frei Otto (right, photo FAR frohn&Rojas)

OBSERVATION 5

Structural design is often confused with structural calculation. But structural calculation is only one of the two phases of structural design. The first phase is structural conception, a creative phase in which a structure is designed according to the structural creativity of the designer, to meet the architectural requirements. The traditional curricula of engineering schools concentrate almost exclusively on calculation, leaving the creative part entirely to each individual’s talent. However, structural creativity is not a completely free concept since it depends on a deep understanding of the fundamental structural concepts.

OBSERVATION 6

We have recently been witnessing a return to an interest in graphic methods, especially for the analysis of large historical structures, for which analytical methods are not the most appropriate methods. This trend also broadens the range of structural types that can be used when the appropriate design tools are employed. The design tools available today, such as 3D modeling software, numerical control machines, etc., enable us to overcome the limitations that have determined the success of analytical statics over the graphic statics: the laboriousness of graphic constructions and the difficult it is to apply it to the three-dimensional case (figure 1.5).

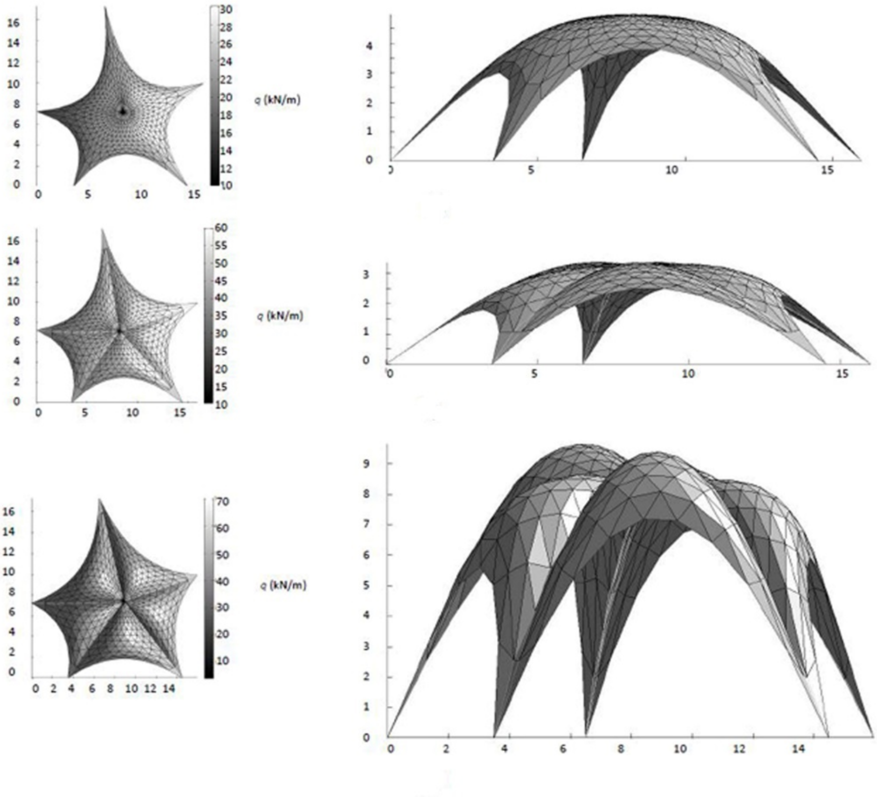


Figure 1.5. Design of compression structures using topological mapping (source Carbonell-Marquez et al., 2015)

These six observations have been brought together in the following four premises on which this PhD project is based.

1.1. Origins of the differences in the language used by architects and engineers

It is possible to identify the moment in history from which the figures of the architect and the engineer, previously united in the profession of the master builder, began to separate and specialize. The discovery of new materials, such as cast iron and steel, in the industrial revolution, and the advent of the first modern structural theories during the seventeenth and eighteenth centuries, gave rise to the need for a new profession, that of the engineer. This figure was an expert and dealt with the technical aspects of design and was responsible for structural safety, leaving the solving of problems related to context, function, and aesthetics, as well as the economic, political, and social aspects to the architect. As engineering became more specialized, it also became more complicated. At the same time, the two professional figures gradually distanced themselves from each other and inevitably began to speak two different languages, the architect spoke a creative language and the engineer spoke an analytical one, resulting in an ever-increasing number of communication problems (Heyman, 2016).

However, the design of the load-bearing structure of a building cannot be considered as a purely analytical problem. The main task of a structure is to allow the creation of the spaces and volumes required by the architectural project. The analytical phase of structural design, the calculation phase, only begins once the structure has already been defined. The first phase, the conceptual design phase, in which the structure is conceived, is creative. This creativity exists in spite of the fact that this design phase requires in-depth knowledge of both the structural analysis principles which lead to the choice of an efficient structural system, and of the mechanical characteristics of the materials.

The creative aspect of structural design was emphasized by Eduardo Torroja. In the introduction to his famous book *Razón y ser de los tipos estructurales* (Torroja, 1957), he wrote: "the birth of a structural complex is the result of a creative process, a fusion of art and technique, of ingenuity and research, of imagination and sensitivity, which goes beyond the realm of pure logic to cross the arcane frontiers of inspiration".

In his writings, Pier Luigi Nervi also highlighted the creative part of structural design. For example, in the article *Criticism of structures. Relations between engineering and architecture*, published in “Casabella Continuità” in March 1959 (Nervi, 2014) he wrote: “The work of the structural designer is confused with that of the individual who is making calculations; I think it is appropriate to highlight the difference between the two functions. The first is ideational and conceptual, dictated by the static sense, and it is accompanied and validated by indicative static calculations. The second is abstract in nature; it is an application of formulas or the resolution of an analytical problem, which can be carried out without any connection with the static fact that determined its setting" (original text in Italian, translated into English by the author).

Therefore, when looking at the projects by Torroja and Nervi, it is not surprising to see that structure always plays a major role, and it often constitutes the architectural space itself. Consider, for example, the roof of the tribune of the Zarzuela hippodrome by Torroja (figure 1.6, left) or the roof of the sports hall in Rome by Nervi (figure 1.6, right).

Figure 1.6. Zarzuela Hippodrome, E. Torroja, 1941 (left) and Sports hall in Rome, P. L. Nervi, 1957 (right)

The buildings by Nervi and Torroja are not isolated examples. The 1950s and 1960s, the period in which the building of reinforced concrete structures was at its peak, are rich in examples of buildings in which structure played a leading role, and structural design was not limited to simply solving analytical problems but to sharing the creativity that is typical of architecture. Some of these examples are the "Palazzo del Lavoro" in Turin and the "Pirelli skyscraper" in Milan by Pier Luigi Nervi; the "Turin Auto Show" by Riccardo Morandi; the restaurant "Los Manantiales in Xochimilco by Felix Candela; the thin shells by Heinz Isler in Switzerland; and the buildings in Brasilia by Oscar Niemeyer (figure 1.7).

Figure 1.7. Clockwise: Palazzo del Lavoro, Turin; Pirelli skyscraper, Milan, Turin Auto Show building; Metropolitan Cathedral in Brasilia; Heinz Isler's thin shell; Los Manantiales restaurant, Xochimilco

The main reason for the dichotomy between engineers and architects lies in the difficulty of the analytical language. This has led numerous authors to try to propose different, less analytical approaches to the themes of structural design, in order to rediscover the aspects related to intuition and creativity, while also complying with the laws of statics.

The approach proposed to the students of architecture at the Polytechnic of Turin, Italy, in the 1970s and 80s is significant. *Princìpi statici e forme strutturali* ("Static principles and structural forms") by Giulio Pizzetti and Anna Maria Zorgno Trisciuoglio presents this approach in depth. In the introduction to the book, the authors themselves describe it as follows (Pizzetti, Trisciuoglio, 1980): "[…] a novel, or at least differently structured, approach to the vision of the static principles and the interpretation of structural forms; an approach that can overcome the dichotomy that is complained about and that favors intellectual synergy between the functional interpretation of a static-resistant mechanism and the analytical formulation of the ways in which it can be established. In short, an approach that allows the designer to make a balanced evaluation of the structural parameters, and it provides them with the basic premises for the formulation of coherent criteria for operational choices". (Original text in Italian, translated into English by the author).

The approach proposed by Daniel Schodek, former professor at Harvard University in Cambridge, Massachusetts, is more traditional. In his book *Structures*, published in 1997, he explained his goals in the preface (Schodek, 1997): "The primary goal of the book is not simply to teach analytical techniques but more generally, to explore their role in the design of structures in a building context. Because of this larger goal, the book covers material discussed not only in specialized engineering curricula but also, to some extent, that covered in architectural curricula as well, the traditional hard boundaries between subdisciplines in engineering (e.g., statics and strength of materials) have also been deliberately softened and a more integrative approach taken”. His intention to review the teaching programs to focus on the design object, structures, rather than on the design process, the analytical calculation, is clear, even though he does not ignore the importance of calculation.

In 2010, the former professors at the Massachussets Institute of Technology, Edward Allen and Waclaw Zalewski published the book *Form and Forces*, in which they propose an approach to the study of structures that starts out from structural design in all its phases. The method is described in the introduction of the book as follows (Allen et al., 2010): “Form and Forces is a project-based introduction to the design of structures for buildings and bridges. […] Each chapter follows the entire design process for a whole structure. […] The projects are carefully chosen to bring out specific lessons that constitute a complete course in Statics and Strength of Materials. […] The fundamentals of Statics and Strength of Materials emerge naturally in the context of the structural design process”. The approach is mainly based on the methods of graphic Statics which, according to the authors, make the understanding of the structural behavior more intuitive, but analytical methods are also introduced when functional to the design process. The approach proposed comes from the authors’ vision of the nature of structural design (Allen et al., 2010): “All great masters of structural design have reminded us repeatedly that structural design is not a science; it is craft that relies on judgement rather than absolute certainty. This judgement must be based on a broad knowledge of structural principles, materials, details of construction, fabrication and erection processes, and analytical techniques both numerical and graphical”.

According to this approach, and in agreement with the idea of Pier Luigi Nervi, structural design is not only calculation, but above all art, based on a type of creativity that must be taught by using in-depth study of structural principles. This art and its teaching make it possible to envision a meeting point between engineers and architects.

According to the authors of this book, this approach can also favor collaboration between architects and engineers because it helps them find common ground and, above all, a common language to make communication easier. Throughout the book, the authors propose fictional but realistic design examples to show how collaboration based on conceptual design using graphic static tools can enhance architectural ideas and lead to better architectural projects. The example shown in figure 1.8, taken from the book *Form and forces* (Allen et. al, 2010), briefly summarizes the conceptual design steps of a fictional project that could arise from good collaboration between an architect and an engineer, from the first architectural idea to the final project. The architect shows the engineer an idea for a small chapel that has a very steep roof that shapes the space of the chapel. This roof is made by using a wooden scissors truss, obtained by lifting the bottom chord of the truss (figure 1.8a). Using a graphic static tool, namely the Cremona diagram, the engineer shows the architect that the stresses in the elements of this truss are too high and that the bottom chords need to be lowered (figure 1.8b). Then the engineer proposes the use of two interior posts instead of one and draws the Cremona diagram again (figure 1.8c). The architect then notices that the bottom chords and the internal posts are in tension, so he proposes replacing them with steel chains. Finally, they both observe that the central part of the bottom chord can be replaced by a lenticular shaped chain in plane in the direction perpendicular to the trusses. This final idea makes the structure 3-dimensional and shapes the space in a way that enhances the first architectural design (figure 1.8d).

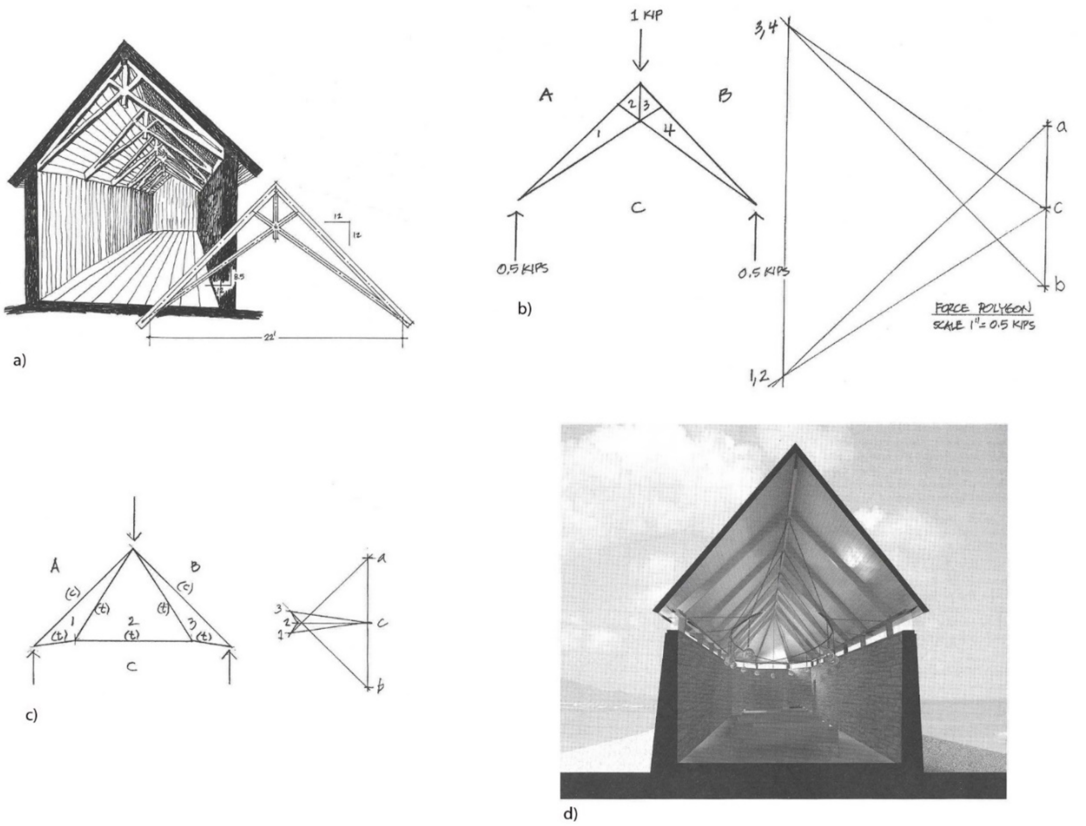


Figure 1.8. Steps of the collaboration between an architect and an engineer based on the conceptual design. a) first idea of the structure from the architect; b) use of the Cremona diagram to show the limits of the structure proposed by the architect; c) proposal of a new structure from the engineer, justified through the Cremona diagram; d) final design arisen from the collaboration (Adapted from Allen et al., 2010, chapter 4)

The approach proposed by Aurelio Muttoni in his book *The art of structures* (Muttoni, 2006), used for the courses on structures at the Mendrisio Academy of Architecture, Switzerland, shares the use of graphic methods for the visualization of structural forms and the calculation of forces with this approach. The innovative aspect of this approach, however, is that teaching follows a "structural path", which starts out from the definition of forces and their condition of equilibrium, then deals with all the structural typologies from the simplest ones, those only subjected to tension and compression (cables and arches), to the more complex two-dimensional (beams and trusses) and three-dimensional (plates and shells) ones (figure 1.9). Muttoni also agrees that there is a need for conciliation between architects and engineers which, in his opinion, can only take place if interests and language are shared: "The separation of the professions, which came from a real need, is considered as irreversible. But, in order to solve the increasingly complex problems we have to deal with, the only possible way is through dialogue and collaboration between the various professional figures. In order to collaborate and design together, common interests are essential, as is using the same language and, above all, understanding each other.

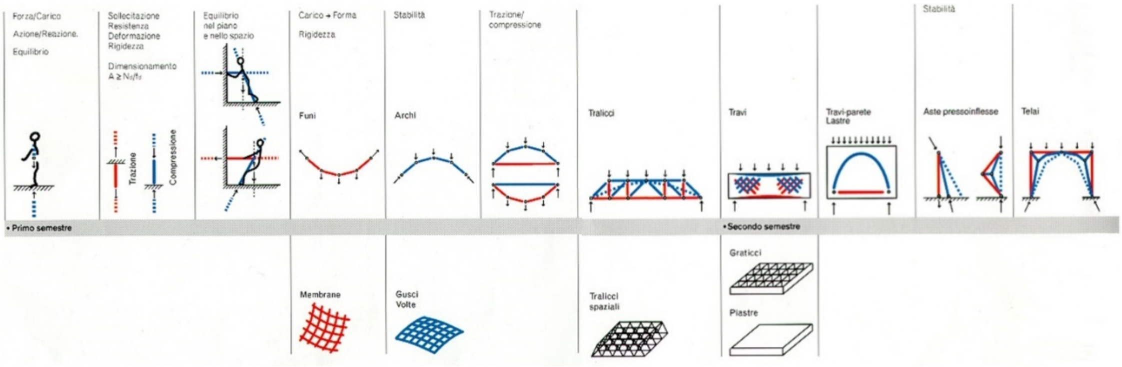


Figure 1.9. The structures' path. (image by Aurelio Muttoni)

The books by Mario Salvadori, *Why buildings stand up* and *Why buildings fall down* (Salvadori, 2007) are more informative, but their goal is, once again, to bring structures out of the purely mathematical sphere. In the preface in the Italian edition of the first book he wrote: "in the 1930s, at the dawn of a long academic career and fresh from a degree in pure mathematics, I had the task of assisting the students at the school of architecture in Rome in the practical classes on the Strength of Materials. The lecturer presented the course in a strictly mathematical form and I, of course, imitated him with results that I considered insignificant at that time, and which I consider simply disastrous today. After years of professional activity, in the 1950s, this juvenile mistake led to me teaching a course on Architectural Structures […] referring, above all, to the physical intuition that we all have just by being alive, but without sacrificing the rigor of the subject. The enthusiasm of the students and their excellent exam results showed me that I was on the right path".

The same refusal to use mathematical formulations also characterizes Malcolm Millais' work, *Building Structures* (Millais, 1997), published in 1997, which proposes a conceptual approach for understanding the structural behavior of any building by using descriptions and diagrams without the use of mathematical ideas.

On the other hand, Heino Engel's approach is completely different. In his book *Tragsysteme = Structure systems* (Engels, 1997), he presents a vast classification of possible structural typologies in graphic form. His intention was not to replace the traditional Statics and Strength of Materials courses but to provide practical help so that the subject could be better understood.

As this brief bibliography shows, all the authors have the same intention: to overcome the gap between architects and engineers by using non-traditional approaches to structural design that favor creative language over analytic language. In order to achieve this goal, all of these approaches make use of graphic structural design and analysis methods and, in general, graphic statics over analytical statics. Graphic statics favors collaboration between architects and engineers and helps reduce the distance between them. The existence of structural design approaches that are closer to this creativity is the second premise on which this work is based.

1.2. Graphic statics and graphic methods

Karl Culmann's graphic statics uses graphical calculation methods, which makes it a very useful tool for understanding the behavior of structures such as funicular structures, arches, beams, and walls. Moreover, it is just as precise as analytical statics. The advantage of using these methods in the teaching of structural is evident, in fact all the didactic approaches presented in the first premise make use of them. The first complete treatise on graphic statics is the book *Die graphische Statick* by Karl Culmann, published in Zurich in 1865 (Culmann, 1866). In the introduction of this book, Culmann refers to the first systematic application of graphic methods by the French mathematician Jean Victor Poncelet (1788-1867). In his book *Traité des proprietes projectives des figures* (Poncelet, 1822), Poncelet published his studies on projective geometry and some graphic methods for the design of vaults and bearing walls. But no graphic statics would exist without the definition of forces as vectors, given for the first time two centuries earlier, in 1608, by the Flemish scientist Simon Stevin (1548-1620). One of the volumes, which is on statics, of his book, *Hyponmemata Mathematica* (Stevin, 1608), analyzes the problem of the equilibrium of two weights lying on two different inclined planes that are connected by a cable. This led to the Parallelogram law, which is the basis for the combination of forces (Capecchi, 2012). At the end of that century, Robert Hooke was the first scholar to explicitly mention the link between the shape of a hanging cable and that of an arch with his famous statement: “ut pendet continuum flexile, sic stabit contiguum rigidum (“as hangs the flexible line, so but inverted will stand the rigid arch”). However, he did not propose any tools, graphics, or analytics that could find the shape of a cable subjected to a system of loads (Hooke, 1676). However, it has recently been shown that the origins of funicular forms go back to the 6th century AD, and the byzantine Farghán was the first designer to use these forms for the construction of the arch of Taq-iKisra (Hernández-Montes et al., 2017; Miccoli et al., 2021a, see next paragraph). It is well documented that the mathematician Giovanni Poleni used a hanging chain model to evaluate the shape of the dome in St. Peter’s church in Rome (Poleni, 1748). The model has been described in detail and considers the real weight distribution of the dome (figure 1.10). The French scientist Pierre Varignon (1654-1722) developed the rules about the composition of forces by Simon Stevin, presenting the concepts of funicular polygons and polygons of forces (Varignon, 1725). The same concepts were used by Culmann (Kraftepolygon and Seilpolygon). Thanks to Karl Culmann, graphic statics became an autonomous discipline and rapidly spread all over Europe. In Italy, Luigi Cremona, a professor at the Polytechnic Institute of Milan and at the University of Rome, included Culmann’s concepts of funicular polygons and polygons of forces in the theory of reciprocal diagrams (Cremona, 1879) leading to the graphic method that bears his name, the Cremona method. This method is mainly used to find the forces in the members of a statically determinate truss, but also to obtain the thrust line of a set of planar loads. The method was developed earlier by J.C. Maxwell and W. P. Taylor, in 1863, but it was not known until Robert Bow developed it in his book *Economy of constructions in relation to framed structures*, published in 1873 (Bow, 1873).

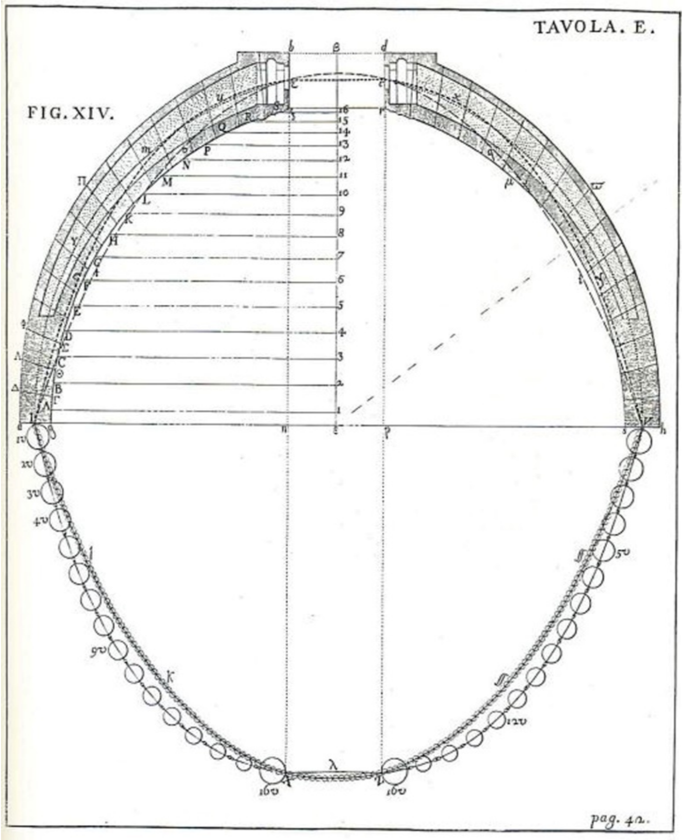


Figure 1.10. Analysis of St. Peter’s dome using graphic statics by Giovanni Poleni (Poleni, 1748)

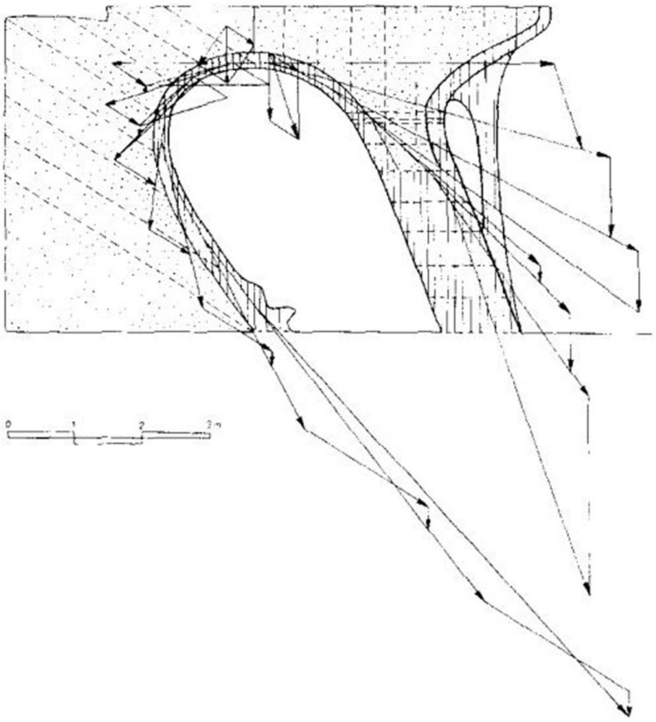


Figure 1.11. Park Güell, Force diagram of the retaining wall toward Muntaña Pelada (Gerhardt et al., 2003)

The drawings for the colonnade of the Güell park by the Spanish architect Antonì Gaudì (figure 1.11) demonstrate in-depth knowledge of graphic statics, while also demonstrating that these methods were used for design purposes (Huerta, 2006). These methods were first applied in Spain for the design of gunpowder warehouses in the first third of the 18th century, about 150 years before modernist architecture (Lluis i Ginovart, 2015). However, Gaudì was the first person to extend the graphic statics methods to 3-dimensions, as can be seen in the design of the Colonia Güell Church, where he used a 3D hanging model (Casals Balaguò et al., 1993). This 3D model was rebuilt in 1989 by Jos Tomlow for his PhD dissertation, and it is currently on display in the Sagrada Familia Museum (Tomlow, 1989). The Cremona graphic method is still used for the analysis of historical constructions within the framework of Limit Analysis (Heyman, 1995; Huerta, 2001). For example, it has recently been applied to the analysis of the dome of "Santa Maria della Sanità" in Naples (Zerlenga et al., 2021). However, the limitations of this method for design purposes were already evident in the works of Gaudì, given the complexity of the graphic constructions and the need for iterations when searching for the thrust line. The funicular shape depends on the load system, which is not known a priori. So, starting out from a first-attempt load distribution, subsequent corrections must be made depending on the shape taken for the thrust line which, in turn, depends on the load distribution. These corrections need to be repeated until the final shape is reached. Each iteration requires the construction of a new force polygon and a new funicular polygon, which makes the process time consuming. Nowadays, these limits can easily be overcome as the graphic methods can be implemented using software which allows the iterativity of the methods to be managed and, at the same time, still enabling the visualization of the link between form and forces. For example, in this paragraph, the Cremona-Maxwell method is formulated in the simplest possible matrix form and implemented in a Matlab program. Thanks to these possibilities, graphic statics is once again a research topic in many European and North American University departments. The Block Research Group at ETH Zurich, for example, is very active in the field of graphic statics. The head of this group, Professor Philippe Block, during his PhD at MIT, developed a method for generating vaulted surfaces in compression - the "Thrust Network Analysis method", which goes beyond the main limitation of the classic graphical methods, that of two-dimensionality (Block, 2007). This group is now working on different research projects on graphic statics. One of these projects is looking into rib-stiffened funicular floor systems, which aims to reduce the amount of concrete and steel normally used in reinforced concrete slabs by using a special floor consisting of a doubly curved funicular shell with vertical stiffeners that transfers the loads to the supports by only using compression forces (Ranaudo et al., 2021; Block et al. 2020). This group collaborates with the chair of structural design, led by Professor Joseph Schwartz, for the teaching of structural design in the faculty of architecture at ETH, and their goal is to improve teaching methods and encourage collaboration between architects and engineers. In North America, Professor Edward Allen and Waclaw Zalewski, from MIT, formed the “Boston Structures Group”, an “informal association of structures teachers, engineers and architects, who share the belief that “structures” is a design discipline and should be taught as such”. Graphical methods are a key ingredient of their approach to teaching structural design, as these methods contribute to visual understanding of the behavior of structures. (Allen et al., 2010). Some of the members of the group, for example Professor John Ochsendorf from MIT, in collaboration with Professor Philippe Block, have been involved in research projects on graphic statics.

The strut-and-tie method, introduced for the first time by the engineers Wilhelm Ritter and Emil Mörsch at the beginning of the 20th century, improved during the 1980s by the structural engineers and scholars Jörg Schleich, Kurt Schäfer, and Mattias Jennewein, and presented in detail in the 1987 publication *Toward a consistent design of structural concrete* (Schleich et al. 1987), uses graphic statics for design purposes, by using models that allow the force flow in reinforced concrete elements to be visualized. Aurelio Muttoni, Joseph Schwartz and Bruno Thürlimann went further and took the strut-and-tie methods into the stress-fields method, which also considers the theory of plasticity. In 1997 they published a book about this new method titled *Design of concrete structure with stress fields* (Muttoni et al., 1997). Both these methods take advantage of graphic methods, which is the visualization of the force flow and, therefore, of the link between form and forces.

Another example of the use of graphic methods for understanding the behavior of structures is that of the limit analysis when applied to the structural analysis of historical stone and masonry structures with arches, vaults, and buttresses. These kinds of buildings were designed centuries before the first structural theories thanks to traditional geometric approaches resulting from experience built up over centuries and the intuition of the master builders. Limit analysis applied to the study of these buildings scientifically reached the same conclusion as that of the master builder: the importance of geometry. Jacque Heymann, former professor at the University of Cambridge, was the first person to reach this important conclusion, which scientifically justifies the construction method of the master builders, and presented the findings of his research in the 1995 book *The Stone Skeleton: Structural Engineering of Masonry Architecture* (Heymann, 1995), cited by many scholars, like Santiago Huerta, who used the findings of Heymann’s research in many of his works, for example in his papers *Mechanics of masonry vaults: The equilibrium approach* and *Structural design in the work of Gaudì* (Huerta, 2001, 2006).

Research projects on the analysis of masonry structures using limit analysis have been carried out by Philippe Block at ETH and by John Ochsendorf at MIT, and these pieces of research are linked to the use of graphic statics and graphic methods (Ochsendorf, Block, 2006).

It is widely recognized that one of the main advantages of graphic statics over analytical statics is the visualization of structural behavior. This is the reason why in this work graphic statics is considered as a tool that favors the formalization of structural intuition which helps to educate structural creativity.

In the following part of this section, the Cremona-Maxwell method is formulated in the simplest possible matrix form, and it is shown that, thanks to this matrix formulation, the method can be used for form finding purposes.

1.2.1. The Farghán matrix: a matrix formulation of the Cremona-Maxwell method

The Cremona diagram, also known as Cremona-Maxwell method (Quinta Ripoll, 1989), is mainly used to determine the forces in the members of a statically determinate truss loaded by a system of point loads acting on the nodes. It can also be used to find the line of thrust of a system of loads, that is, the shape of a cable hanging from two points that is subjected to a set of point loads. The equilibrium form of the structure is not known a priori and there can be more than one solution (i.e. the cable can have more than one equilibrium shape). The following example explains the situation (figure 1.12).

The Cremona method is used to find a possible equilibrium form for the cable in figure 1.12, fixed at point 1 and 7 and subjected to the loads P2, P3, P4, P5, and P6. Bow's notation (Bow, 1873) is used to identify the forces. The load line is drawn to scale on the right side of figure 1.13. A trial pole O' is chosen in order to define a 1st attempt force polygon. A set of rays from *ao'* to *fo'* are drawn in the force polygon. Parallel to each ray, the corresponding segments of the trial form diagram are drawn. Point 1' and point 7' are marked in the form diagram (see figure 1.13).

As there is an infinite number of polygons that are funicular to the set of loads, additional conditions must be set in order to select the polygon passing through points 1 and 7. Ray 1'7' is drawn in the first funicular polygon and a parallel line going through O' is drawn in the polygon of forces. The intersection of the previous line with the vertical line *af* defines point *p*, to which ray 17 must pass through (see figure 1.14).

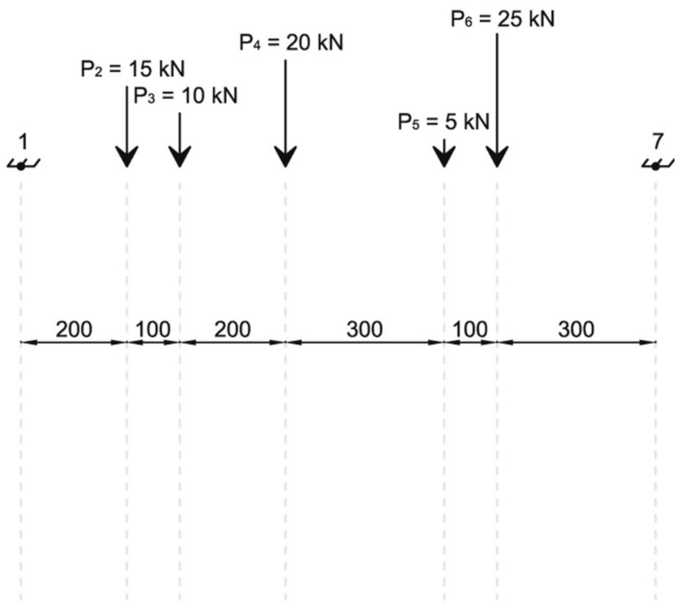


Figure 1.12. data from the example: position of the fixed points, x-position of the force, value of the forces

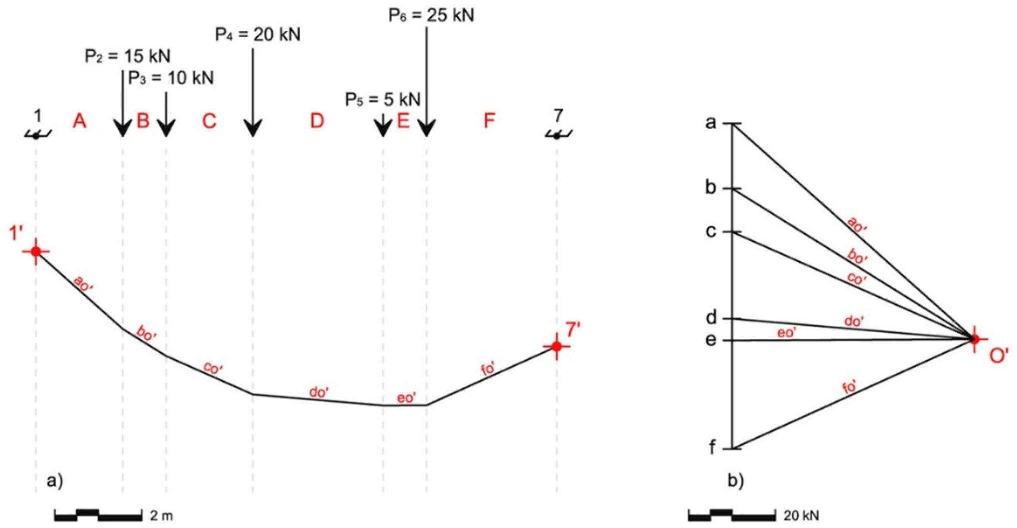


Figure 1.13. a) 1st attempt funicular polygon, b) 1st attempt force polygon

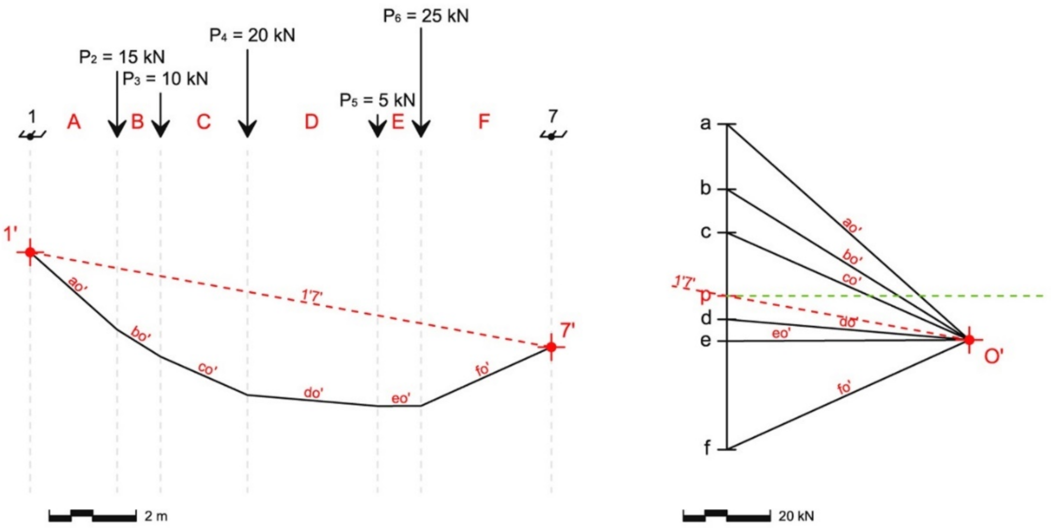


Figure 1.14. Intermediates steps to find the funicular polygon passing through points 1 and 7

A pole O located on ray 17 is a possible solution for the funicular polygon. Segments of the force polygon are in tension on the right side of line *af* and in compression on the left side. Once the new pole has been chosen, the funicular polygon is completely defined, see figure 1.15.

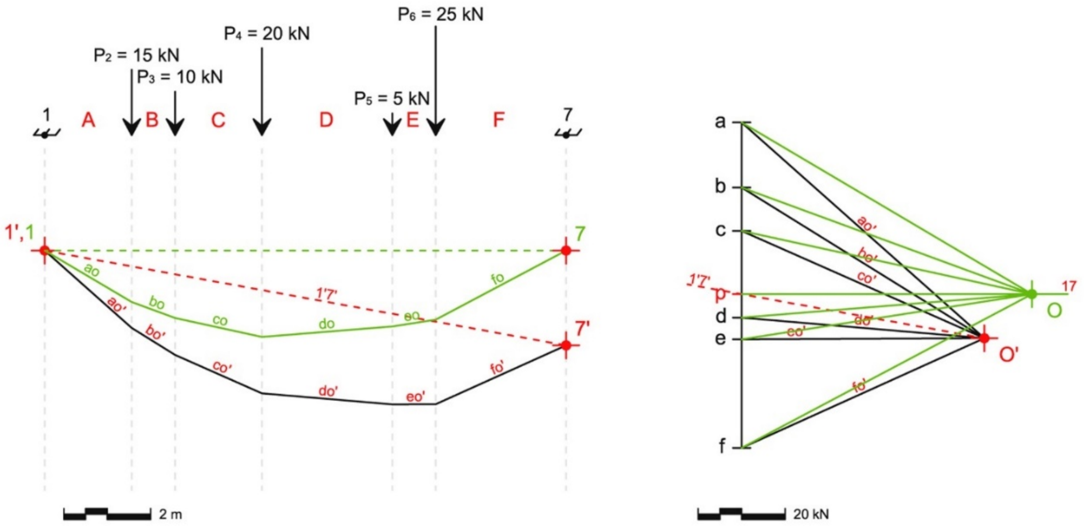


Figure 1.15. Funicular polygon passing through points 1 and 7 (left) and the corresponding force polygon (right)

In order to select a specific funicular polygon, another condition must be set. For example, a given value of the horizontal component H of the tension in the cable. H = 30 kN is imposed in figure 1.16.

So, from the graphical method proposed by Cremona, finding the final funicular polygon requires the construction of at least two diagrams: one for the first attempt and, starting out from this diagram, one that fulfills all the boundary conditions. Every change in data (for example the value of the forces or their position) requires the construction of a totally new funicular polygon, going through all the steps from the beginning. For this reason, the graphical method may be overly complicated for optimization purposes.

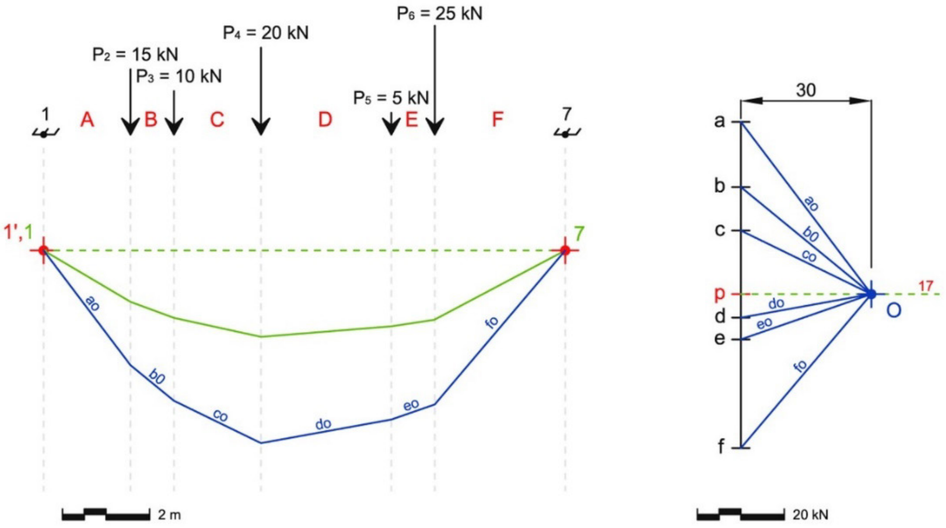


Figure 1.16. Funicular polygon corresponding to H=30 kN

1.2.1.1. The Farghán Matrix

The Cremona graphic diagram is developed here in the simplest possible matrix form so that it can be implemented in a MATLAB program (MATLAB, 2020), see Appendix A. In doing so, the iterative process of selecting the final funicular polygon becomes automatic and, at the same time, we still have the advantage of using the graphic method of linking form and forces. As the Cremona method is based exclusively on equilibrium, equilibrium equations in the nodes of the cable are set in the methodology presented. The situation is summarized in figure 1.17.

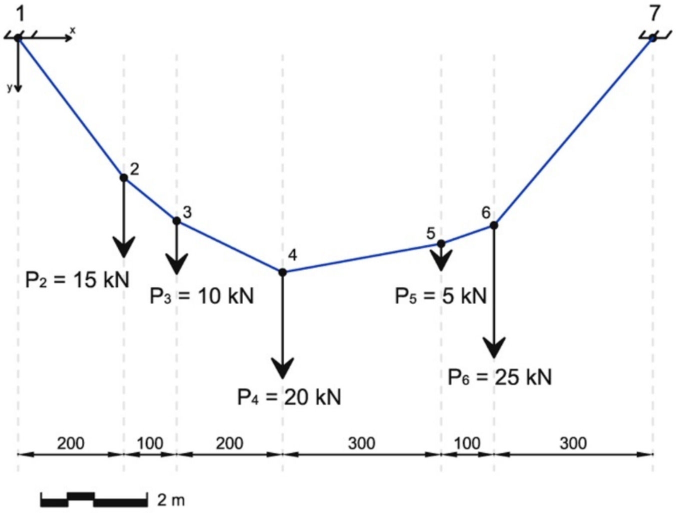


Figure 1.17. Representation of a possible funicular polygon

The data for the problem are:

- Position of the fixed points (x_1,y_1 and x_7,y_7);
- x-coordinates of the line of application of the loads (x_2 to x_6);
- Direction, sense, and magnitude of the forces (P_2 to P_6).

The unknowns are:

- the value of the horizontal component of the cable tensile force: H;
- the y-coordinates of the nodes of the cable (y_2 to y_6).

If the structure is in equilibrium, then each one of the nodes must be in equilibrium. For example, the forces acting on node 2, see figure 1.18, are: the tension force in the segment of cable 1-2 (T_2), the tension force in the segment of cable 2-3 (T_3) and the force applied at node 2 (P_2). By setting the horizontal and vertical equilibrium at node 2, the following equations are obtained:

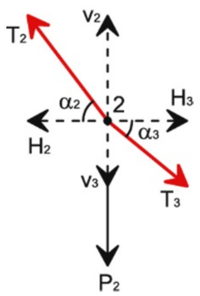


Figure 1.18. Equilibrium at node 2

$$\sum F_H = 0 \rightarrow H_2 = H_3 = H$$
$$\sum F_V = 0 \rightarrow V_2 - V_3 = P_2 \qquad [1]$$

with H_2 and V_2 and H_3 and V_3 as the horizontal and vertical components of T_2 and T_3, respectively (figure 1.18). If α_2 and α_3 are the angles of inclination from the horizontal axis of T_2 and T_3 (figure 1.18) then:

$$\tan\alpha_2 = \frac{V_2}{H_2} = \frac{V_2}{H}$$
$$\tan\alpha_3 = \frac{V_3}{H_3} = \frac{V_3}{H} \qquad [2]$$

Moreover, α_2 and α_3 can be expressed as functions of the coordinates of the nodes defining the corresponding segment of cable as follows:

$$\tan\alpha_2 = \frac{y_2 - y_1}{x_2 - x_1}$$
$$\tan\alpha_3 = \frac{y_3 - y_2}{x_3 - x_2} \qquad [3]$$

The vertical components, V_2 and V_3 are deduced from Eq. (2) and (3) (Eq. 4), and the value of P_2 is obtained by substituting their values in the second equations of Eq.(1) (Eq. 5).

$$V_2 = H\frac{y_2 - y_1}{x_2 - x_1}$$
$$V_3 = H\frac{y_3 - y_2}{x_3 - x_2} \qquad [4]$$

$$\sum F_V = 0 \rightarrow H\left(\frac{y_2 - y_1}{x_2 - x_1} - \frac{y_3 - y_2}{x_3 - x_2}\right) = P_2 \qquad [5]$$

Eq. (5) can be generalized for a generic node i as follows:

$$P_i = H\left(\frac{y_i - y_{i-1}}{x_i - x_{i-1}} - \frac{y_{i+1} - y_i}{x_{i+1} - x_i}\right)$$
$$\rightarrow \frac{P_i}{H} = -\left(\frac{1}{x_i - x_{i-1}}\right)y_{i-1} + \left(\frac{1}{x_i - x_{i-1}} + \frac{1}{x_{i+1} - x_i}\right)y_i - \left(\frac{1}{x_{i+1} - x_i}\right)y_{i+1} \qquad [6]$$

Eq. (6) can be extended to all the nodes leading to a linear system that can be written in matrix form as

$$\frac{1}{H}\mathbf{P} = \mathbf{F}\mathbf{y} + \mathbf{k} \qquad [7]$$

where **P** is a vector of *n-2* components: the applied forces on nodes 2 to *n-1* (**P**=(P_2, P_3, ... , P_{n-1})). Vector **y** is the *n-2* components vector of the unknowns, which is formed of the vertical coordinates of the funicular polygon (**y**=(y_2, y_3, ... , y_{n-1})). **k** is a *n-2* components independent vector, and all its elements are equal to zero except for the first and the last ones (**k**=($-y_1/(x_2-x_1)$, 0, 0,...., 0, 0,$-y_n/(x_n-x_{n-1})$))). Finally **F** is the (*n-2*)×(*n-2*) matrix known as the “Farghán matrix” (Miccoli et al., 2021a), whose components f_{ij} are:

for i=2

$$f_{2j} = \begin{cases} \dfrac{1}{x_2 - x_1} + \dfrac{1}{x_3 - x_2} & for \quad j = 2 \\ \dfrac{-1}{x_3 - x_2} & for \quad j = 3 \\ 0 & otherwise \end{cases}$$

for i=3 to n-2

$$f_{ij} = \begin{cases} \dfrac{-1}{x_i - x_{i-1}} & for \quad j = i - 1 \\ \dfrac{1}{x_i - x_{i-1}} + \dfrac{1}{x_{i+1} - x_i} & for \quad j = 1 \\ \dfrac{-1}{x_{i+1} - x_i} & for \quad j = i + 1 \\ 0 & otherwise \end{cases} \qquad [8]$$

for i=n-1

$$f_{(n-1)j} = \begin{cases} \dfrac{-1}{x_i - x_{i-1}} & for \;\; j = i - 1 \\ \dfrac{1}{x_i - x_{i-1}} + \dfrac{1}{x_{i+1} - x_i} & for \;\; j = i \\ 0 & otherwise \end{cases}$$

The above linear system of equations has been implemented in a MATLAB program, see Appendix A.

The choice of one specific funicular polygon from among the possible solutions of the linear system can be carried out in three different ways, and the solution chosen depends on the designer. So, in this program (see Appendix A) it is possible to choose between:

- Selecting the value of the horizontal component of cable tension H;
- Selecting the y-coordinate of a certain point of the cable. In this case, the system is solved by iterating the value of H until the target coordinate is reached;
- Carrying out an optimization process. In this case, the optimization parameter G, adopted as the change in length of the cable/arch assuming linear elastic behavior, formulated as:

$$\Gamma = \sum_{i=2}^{n-1} T_i L_i \qquad [9]$$

where:

- n = number of nodes;
- T_i is the tension force in the segment of the cable i – (i–1);
- L_i is the length of the segment of the cable i – (i–1). In this case, for a given set of loads, the value of H is iteratively modified within a chosen range of values, and the parameter Γ is calculated for each funicular polygon. The “optimal” polygon is the one with the lowest Γ.

The methodology presented has been used to solve the example in figure 1.17 for the following four alternatives:

- Setting a value for H = 10 kN;
- Ensuring that y-coordinate of the lowest point of the cable is equal to 200 cm;
- Searching for the form that optimizes the parameter G;
- Ensuring that the cable passes through point (600,200).

Figure 1.19 shows the results obtained for the four cases above.

In order to find the same forms using the graphical method, solutions a) and b) would have required two graphic constructions, solution c) could not have been found and solution d) would have only been found by using a trial-and-error method.

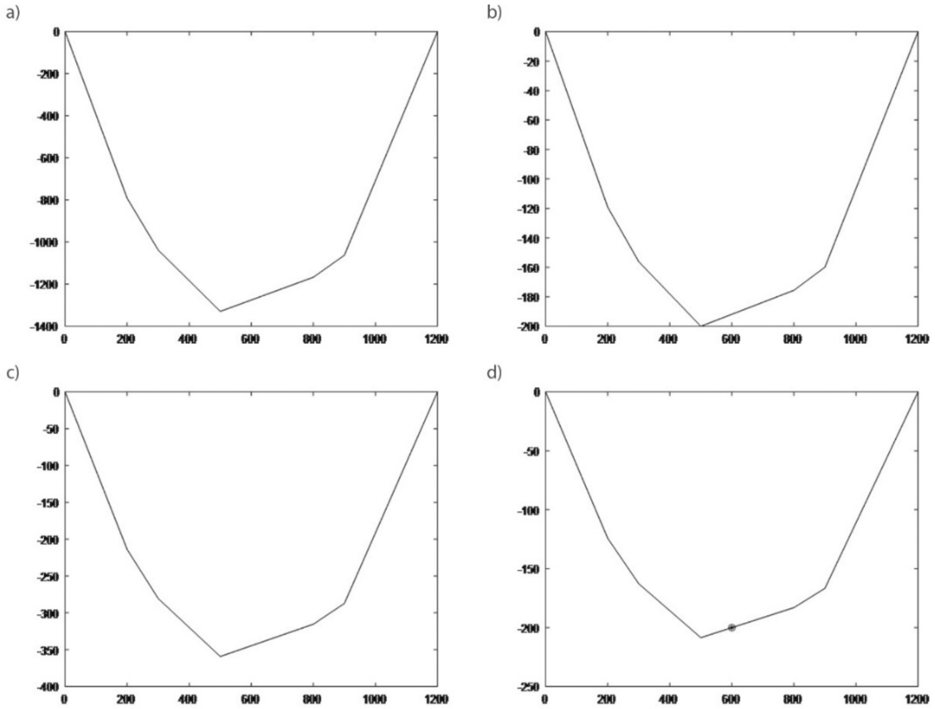


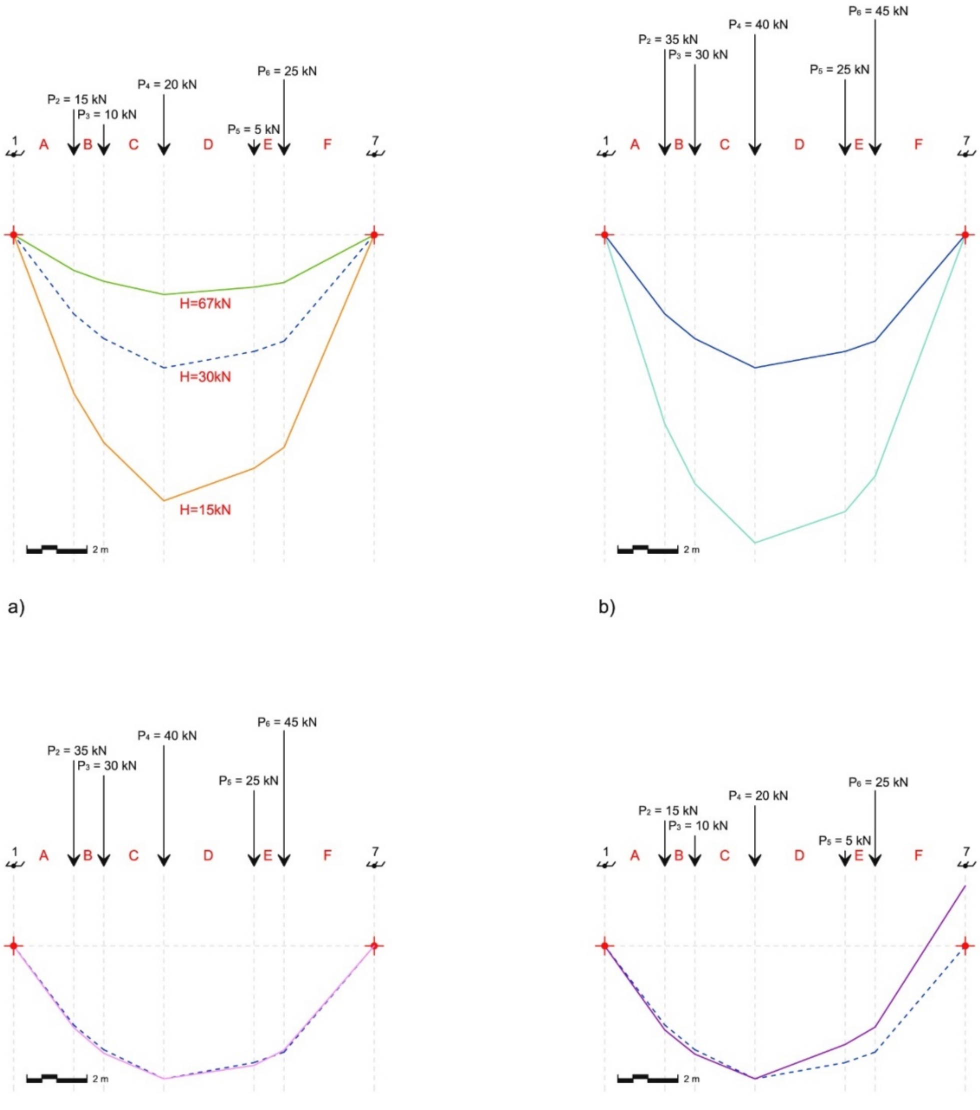
Figure 1.19. Results from the Matlab program developed: a) cable form for H=10 kN; b) cable form with a minimum y-coordinate point equal to 200 cm; c) cable form that optimizes Γ parameter; d) cable form passing through point (600,200)

1.2.1.2. Form-finding with the Farghán matrix

Thanks to its matrix formulation, the Cremona-Maxwell method can also be used for form-finding purposes. Form-finding is a trial-and-error process. The funicular form of a cable depends on the loads applied to the cable and also on the position of the fixed points. An infinite number of funicular solutions based on a set of loads can be found for any given position of the fixed points, and each solution has a different cable length. In order to select a certain funicular shape, the value of the tension force in the cable needs to be set. In other words, once all the conditions - loads, position of the fixed points, and the value of the tension force in the cable are set, the funicular shape is unique. According to the above, the use of funicular shapes for form-finding purposes might seem contradictory, but this is not the case. If it is possible to change the loads (value and/or position), the position of the fixed points, and the tension force in the cable, then all or any of these changes can be used to obtain the desired shape.

Figure 1.20 shows how the equilibrium shape in the example in figure 1.17 changes because of a modification in the value of H (figure 1.20a) or because of an increase in the value of the forces, which is equal for all the forces, that maintains a constant value of H (figure 1.20b). By changing the value of H and increasing the value of the forces, the equilibrium configuration when the position of the lowest point is fixed can be obtained (figure 1.20c). As shown in figure 1.20d, changing the vertical position of the right end means that a new equilibrium configuration is obtained.

There are various ways of using the matrix formulation of the Cremona-Maxwell method for form-finding purposes. Here the optimal equilibrium shapes are obtained by increasing or decreasing the magnitude of the loads applied along the cable Pi (which act at certain positions) and/or changing the position of the fixed points (i.e., the ends of the cable) to get as close as possible to a previously defined target shape. The proximity between the equilibrium and the target shapes is evaluated by using the parameter ΔA, defined as the area between the two curves (see figure 1.21). Each change in the value of the loads and/or the position of the fixed points corresponds to a different value of ΔA. The aim of the procedure proposed is to find the conditions (loads and ends position) that minimize the value of ΔA.



a) b) c) d)

Figure 1.20. Changes in the funicular polygon caused by: a) a change in the value of the force H; b) an increase in the value of the forces keeping the value of H constant; c) an increase in the value of the forces keeping the position of the lower point fixed; and d) a change in the position of the right end of the cable

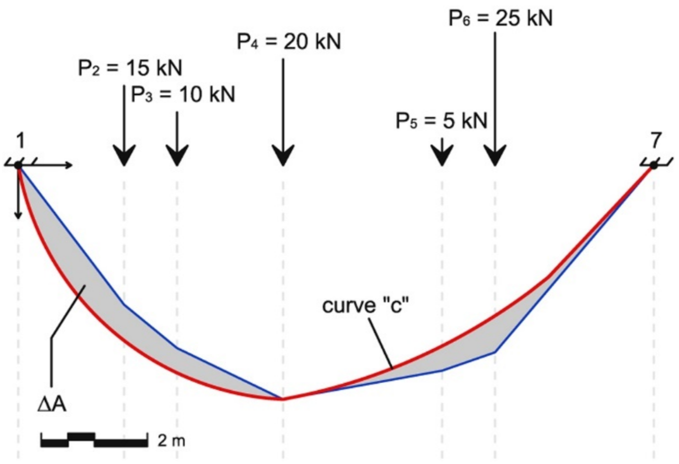


Figure 1.21. Area between the line of thrust of the loads and the target curve “c”

The input data of the problem in the form-finding procedure are

- The initial position of the fixed points (x_1,y_1) and (x_n,y_n).
- The range of possible values for y_1 and y_n and their steps of variation. For example, if the chosen range of possible values of y_1 is (-200 cm, +200 cm) and the step is 10 cm, the possible values of y_1 are: -200 cm, -190 cm, -180 cm, … , 0, 10 cm, 20, cm, …, 180 cm, 190 cm, 200 cm.
- The vector of the initial forces [P_i] (i=2, …, n-1)
- The variation range for the forces P_i and the corresponding step. For example, if Pi = 30 kN, the variation range is (P_i - 10 kN, P_i + 10 kN) and the step is 2 kN, the equilibrium shapes are calculated for the following values of Pi: 20, 22, 24, 26, … , 40 kN. The variation range must be applied to each singular load P_i without changing all the other components of vector [P_i]. Then, this range is applied to all the load pairs (P_i, Pj), with i = 2, …, n-2, j = 3, …, n-1, i < j: [(P_2, P_3); (P_2, P_4); …; (P_2, P_{n-1}); (P_3, P_4); …; (P_3, P_{n-1}); …; (P_{n-2}, P_{n-1})], without changing all the other components of vector [P_i]. Then it is applied to all the triplets (P_i, P_j, P_k), with i = 2, n-3; j = 3, n-2; k = 4, n-1; i < j < k: [(P_1, P_2, P_3); (P_1, P_2, P_4); …; (P_1, P_2, P_{n-1}); (P_1, P_3, P_{n-1}); …; (P_1, P_{n-2}, P_{n-1}); …; (P_{n-3}, P_{n-2}, P_{n-1})], without changing all the other components of vector [P_i]. Then this range is applied, if there are any, to all the quartets, quintets, etc., using the same criterion. In this way the number of all the possible vectors of loads [P_i] to consider is equal to:

$$a = \frac{\left(P_{i,max} - P_{i,min}\right)}{p} \sum_{z=1}^{k} \frac{k!}{z!\,(k-z)!} \qquad [10]$$

Where $P_{i,max}$ is the maximum value of the force in the range, $P_{i,min}$ is the minimum value of the force in the range, p is the step of the forces variation and k is the length of vector $[P_i]$.

If b and c are the number of possible positions of the left and right ends of the cable, respectively, then the total number of combinations of loads/cable end positions is:

$$n_{comb} = a \cdot b \cdot c \qquad [11]$$

- The x-vector made up of the x_i (i=2, …, n-1) position of the forces.
- The target shape “c”.
- The coordinates of a point through which the equilibrium shape must pass (it should be a point of the target shape “c”).

The outputs of the procedure are:

- The final position of the fixed points (x_1,y_1) and (x_n,y_n);
- The vector of the final forces $[P_i]$ (i=2, …, n-1);
- The y-vector collecting the y_i (i=2, …, n-1) positions of the cable at x-cordinates x_i (1=2, …, n-1).

Note that the equilibrium shape that is obtained still has all the advantages of being funicular (so the structure is only subjected to tension or compression), but at the same time the shape fits a target curve defined a priori, which is not necessarily funicular under dead loads.

The procedure above has been implemented using a simple routine in the Matlab program. So, by using an iterative process, the final line of thrust of the loads is the one for which the area between the line of thrust of the loads and the target curve ΔA is the lowest (see figure 1.21).

This procedure has been applied to the analysis of the arch of the Palace of Ctesiphon, the imperial palace of the Sassanid Empire, in order to demonstrate that its asymmetric shape came from a differential settlement of the foundations. The analysis is presented in the following section.

1.3. The importance of the history of constructions and of structural engineering

Unlike the teaching programs of the schools of architecture, in which the courses on the history of architecture are usually preparatory to those of architectural design, history of structural engineering and constructions are not mentioned very often in the teaching programs of structural engineering schools. The reason for this is probably the fact that the analytical aspect of design is preferred to the creative element in traditional programs, meaning that these programs focus more on scientific theories than on history. However, if the focus moves towards the creative part of structural design, avoiding history becomes impossible, as the historical analysis of buildings helps students to learn about structural creativity.

An overview of the state of research on the teaching of the history of constructions in Europe at the beginning of the 21st century was presented in the volume *Construction history, research perspectives in Europe* (Becchi et al., 2004), the fourth volume in the series *Between Architecture and Mathematics*" published by the Eduardo Benvenuto Association in Genoa, Italy. The editors presented the work done in the preparation of the volume as follows: "[…] a small step towards the constitution of an international scientific community that is interested in architecture as well as mechanics; in construction as well as in its history. A community which, so far, has not known how to find the essential points of contact and dialogue, and which has avoided the onus of long-term initiatives".

Bill Addis's contribution on the state of construction history in Great Britain even states (Addis, 2004): "As a formal academic discipline within the higher education system, the state of Construction History in Britain is not healthy. Indeed, it is now in a worse state than one or two decades ago. There are no university departments of Construction History and hardly any formal lecture courses in the subject at undergraduate or post-graduate level. Likewise, there is no formal research program on the subject".

However, the UK is home to one of the most important associations for the history of constructions, the "Construction History Society", which brings together architects, engineers, archaeologists, academics from various disciplines, and historians. These professionals and scholars who are interested in the field of construction, especially in studying how historical buildings were constructed, what materials were used, how much they cost and, above all, what lessons can be learnt from these buildings today. This association is now organizing their tenth annual conference, which will be held in Cambridge in April 2023.

In Spain, as described in the contribution by Santiago Huerta, professor at the Faculty of Architecture of the Polytechnic University of Madrid, the situation is very different. He wrote that, in the 1990s , the history of construction began to be considered as an independent discipline, starting with the first books on the theory and history of construction supported by the Institute “Juan de Herrera” in Madrid, and followed by the success of the seminar “Historia de la construcción. Las fábricas de piedra hasta el Renacimiento” (“History of construction. From the stone factories up until the Renaissance”) held in Madrid in 1995 and the First National Congress on the History of Construction held in Madrid in 1996, in which over ninety authors took part, which shows the interest of architects, engineers, and scholars of both disciplines in the subject. This success led to the creation of the “Sociedad Española de historia de la construcción” (SEHC) (“Spanish Society for the History of Construction”), which has the following objective (Huerta, 2004): “The main objective of the Society was to create a link between the different professionals and scholars working in construction history in Spain, to promote and spread interest studies and research on the topic and to begin a discussion on the definition of the discipline itself. To achieve this, some concrete objectives were defined: 1) the publication of books; 2) the organization of a biennial national congress; 3) the promotion of the study of construction history through seminars and exhibitions; 4) the publication of a newsletter and a journal; 5) the improvement of this study at a university level.”

The Spanish experience, which is still expanding - the 9th national congress was held in 2019, demonstrates that the interest in these areas is alive and well, and that history of construction can be a research topic at university level.

In Italy, the history of construction is a discipline that is found almost exclusively in the curricula of the faculties of architecture and, consequently, research in this field is mainly carried out by architects. However, there are some notable exceptions. The Italian Association of the History of Engineering (AISI), for example, is dedicated to promoting the study and the diffusion of the history of engineering in all its aspects, from antiquity to the present day. In the last conference on the History of Engineering organized by this association, the fifth international conference and the ninth national conference, held in Naples on 16 and 17 May 2022, about one third of the presentations focused on the history of structural engineering (D’Agostino et al., 2022). But the initiative carried out at the University of Rome Tor Vergata is even more significant. Italian structural engineering experienced its most magnificent period during the mid-twentieth century thanks to the work of great engineers such as Pier Luigi Nervi, Riccardo Morandi, Silvano Zorzi, and Sergio Musmeci. However, this was followed by a rapid decline that continues today. Moreover, the importance of this period in the European and international development of reinforced concrete structures and, more generally, of structural engineering, is not properly appreciated. In order to fill this gap, since 2011, professors Sergio Poretti and Tullia Iori, of the University of Rome Tor Vergata, have been working on the research project financed by the European Research Council ERC "SIXXI: XX Century Structural Engineering, the Italian contribution" (Iori, Poretti, 2016) with the following objective: “the general goal of the research is to make a major contribution to the international history of the role of engineering in architecture […]. The project aims to bring out the fundamental role played by Italian structural engineering in the history of modern architecture, which, to date, has been largely ignored”. Poretti and Iori have underlined the need for significant progress to be made on the historiography of modern structural engineering and the need for a new figure, that of a specialized historian capable of “addressing structures on the basis of the intrinsic characteristics of individual works and analyzing the project decisions that were made in terms of mechanical development. Fundamentally, such an investigation would reconstruct the genesis of engineering work based not only on its architectural nature, but also, and especially, on each project’s scientific characteristics. This activity requires a cross-examination of the history of both science and architecture and requires the development of a new figure: the engineering historian, an engineer with a profound knowledge of structural mechanics, but who can also overcome any physiological idiosyncrasy for history”. The works of Nervi, Morandi, Musmeci, and many other structural engineers of their time are indisputable examples of structural creativity and certainly the result of personal talent. Nevertheless, these works are also the result of a series of historical, scientific, and technological contingencies that produced such a thriving period for Italian structural engineering. In order to ensure that this period of creativity does not remain in the past, but can also be applied to the future, it is necessary to discover all the contingencies that caused it, and this is exactly what Tullia Iori and Sergio Poretti’s work aims to do.

The study of the great engineers of the past and their works from a historical, scientific, technical, and technological perspective favors the teaching of structural creativity, but this is an area that is almost completely ignored in the training of engineers, even though many engineers, professionals, and scholars have recently begun to recognize the importance of history. For example, The Swiss journal “Archi” is currently home to a column about conceptual design in which, on a monthly basis, they publish contribution from experts who look at the masters of the past to offer a modern and innovative reinterpretation of their work. The aim of this column is “to create a space for reflection, a bridge between the disciplines of architecture and structural engineering to reinterpret the meaning of the integration between form, strength, and material" (Gozzi and Boller, 2022; original text in Italian, translated by Stefano Miccoli), starting out from the analysis of the work of great engineers from the past. Contributions on the work of Pier Luigi Nervi (Romeo, 2022), Eduardo Torroja (Antuña, 2022), Robert Maillart (Zastavni and Gozzi, 2022), and Henry Lossier (Miccoli, 2022) have already been published. The work of the French engineer Henry Lossier can be taken as an example of structural creativity and his approach to structural design is very up to date. The analysis of his work is presented in the following section.

1.3.1. Creativity and scientific accuracy. The design approach of Henry Lossier (Miccoli, 2022)

Structural creativity does not depend solely on personal talent, but also on in-depth knowledge of the fundamental structural principles such as equilibrium, stability, resistance, stiffness, ductility, and durability, as well as knowledge of the physical and mechanical characteristics of structural materials. A certain familiarity with construction methods and techniques is also required, and these must be adapted to the context and the materials used. Finally, a language that encourages creativity is useful, a language which makes it possible to deal with and resolve the themes of statics while maintaining a visual link between forces and form.

Henry Lossier, a Swiss engineer who mainly worked in France in the first half of the 20th century and was undoubtedly talented, carried out research on building materials and construction techniques and was an expert in graphic statics. It is therefore no surprise that his works can be taken as an example of structural creativity.

1.3.1.1. Graphic statics in the work of Henry Lossier

Henry Lossier was born in Geneva in 1878 and studied civil engineering at Zurich Polytechnic between the end of the 1800s and the beginning of the 1900s. This was just after the publication of Culmann's treatise on the methods of graphic statics (Culmann, 1866). Culmann's work was later developed on by his successors at the chair of structural design at ETH, Wilhelm Ritter from 1873 to 1904 and Emil Mörsch from 1904 to 1916. Thanks to Karl Culmann and his successors, graphic statics became an autonomous discipline that spread rapidly throughout Europe and had a huge influence on the design of some of the most important modern structures. Maurice Koechlin, the co-designer of the Eiffel Tower, was a pupil of Culmann. Robert Maillart studied in Zurich when the chair of structural design was held by Ritter. In Italy, Luigi Cremona included the concepts of the polygon of forces and the funicular polygon, typical elements of graphic statics, in his theory of reciprocal figures (Cremona, 1872). Pier Luigi Nervi and Riccardo Morandi were introduced to the graphic methods through the work of Cremona. In Spain, Mariano Rubió y Bellvé, Gaudi's engineer, the vault builder Rafael Gustavino, as well as Eduardo Torroja and Felix Candela were trained in the field of graphic statics (Allen and Zalewski, 2010). Henry Lossier was one of the main figures involved in the spread of graphic statics. In fact, after graduating as the best in his year, he held the position of professor of graphic statics at Zurich Polytechnic from 1904 to 1906. This position also undoubtedly influenced his professional activity.

1.3.1.2. The research of Henry Lossier

Although as early as 1908 Lossier devoted most of his time to his professional work as a designer of reinforced concrete structures, he was an active researcher, who mainly focused on two themes in his extensive and fruitful works: innovative theoretical research on concrete and on construction methods and the calculation of specific structural types in reinforced concrete (in particular vaults and bridges). Lossier's interest in concrete stemmed from the specific period in which he lived and worked, that is, the First World War. In fact, during the war, the lack of traditional building materials such as wood and steel meant that concrete, a material that was hardly known at that time, played an important role, especially in the construction of large-span industrial buildings (Espitallier, 1919). In dealing with this type of construction, a particularly creative aspect of his design process emerged. When dealing with new materials, whose physical and mechanical characteristics are not yet fully known, it’s quite normal to use forms that are typical of other more well-known materials. The first cast iron bridges, for example, took the shapes of the more traditional stone arch bridges, which did not fully exploit the properties of the new material (figure 1.22). Lossier, on the other hand, abandoned the flat forms that were typical of wooden and steel constructions and rediscovered and explored forms that were typical of stone and masonry constructions, such as arches and vaults. In his article dedicated to domes and vaults in reinforced concrete, he explores the additional opportunities offered by reinforced concrete, as a result of the tensile strength provided by the reinforcement. He also analyzed construction problems (Lossier, 1928).

Figure 1.22. Coalbrookdale bridge on the Severn river, England. Arch. T. Farnolls, eng. A. Darby, 1779 (Photo by Johnson Architectural Images)

He also contributed to the field of reinforced concrete technology with a patent on the reinforcement of reinforced concrete beams that improved the adhesion between concrete and steel. This patent followed an extensive test campaign carried out at the Zurich Polytechnic laboratories (figure 1.23) (Vautier, 1903).

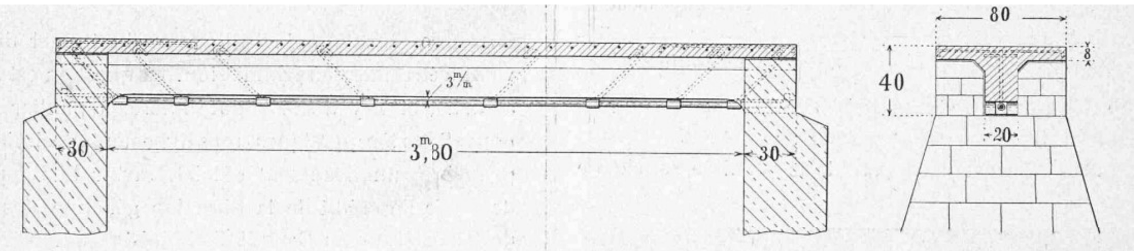


Figure 1.23. Reinforced concrete beam of the Lossier system (Vauiter, 1903).

Henry Lossier's research spans a period of over 50 years, and it includes all the key stages in the development of concrete as a building material. This intense research was also fundamental for the development of his structural creativity. One of his most famous projects is the hangar for airships in Ecausseville, an example of structural creativity resulting from the synthesis of talent, research, and training in the field of graphic statics.

1.3.1.3. The Ecausseville airships hangar

In order to cope with the intensification of German submarine warfare, the French Navy decided to build twelve airship hangars, which would allow for increased surveillance of the ports on the coast of the English Channel and enable them to escort naval convoys that would defend them from German attacks. The Ecausseville hangar was built between 1917 and 1919, and it was designed by Eng. Henry Lossier (Figure 1.24 and 1.25).

Figure 1.24. Ecausseville airship hangar. Exterior

Figure 1.25. Ecausseville airships hangar. Interior

The building, 150 meters long, 40 meters wide, and 31 meters high, guarantees a free profile consisting of a rectangle that is 24 meters wide and 16 meters high, surmounted by a semicircle with a 12 meter radius, which allows an airship to enter (figure 1.26). The entire building is constructed in reinforced concrete. The main supporting structure is characterized by 27 portals, placed at regular spans of 6.25 meters, each consisting of an arch with three hinges placed at the top of two triangular lattice piers. On these portals there are longitudinal thin-section beams on which the covering tiles, which act as an external skin, are finally placed.

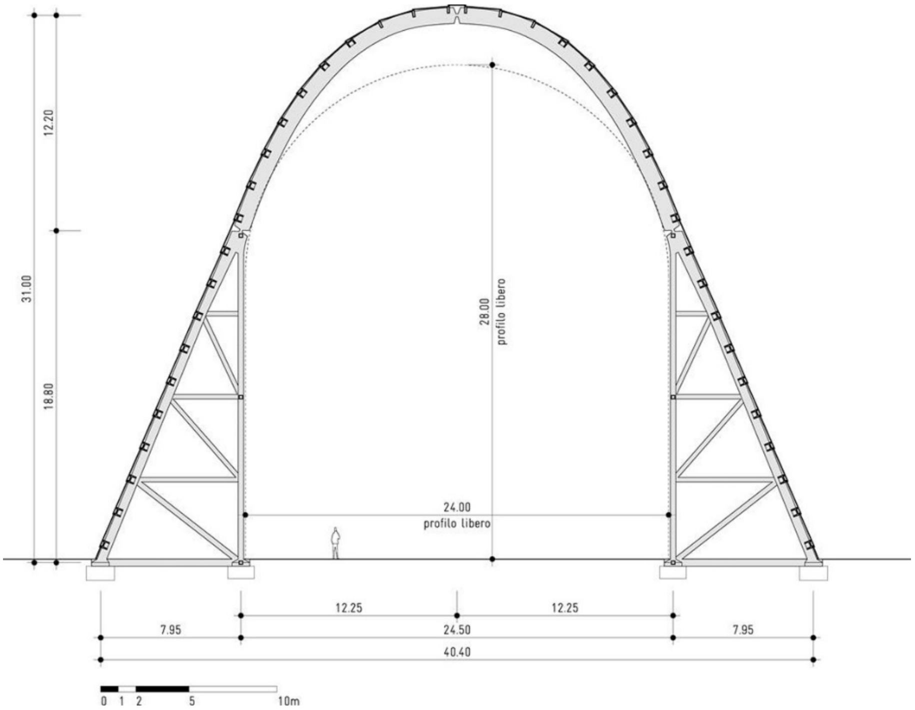


Figure 1.26. Ecausseville airships hangar. Cross-section (drawing by Roberto Guidotti)

The hinges of the arches (figure 1.27) were constructed by weakening the concrete section and by increasing the number of reinforcing bars. The bars that cross the section are compressed, while the stirrups, perpendicular to the axis of the arch, allow the friction of the concrete to increase the resistance and, above all, the ductility of the concrete.

The three 50 meter structurally independent sections are longitudinally stabilized by diagonal rods placed at the ends of each section. These elements, together with the secondary beams and some of the portal rods, form stable trusses (figure 1.28). Other longitudinal bars connect the different portals in order to stabilize the internal chords of the piers. The structure is supported by foundation plinths placed at the bases of each pier.

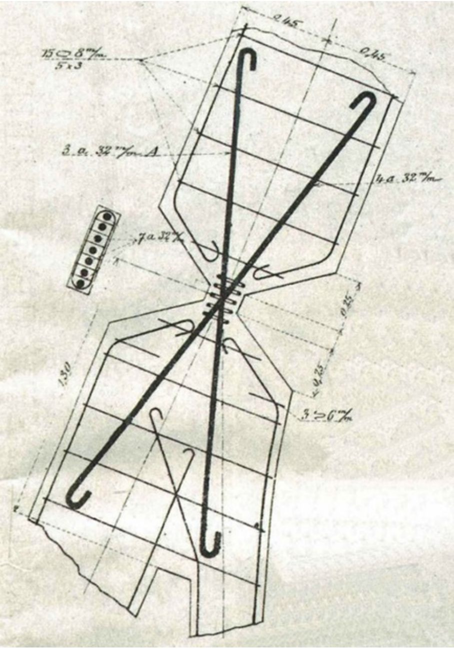


Figure 1.27. Ecausseville airships hangar. Structural detail of the hinges (Espitallier, 1919)

There are several reasons why this building can be considered as an example of structural creativity. The first is because it adapts and responds to functional needs by using a shape that maximizes internal space, but at the same time minimizes the use of material by making the most of its mechanical characteristics. In order to determine the shape of the vault, Lossier certainly used graphic statics methods, even if the shape he chose is not that of the catenary, which would have been the natural one for a load uniformly distributed along the development of the arch. However, he chose a semi-circular shape that is easier to implement, and which, therefore, favors constructive aspects over the formal aspects. The arches, however, have a 40x90 centimeter rectangular cross section, with reinforcement consisting of longitudinal bars and stirrups, and it is therefore able to bear the bending stresses due to both the (minimum) deviation of the shape created from the natural shape of the permanent loads (figure 1.29), and especially to the shape related to the asymmetrical variable loads and to wind (figure 1.30).

Finally, the creativity of this project also lies in the use of a relatively new material, whose behavior was hardly known at the time but whose potential was fully exploited. The design and construction solutions proposed by Lossier, ranging from the shape of the arch to the detail of the hinges, are not in fact derived from the construction practices used for other materials, they exploit the physical and mechanical characteristics of concrete instead.

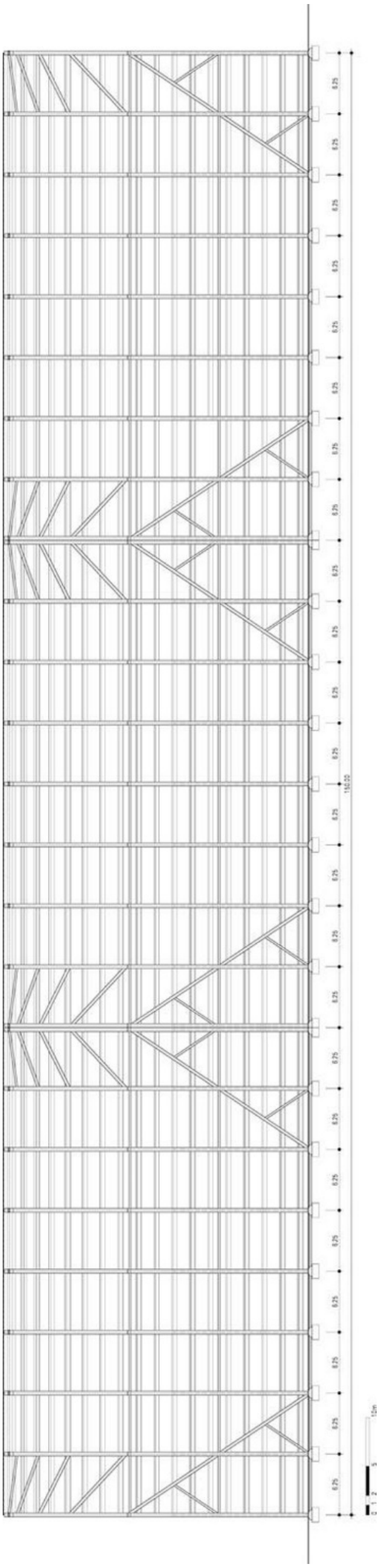


Figure 1.28. Ecausseville airship hangar. Longitudinal sections (drawing by Roberto Guidotti)

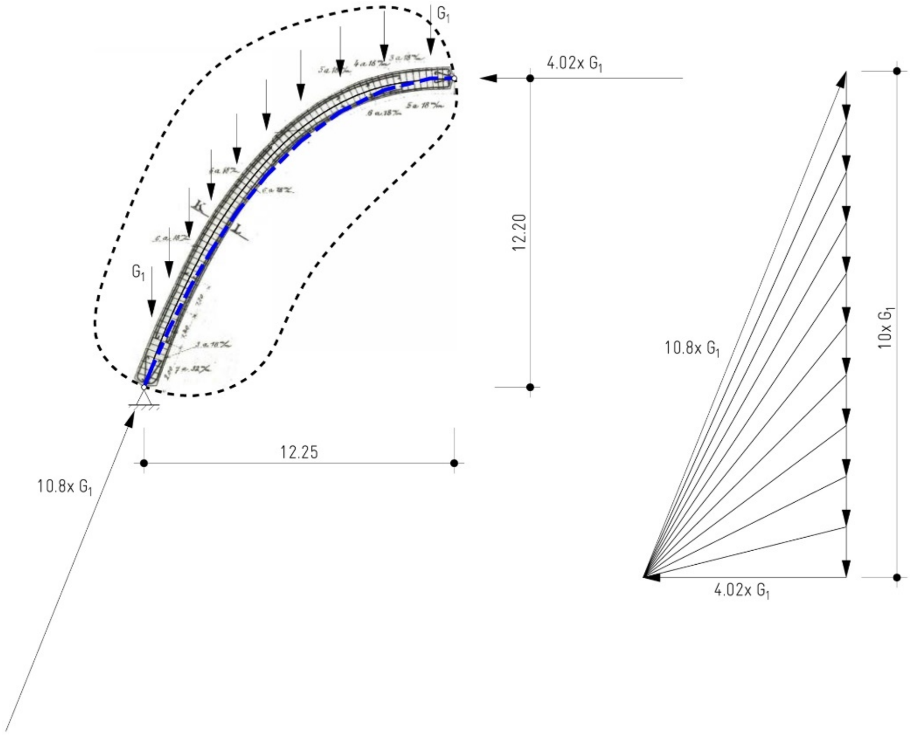


Figure 1.29. Graphic analysis of the shape of the arch of the Ecausseville hangar. Thrust line of the permanent loads (drawing by Roberto Guidotti)

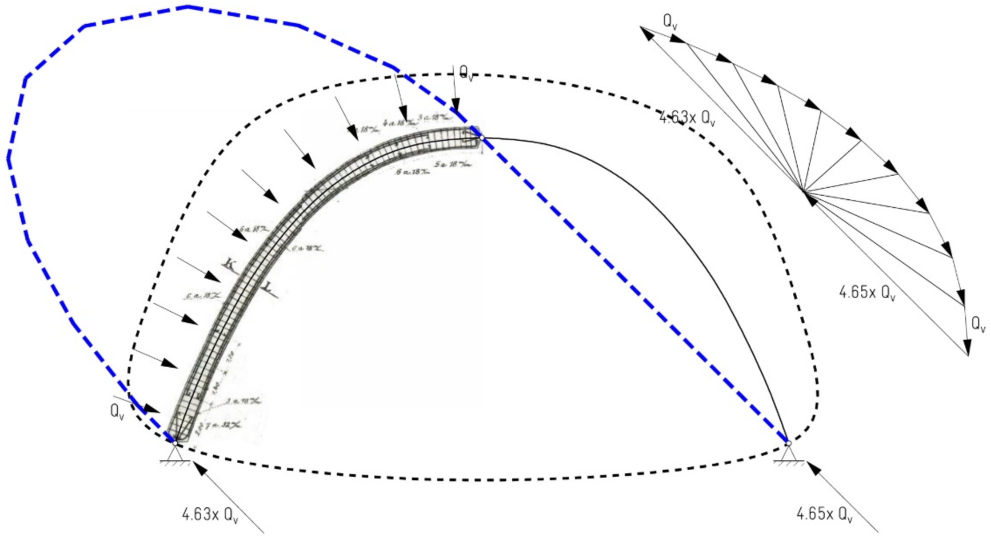


Figure 1.30. Graphic analysis of the shape of the arch of the Ecausseville hangar. Thrust line of the wind loads (drawing by Roberto Guidotti)

1.3.2. The history of structural engineering

There is also another area of history that contributes to the creation of structural intuition: the study of the history of structural engineering, which is very significant from the perspective of scientific clarity and the awareness of existing structural methods. The volume by Karl Eugen Kurrer *The history of the theory of structures: from arch analysis to computational mechanics* (Kurrer, 2008) is a complete treatise on the history of structural theories with an impressive bibliography, including the classic *History of strength of materials* by Stephen Timoschenko (Timoschenko, 1953) and *A History of Civil Engineering: An Outline From Ancient to Modern Times* by Hans Straub (Straub, 1964) which contains a chapter on the separation of the paths of architecture and engineering caused by the intervention of analytical language and scientific methodology. Interest in this area is mainly based on the fact that it is possible to witness the progressive distancing of the figures of the architect and the engineer by following the historical development of structural theories. However, it is also possible to identify the moments when the analytical and creative methods have gotten closer.

Research in the field of the history of structural engineering is multidisciplinary and combines both historical and scientific methods. And as a multidisciplinary area, the goal of this kind of research is not only to analyze and describe a past event from an historical perspective, but also to make scientific progress in the field of structural engineering. The following section presents an example of this kind of multidisciplinary research that has achieved both goals.

1.3.2.1. New historical records about the construction of the arch of Ctesiphon and their impact on the history of structural engineering (Miccoli, 2021a)

A piece of historical research about the construction of the ancient Arch of Taq-iKisra, part of the imperial palace of the Sasanian Empire in the city of Ctesiphon, has been carried out. The information obtained, an analysis using graphic statics, the use of a physical model with hanging chains, and an ad hoc optimization program written in MATLAB have shown that the designer of this sixth century AD arch, a Byzantine named Farghán, was aware of the effects of the uneven distribution of loads and the differential settlements of the foundations on the equilibrium shape of structures working exclusively in compression and was able to control them. This discovery predates the earliest statement about the link between the shape of the catenary and that of an arch, by Robert Hooke, by eleven centuries and highlights the importance of this building not only because of its historical, archaeological, and architectural significance, but also because of its importance in the history of structural engineering. The building is currently in need of restoration to stop its collapse, and an awareness of the way it was designed could be of practical use for the definition of the intervention needed.

1.3.2.1.1. Introduction

The Arch of Taq-iKisra (the Palace of Khosrow; figure 1.31) is the most significant remaining monument of the Sasanian Empire and it is widely recognized as one of the most important pieces of architectural world heritage (Sarre, 1999). The arch, made of bricks and mortar, is about 30 m tall and 25 m long, and it is still the longest brick-arch in the world (Gronlund, 2021).

Figure 1.31. The Arch of Taq-iKisra (the Palace of Khosrow) today (left), and a close-up view of the vault showing bricks and mortar layers (right). Source of right-hand photo: Bruno, 1966

A study conducted by Hernández-Montes et al. investigated the reasons for the unusual shape of the arch, which is close to that of a catenary and slightly asymmetric, and they concluded that the arch has a multi-catenary shape that takes the real weight of the arch into account. This suggests that the designer–builders were probably aware of the natural shapes working in compression, and these researchers also deduced that the asymmetric shape came from a differential settlement of the foundations (Hernandez-Montes et al., 2017). Nevertheless, the authors of this work found no records to prove this hypothesis. However, these records were found in the ancient epic poem *Shahnameh*, written by the Persian poet Ferdowsi around AD 1000, in which some details about the construction of the building are reported, confirming the hypothesis on the differential settlement of the foundations (Ferdowsi, 1888, 1923). The description explains that the architect, the Byzantine Farghán, waited four years for the walls to settle before building the arch. He knew that the settlement would have caused its collapse, thus demonstrating that he was aware of the effect of differential settlement on the shape of the arch. An analysis using graphic statics and laboratory tests using hanging chain models, taking into account the differential settlement mentioned in the *Shahnameh*, have shown that the shape of the arch corresponds to the line of thrust of the real loads considering the settlement of the foundations. An ad hoc optimization program written in MATLAB (MATLAB, 2020), which is based on a simple matrix formulation of the Cremona method, has been used to find the differential settlement that minimizes the distance between the line of thrust of the loads and the axis (the line connecting the middle point of each arch section) of the real arch, obtaining a value that is very close to the one mentioned in the *Shahnameh*.

1.3.2.1.2. History of the building

The Taq-iKisra is part of the imperial palace of the city of Ctesiphon. The exact date of its construction is unknown: Emil Herzfeld, for example, attributed it to the period of Shapur I based on a comparison with the facades of the Parthian palace of Assure; other scholars believe that the construction began under the reign of Khosrow I (Bruno, 1966). However, according to the records found in the *Shanahmeh*, it was built during the reign of Khosrow II in the sixth century AD by a Byzantine architect named Farghán. It is located close to a bend in the river Tigris, near the modern city of Salman Pak, Iraq, about 35 km south of Baghdad, but it was originally part of the ancient city of Ctesiphon. Shortly after its completion, in AD 637, the Arabs defeated the Persian Empire and captured the palace, which was then used as a Mosque and later gradually abandoned. The palace was at risk of demolition during the foundation of Baghdad (AD 762–767). The Caliph Mansur wanted to use the material of the palace to build the new city, but he was persuaded by his counsellor, Khalid the Barmecide, to find the material elsewhere because the palace had become a symbol of Arab supremacy. Khalid said to the Caliph: “this ancient palace had become an abiding proof of the might of Islam; it was an enduring monument, for all who should behold it, of how the worldly glory of its builder, the great Chosroes, had come to naught before the religion of the Arabs, who had overthrown the Persian monarchy, and whose sovereign now ruled in its stead”. Khalid also added that, when the palace was used as a mosque, the Caliph Alì prayed there, so it could not be demolished, as it had become a symbol of the Islamic religion. Mansur did not follow this advice and began the demolition of the building, but he soon realized that the cost of demolishing the palace and transporting the material was higher than procuring new material, so the demolition was interrupted. The same danger reappeared during the tenth century AD, when the Caliph Ali Muktafi demolished part of the building to use its material for the construction of the Taj Palace in Baghdad (Le Strange, 1922). Then, the building was totally abandoned and forgotten until the first European travelers reached the area in the seventeenth and eighteenth centuries, but the first ones who arrived did not recognize it as the Palace of Ctesiphon, considering the building to be a temple of the sun, or the work of a Roman emperor (Reuther, 1929). Around the middle of the nineteenth century, the French artist Eugène Flandin and the architect Pascal Coste carried out an archaeological expedition to ancient Persia and reached the area of Ctesiphon. They recognized the building as the Palace of Khosrow II and were struck by its magnificent and immense “elliptic” vault, stating that “the Romans had nothing similar or of the type!” (Flandin and Coste, 1851). Figure 1.32 shows a drawing of the building by Pascal Coste as it appeared to them. Marcel August Dieulafoy and his wife Jane Magre managed to take photographs of the Palace during their archaeological trip to Persia during the 1880s (Dieulafoy, 1885) just before a devastating flood caused the collapse of the north wing of the Palace in 1888 (Keall, 1987).

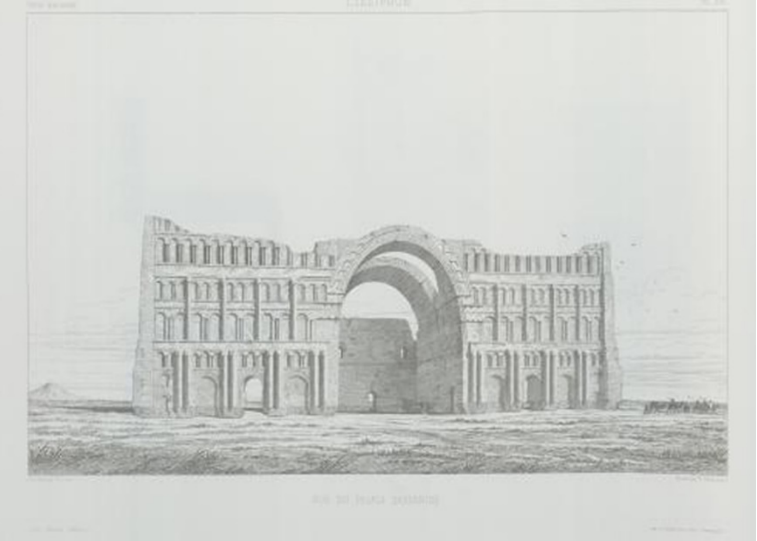


Figure 32. Drawing of the Palace of Ctesiphon. Source Flandin and Coste, 1851

Three German archaeological expeditions took place at the beginning of the twentieth century: the first in 1907–1908 by the archaeologists Ernst Emil Herzfeld and Friedrich Sarre, who managed to produce a plan of the building; the second, in 1928–1929, whose main objective was to unearth archaeological finds to be put on display in the History Museum of Berlin, while also confirming the plans of the first expedition; the third, directed by E. Kühnel, director of the Islamic section of the History Museum of Berlin, was carried out in collaboration with the New York Metropolitan Museum of Arts. In the second half of the twentieth century, the aim of the expeditions changed. The interest of the archaeologists moved to the palace itself, to its valorization, and, therefore, to its restoration. In the early 1950s, Professor J. F. Van der Haeghen, a structural engineer and professor of stability of structures at the University of Louvain, made the first ever study of the stability of the construction and of the causes of its damage, based on the drawings and photographs collected during the expeditions mentioned earlier (Lacoste, 1955). After calculating the loads acting on the arch, he performed a graphic static analysis, proving that the thrust line lies completely inside the depth of the arch (figure 1.33), but he also identified the main reasons for the collapses and the damage in the thermal expansion of the vault and the walls, which differ both in terms of exposure and in terms of thickness, causing internal stresses that led to cracking and collapses.

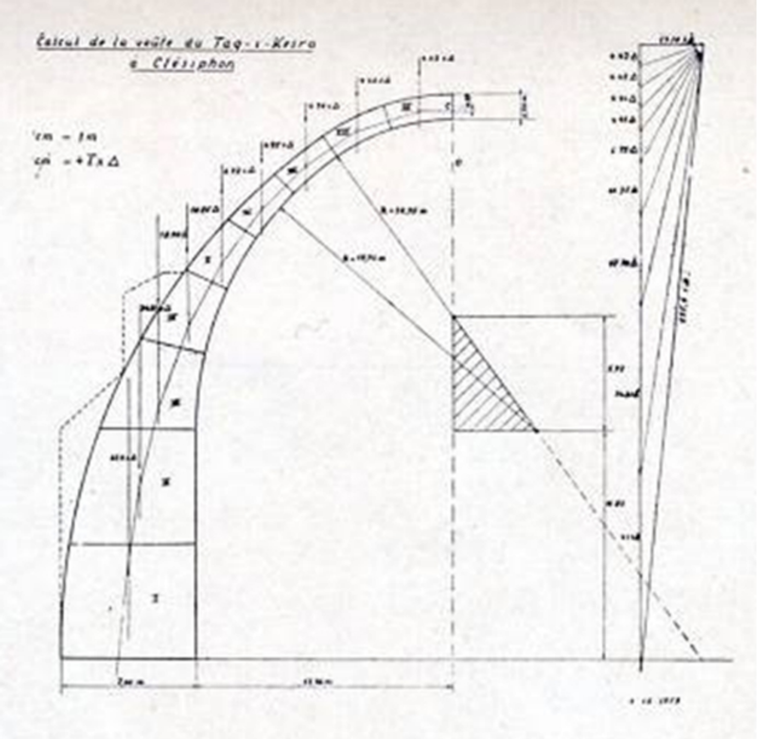


Figure 1.33. Graphic static analysis of the arch of Ctesiphon. Source: Lacoste, 1955

Using the analysis by Professor Van der Haegen, Professor M. H. Lacoste, president of the Royal Academy of Architecture of Brussels, suggested the further research that was needed to properly restore the building: an analysis of the brick and the mortar, drainage of the soil to study the foundations and the damage caused by water infiltrations, an on-site analysis of the cracks of the vault to confirm the hypothesis about their nature, and the study of possible methods to protect the vault against rain and heat (Lacoste, 1955).

The stated goal of the Italian expedition, which took place in 1964–1966, was to prepare the ground for the restoration of the building; they conducted excavation tests and a photogrammetric survey of the intrados of the vault, and they carried out conservative restoration work on the surfaces. Nevertheless, the restoration project presented to the General Directorate of Antiquities of Iraq by the Italian architect Andrea Bruno did not involve the vault, and it was not carried out. The restoration of the south wing took place in 1972 and the reconstruction of the north wing began in 1975, but the restoration was interrupted by the sensitive political situation in the area, firstly because of the war between Iran and Iraq during the 1980s, then because of the Gulf War at the beginning of the 1990s, and the Iraq War during the first decade of the new millennium (Persian Dutch Network, 2018). In 2013, a Czech company, ProjectyZeman, was contracted to conduct some research on the structure of the building with the aim of proposing a strategy for its rehabilitation. As detected in the 1950s by Professor Van der Haegen, the Czech company identified exposure to weather as the main damage issue, particularly the ingress of rainwater that could cause the propagation of cracks, so a roofing solution was proposed, consisting of a layer of concrete, which was completed in 2017 (Chandra Makoond, 2015). Unfortunately, this restoration could not stop the deterioration of the vault, and the vault suffered further collapses in March 2019 (Persian Dutch Network, 2019). The possibility of an ISIS attack in 2014–2016 prompted the Persian-Dutch pianist, journalist, and music historian Pejman Akbarzadeh to record a documentary about Taq-iKisra before its possible destruction and to start a campaign to raise awareness of the importance of the building (Akbarzadeh, 2017). The situation has now become critical; the monument is in serious danger of collapse and needs urgent intervention. This is the reason why a piece of historical research about the construction of the building has become even more important. Even though history is undoubtedly about the past, the aim of historical research should be focused on the present (Chang, 2017). Finding out how the arch was designed and constructed could definitely be of practical use for the definition of the intervention needed. In January 2021, the Swiss based agency Aliph, the international alliance for the protection of heritage in conflict areas, announced the provision of a US$700’000 fund towards stabilization measures. The restoration team, which is a collaboration between the University of Pennsylvania and the Iraq State Board of Antiquities, is at work.

1.3.2.1.3. Peculiarities in the shape of the arch

Besides the outstanding dimensions of the vault, there are two main characteristics that make the Arch of Taq-iKisra unique: its shape, which, visually, is close to a catenary, thus differing from the typical parabolic or semi-circular roman arch; and its asymmetry. Nowadays, all structural engineers are aware that a catenary is the shape taken by a cable loaded by its self-weight, and that there is a link between the shape of a cable and that of an arch. This link was first written about and published by Robert Hooke in 1676 (Hooke, 1676). Therefore, the shape suggests the use of graphic statics to check the stability of the arch a posteriori, verifying that the line of thrust is contained inside the depth of the arch. The first structural analysis performed on the arch of the Palace of Korsow II by the Belgian engineer J. F. Van der Haeghen was indeed a graphic analysis of the line of thrust (figure 1.33). The same analysis was performed by J. F. D. Dahmen and J. A. Ochsendorf (figure 1.34) to evaluate the magnitude of internal compressive forces and the safety of the arch (Dahmen and Ochsendorf, 2012), but the aim of this kind of analysis is to evaluate the stability of an existing building and provides no clues to how it was designed.

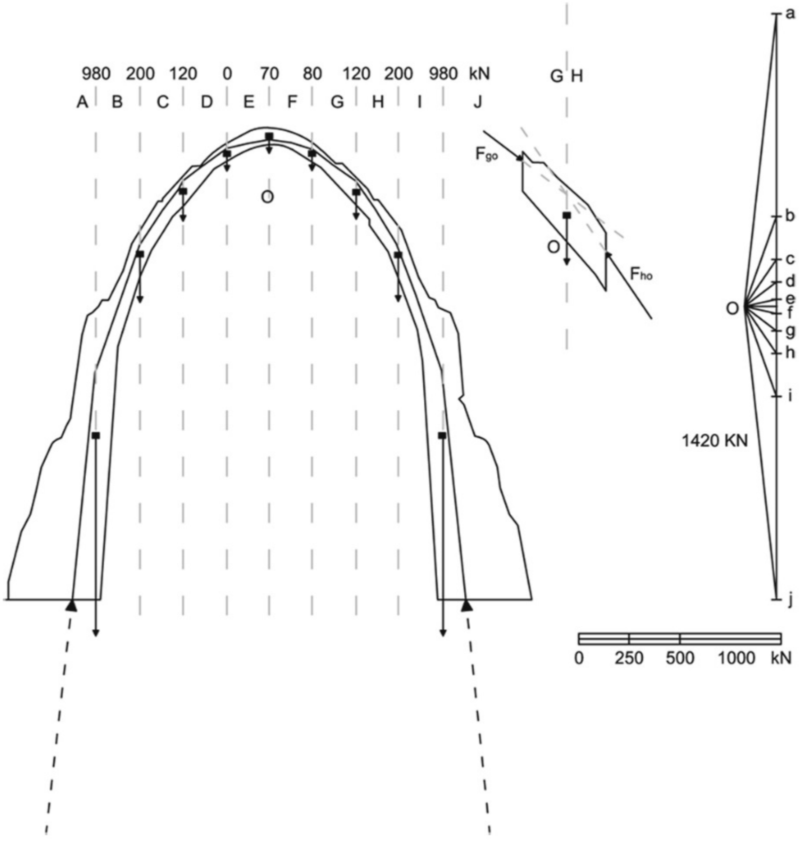


Figure 1.34. Thrust-line analysis of the Taq-iKisra. Adapted from: Dahmen and Ochsendorf, 2012

Hernández-Montes et al. were the first experts to question not only if the arch was stable, but also how it had been designed and whether the non-symmetric catenary shape had been made on purpose based on the construction of hanging chain models. The authors of this study obtained the equilibrium configuration of the arch mathematically as a combination of segments from different catenary curves and through a hanging chain model using two chains with different specific weights, one for the arch and another for the walls, concluding that the configuration is compatible with the actual geometry of the arch. This result suggests that the designers were aware of the shapes working in compression and able to control them for design purposes, but the authors could not find any record that could either prove this insight or explain the reason for the non-symmetric shape. They made a hypothesis of a differential settlement of the foundations to explain it.

A piece of historical research has been carried out to find records to support the hypothesis formulated by Hernández Montes et al. These records have been found in the ancient Persian poem *Shahnameh*, where some details about the construction of the building are reported, which are presented in the following paragraph.

1.3.2.1.4. The construction of the building

The *Shahnameh*, literally 'The book of the kings', tells the history of Persia over a period of 2000 years, until the Arab conquest in AD 651. It can be divided into two parts, legendary and historical, the latter ranging from the exploits of Alexander the Great to the end of the Sasanian Empire. In the chapter dedicated to King Khosrow II (AD 570–628), a description of the construction of the Taq-iKisra building is presented. The most significant parts are mentioned here.

How Khursau Parwiz (Kosrow II) built the Palace of Mada'in

'[…] Khursau Parwiz
Sent men to Rúm, Hind, Chin […]
Three thousand famed artificers, of whome
He chose two hundred - master of their craft,
Who knew the use of brick and mortar well […]
They chose a Rúman matchless in the world […]
Said the Sháh: -
"Accept this contract at my hands and heed

These mine instructions: I require a building
Such that although my sons and race shall dwell
Therein for many a year it will not fall
To ruin through the rain or snow or sun.
The expert undertook the Sháh' commission,
And said: "For this I am competent.'

King Khosrow II sent his men to all the main countries of the known world to find the right designer for a building that would last for the generations to come, and he selected a Byzantine (Rúman) architect who was 'matchless in the world'.

'[…] when the walls
Belonging to the palace had been reared
[…]
The Sháh appointed a man […]
Who went and made inspection of the walls.
The artist brought silk which the company
Turned to a slender cord by twisting it.
Then from the wall-top of the royal palace
He measured to the level of the ground
And after measuring the twisted cord
[…]
He took it to the royal treasury,
And having sealed it gave it to the keeper.'

After building the walls, the architect Farghán asked the king to measure them with a silk cord and keep the cord safe in the royal treasury.

'But though the Sháh bade: "Haste!" I will not urge
The work for forty days but let it settle.
The Sháh selected me, and when the time
Is ripe the palace-wall shall be as Saturn.
Let not the Sháh wrath aggravate my toils.
[…]
That honest workman
Knew that experts would blame him when he built
The palace hastily and, if it fell,
That he himself would lose his livelihood.
That night he disappeared: none saw him more.'

Knowing that the walls needed to settle before starting the construction of the arch and under pressure from the king to complete the palace, Farghán ran away.

> *‘He sought for one for three years but they found*
> *None of surpassing worth, and people still*
> *Talked much about the former architect,*
> *Who in the fourth year reappeared.*
> *[…]*
> *The Rúman said: “if now*
> *The King will send me with a trusty man*
> *I will explain to him about my doings*
> *And pardon will ensue on explanation.”*
> *[…]*
> *The clever Rúman took the measuring-line*
> *And with the Sháh’s own representative*
> *Tried the walls height and found that it had sunk*
> *Seven cubits.*
> *[…]*
> *The Rúman then spake thus: “If I had carried*
> *The buildings to their height no wall, O Sháh!*
> *No vaulting and no work had stood, and I*
> *Could not have stayed at court.’*

Farghán came back after four years and proved to the King that the height of the wall had decreased by seven cubits (ca 3.1 m), so if he had completed the building earlier, it would have collapsed.

> *“[…] Thus much time passed away,*
> *The Sháh was eager for the work’s completion,*
> *After seven years it was achieved.”*

Farghán then completed the palace over the following seven years, taking the new height of the wall as the starting point for the design of the arch. The historical source found in the *Shahnameh*, which describes the procedure of the construction of the Taq-iKisra Palace, has confirmed the hypothesis that the asymmetric shape of the arch derives from a differential settlement of the walls. Therefore, the architect was aware of the consequences of possible differential settlements and uneven load distribution on the equilibrium shape of the arch and was able to design the shape of the arch according to the loading and geometrical conditions. This suggests that this building might be the first example of the application of modern structural design based on funicular geometry rather than classical geometry. In fact, the usual procedure for the design of arches at that time, up until the growth of the first structural theories in the seventeenth century (Heymann, 2016; Walker, 2011) was to use geometries that were easier to build, mainly semi-circular, that were not connected to the path followed by the forces and therefore needed to use more material in order to contain the line of thrust even though the shape was not funicular. Funicular shapes are more difficult to construct, and they need models to define them, such as hanging chain models. The shape of the Arch of Taq-iKisra is undoubtedly funicular, and this is extremely interesting for the history of structural design, as it suggests that the knowledge of the link between the shape of a flexible hanging chain and that of an arch was known 1000 years before Robert Hooke. The use of hanging models for design purposes was also present in the reconstruction of St Paul's Cathedral in London by Christoph Wren and Robert Hooke (1690) (Heymann, 1998) and the analysis of the dome of St Peter's Cathedral in Rome by Giovanni Poleni (1748) (Poleni, 1748; Mainstone, 2003). The Arch of Taq-iKisra also predates these constructions. The steps that were likely to have been used by the architect Farghán to design the shape of the arch are retraced here using graphic statics and a hanging chain model to show that the shape of the arch corresponds to the line of thrust obtained by considering the real loads and a differential settlement equal to that mentioned in the "Shahnameh".

1.3.2.1.5. Analysis of the shape of the arch

1.3.2.1.5.1. The geometry and material properties of the arch

The geometry and material properties adopted in this study were obtained from Chandra Makoond (Chandra Makoond, 2015). The geometry is drawn to scale in figure 1.35. The height of the arch is 30.3 m, it spans a length of 25.6, and, as can be observed, the arch is not symmetric on the vertical line drawn from the middle point between the supports. The arch is made of masonry: clay bricks and gypsum mortar. The thickness of the walls increases from 2.1 m (at the height of 19.3 m) to 7.4 m at the base, while the thickness of the arch (the part above 19.3 m) increases from 1.35 m to 2.1 m. The mechanical properties of the masonry are taken from Hernández-Montes et al. and shown in table 1.1

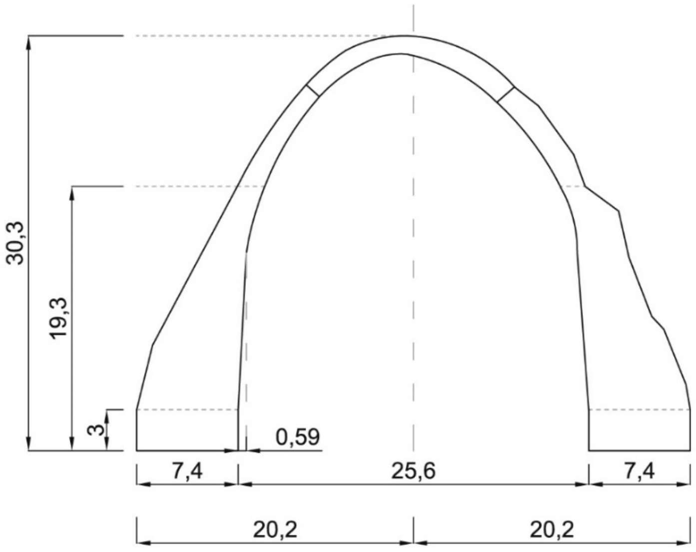


Figure 1.35. Actual cross-section of Taq-iKisra arch (dimensions in metres). Adapted from Chandra Makoond, 2015

Table 1.1. Material properties for different masonry arrangements

	Masonry unit			
	Horizontal	**Horizontal (sat.)**	**Vertical (dry)**	**Vertical (sat.)**
Bulk density (kg/m^3)	1298			
Elastic Modulus (MPa)	1060.11	728.46	636.07	437.08
Poisson's ratio (ν)	0.167			
Compressive strength (MPa)	1.06	0.73	0.64	0.44

1.3.2.1.5.2. Hanging chain model

The steps that were followed for the design of the shape of the Taq-iKisra arch are deduced and repeated using a hanging chain model. The model shows that the shape of the arch derives from the weights of the walls and of the arch, and, above all, from a differential settlement of the base of the walls that is equal to 3.08 m. It is likely that Farghán, the architect of the building, used hanging chain models to derive the correct shape of the building.

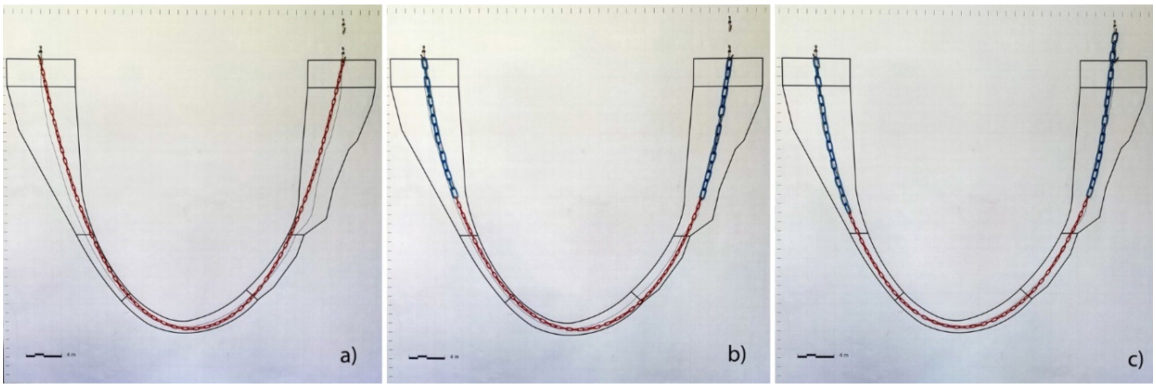


Figure 1.36. Hanging chain model of the Taq-iKisra Palace. (a) First attempt catenary with one chain; (b) second attempt catenary with two chains; (c) differential settlement.

The first step of the experiment is shown in figure 1.36a. A chain with a specific weight equal to 0.657 g cm−1 is hung at points A and B and passes through point O (see the position of points A, B and O in figure 1.37). The catenary curve taken by the chain is symmetric about a vertical line passing through point O and does not retrace the actual shape of the axis of the cross-section of the building.

The second step is shown in figure 1.36b. A second chain (the thicker one) with a specific weight equal to 1.5798 g cm−1 is used to model the walls sustaining the arch, as the thickness of the walls is much greater than that of the arch. The scale factor is:

$$\frac{1298\,kg/m^3\,x1.78\,m\,x\,1\,m}{0.06571\,kg/m} = 35161.16 \qquad (1)$$

Hence the thicker chain corresponds to a thickness equal to

$$\frac{0.15798\,kg/m\;\;x\,35161.15}{1298\,kg/m^3\;x\,1m} = 4.28\,m \qquad (2)$$

The thicker chain is used up to a height equal to 16 m. The third step is shown in figure 1.36c. The support on the right is lifted up by 7 cubits (ca 3.08 m) in order to model the differential settlement of the walls mentioned in the construction description given in the *Shahnameh*. Figure 1.36c shows that the shape obtained in the last step is the one that best fits the axis of the real arch, thus showing that the shape of the arch of Taq-iKisra was designed to consider both the weights and the differential settlements of the supports. This type of design allowed the architect to optimize its thickness and therefore its weight.

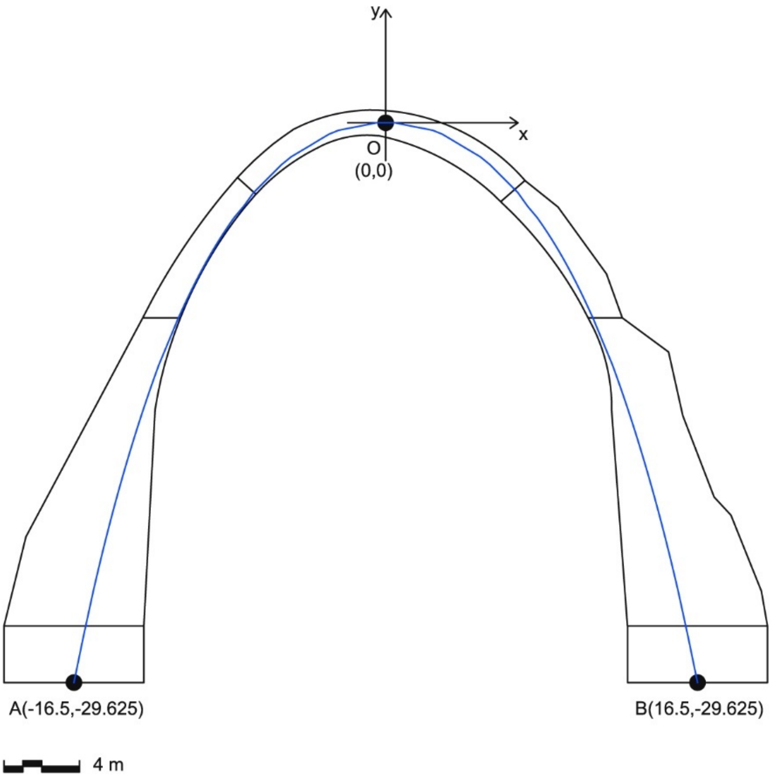


Figure 1.37. Catenary passing through O, A, and B plotted inside the arch cross-section.

1.3.2.1.5.3. Graphic statics

Starting out from the geometry of the arch surveyed by the Czech company ProjectyZeman, the equation of a catenary curve passing through points O, A, and B in figure 1.37 is calculated:

$$y(x) = -7.085\cosh\left(\frac{x}{7.085}\right) + 7.085 \tag{3}$$

The catenary is plotted inside the geometry of the arch (see figure 1.37). It is deduced that the curve of a hanging chain passing through points O, A, and B was the starting point for the design of the arch. In order to use graphic statics for the next steps, a constant thickness of 1.78 m (the average depth of the arch above the walls) is assigned to the first attempt catenary arch. The arch is divided into horizontal stripes up to a height of 19.3 m (the part of the walls) and normal segments for the arch zone (figure 1.38), and the weight of each part of the arch generated by the subdivision is obtained from the drawing by multiplying the area of each part by the specific weight of the material. The values of the loads are given in table 1.2.

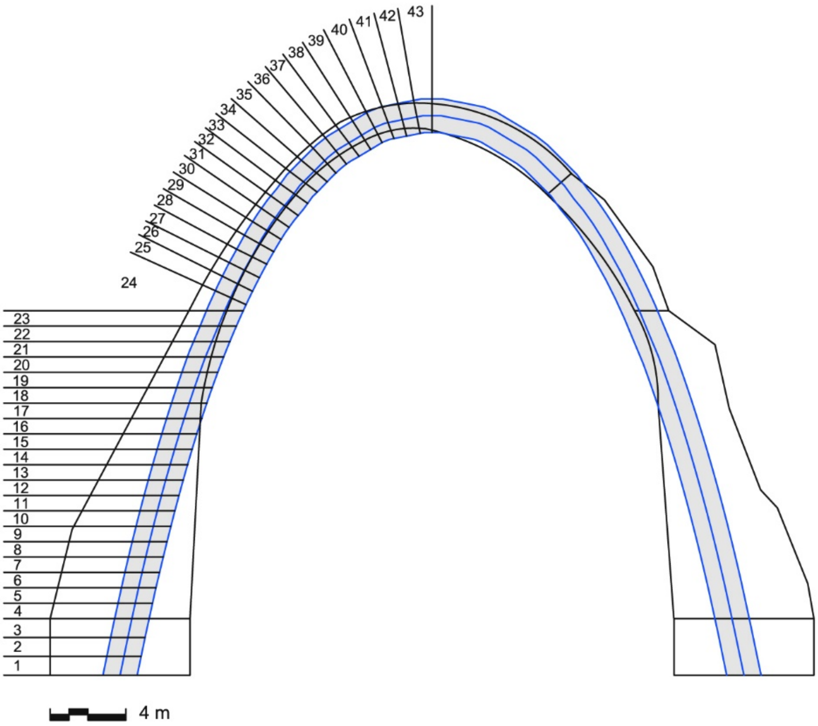


Figure 1.38. Subdivision of the catenary arch in stripes and segments

Table 1.2. Loads for each arch stripe and segment in the first step

Stripe n°	Area (m^2)	Specific weigth (kg/m^3)	Mass (kg)	Load (kN)	Stripe n°	Area (m^2)	Specific weigth (kg/m^3)	Mass (kg)	Load (kN)
1	1.8152	1298	2356	23.1	23	1.572	1298	2040	20.0
2	1.8152		2356	23.1	24	1.4356		1863	18.3
3	1.8184		2360	23.1	25	1.4606		1896	18.6
4	1.4845		1927	18.9	26	1.4418		1871	18.4
5	1.4846		1927	18.9	27	1.4418		1871	18.4
6	1.4862		1929	18.9	28	1.4434		1874	18.4
7	1.4876		1931	18.9	29	1.4418		1871	18.4
8	1.4903		1934	19.0	30	1.4414		1871	18.3
9	1.4941		1939	19.0	31	1.4418		1871	18.4
10	1.4953		1941	19.0	32	1.4438		1874	18.4
11	1.5004		1948	19.1	33	1.4331		1860	18.2
12	1.5056		1954	19.2	34	1.4418		1871	18.4
13	1.5056		1954	19.2	35	1.4413		1871	18.3
14	1.5056		1954	19.2	36	1.4418		1871	18.4
15	1.5117		1962	19.2	37	1.4418		1871	18.4
16	1.5188		1971	19.3	38	1.439		1868	18.3
17	1.5239		1978	19.4	39	1.4416		1871	18.3
18	1.5286		1984	19.5	40	1.4509		1883	18.5
19	1.5417		2001	19.6	41	1.4347		1862	18.3
20	1.5543		2017	19.8	42	1.4446		1875	18.4
21	1.5543		2017	19.8	43	1.5484		2010	19.7
22	1.561		2026	19.9					

The loads are applied at the center of mass of each piece of arch. The shape corresponding to this system of loads is obtained by using the Cremona diagram, as shown in figure 1.39. In the second step, a constant depth equal to 4.28 m is assigned to the first nineteen stripes to better model the real situation. The new loads corresponding to stripes 1 to 19 are given in table 1.3. The shape corresponding to this system of loads is obtained through the Cremona diagram, as shown in figure 1.40.

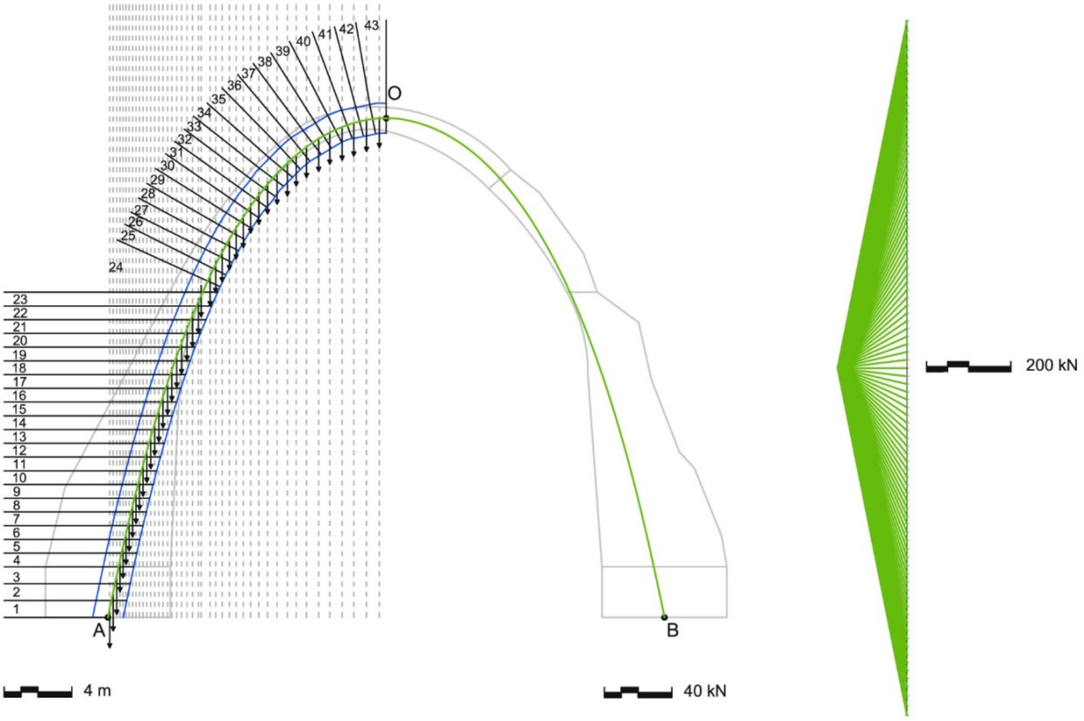


Figure 1.39. Force polygon (right) and funicular polygon (left) of the first attempt load system

As can be seen in figure 1.40, the load lines need to be updated based on the new position of the funicular polygon. The loads are at the center of mass of each part of the catenary arch that corresponds to the last funicular polygon, and a new funicular polygon is calculated by using graphic statics. The result is shown in figure 1.41.

A differential settlement of 3.08 m (equivalent to 7 Roman cubits, as described in the 'Shanhameh') is then modelled by lowering the right-hand side support to scale. The new funicular polygon is obtained graphically by using the Cremona diagram and shown in figure 1.42.

The horizontal thrust acting at the supports is equal to 1700 kN. However, the reaction at the supports is close to vertical as the weight of the arch is very high, so it approximates the vertical reaction (ca 13 500 kN).

Table 1.3. Loads for arch stripes 1 to 19 in the second step

Stripe n°	Area (m^2)	Specific weigth (kg/m^3)	Mass (kg)	Load (kN)
1	4.3700	1298	5672	55.6
2	4.3700		5672	55.6
3	4.3700		5672	55.6
4	3.5696		4633	45.4
5	3.5728		4637	45.5
6	3.5808		4648	45.6
7	3.5857		4654	45.6
8	3.5893		4659	45.7
9	3.5943		4665	45.7
10	3.6003		4673	45.8
11	3.6127		4689	46.0
12	3.6222		4702	46.1
13	3.6296		4711	46.2
14	3.6374		4721	46.3
15	3.6459		4732	46.4
16	3.6560		4745	46.5
17	3.6670		4760	46.7
18	3.6802		4777	46.8
19	3.6944		4795	47.0

The results obtained are summarized in figure 1.43, where the funicular polygons corresponding to the three steps considered are represented inside the cross-section of the real arch. The grey strips represent the middle third of the sections (the core). The last funicular polygon is completely contained inside the core, so the resulting arch is totally compressed. Therefore, the last funicular polygon is the one that best fits the real shape of the arch, and it also explains its asymmetric shape. This suggests that the shape of the arch is based on a design that takes into account the differential settlement of the walls.

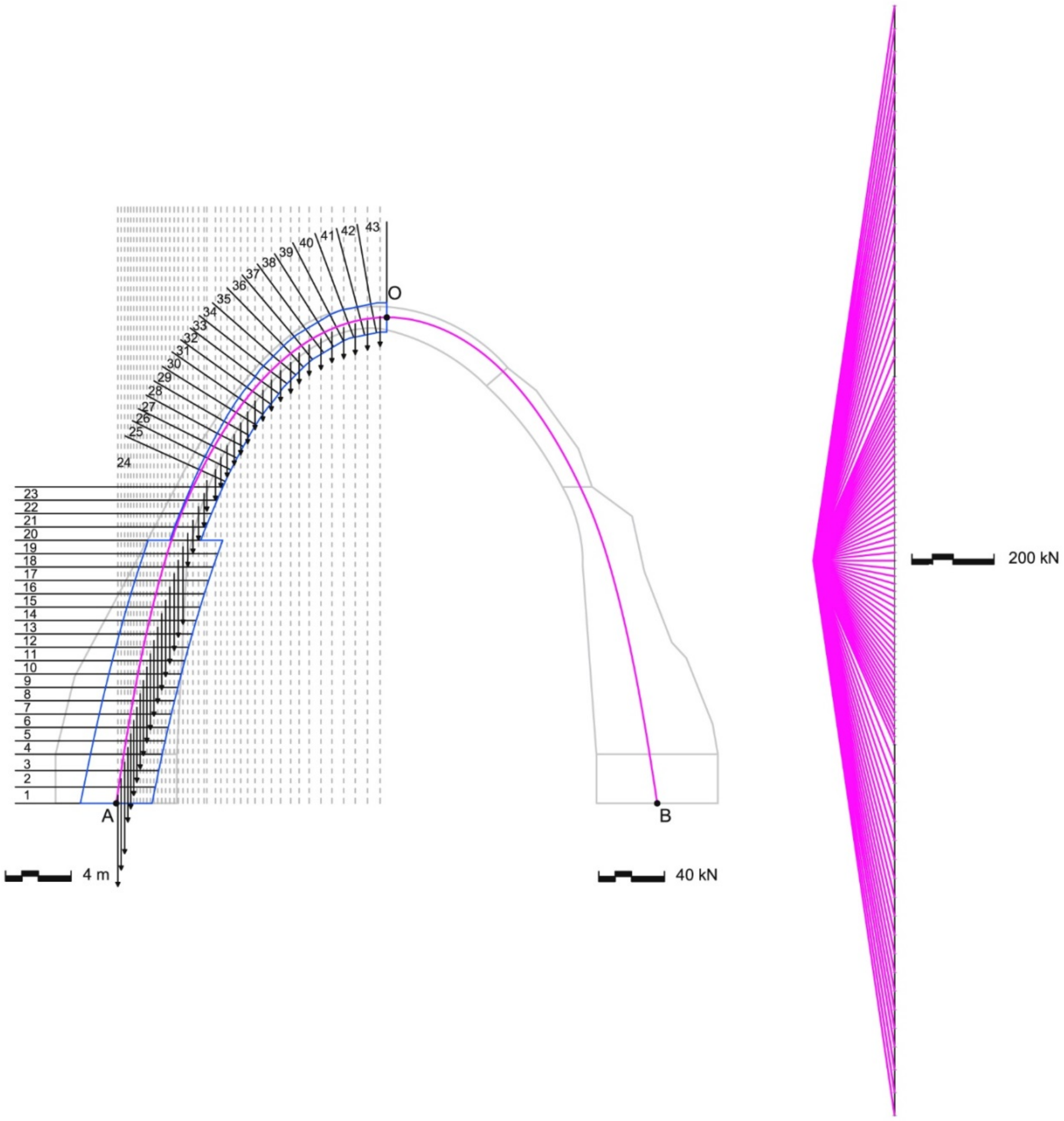


Figure 1.40. Force polygon (right) and funicular polygon (left) of the second step

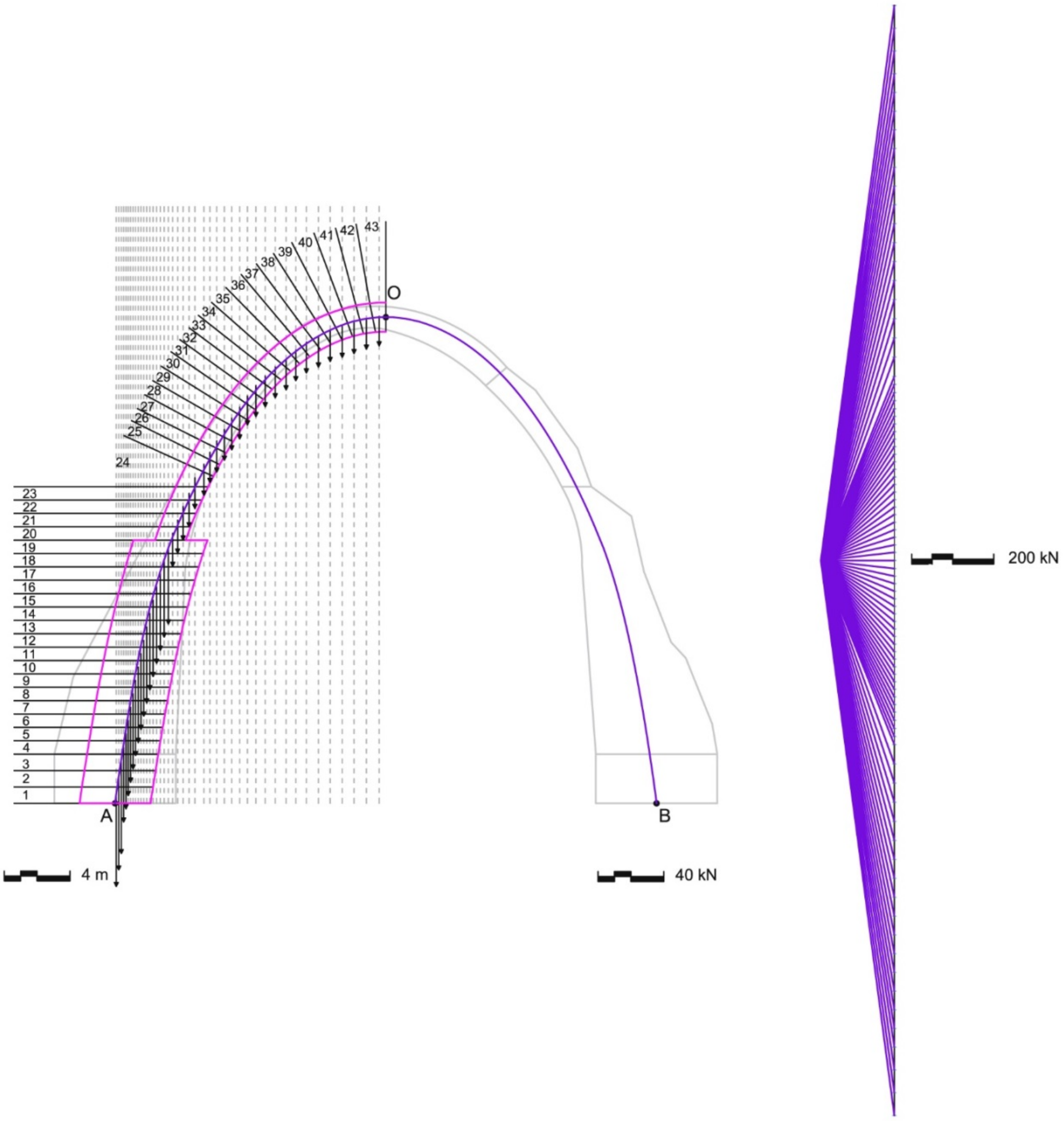


Figure 1.41. Force polygon (right) and funicular polygon (left) of the second step based on the correction of the load lines

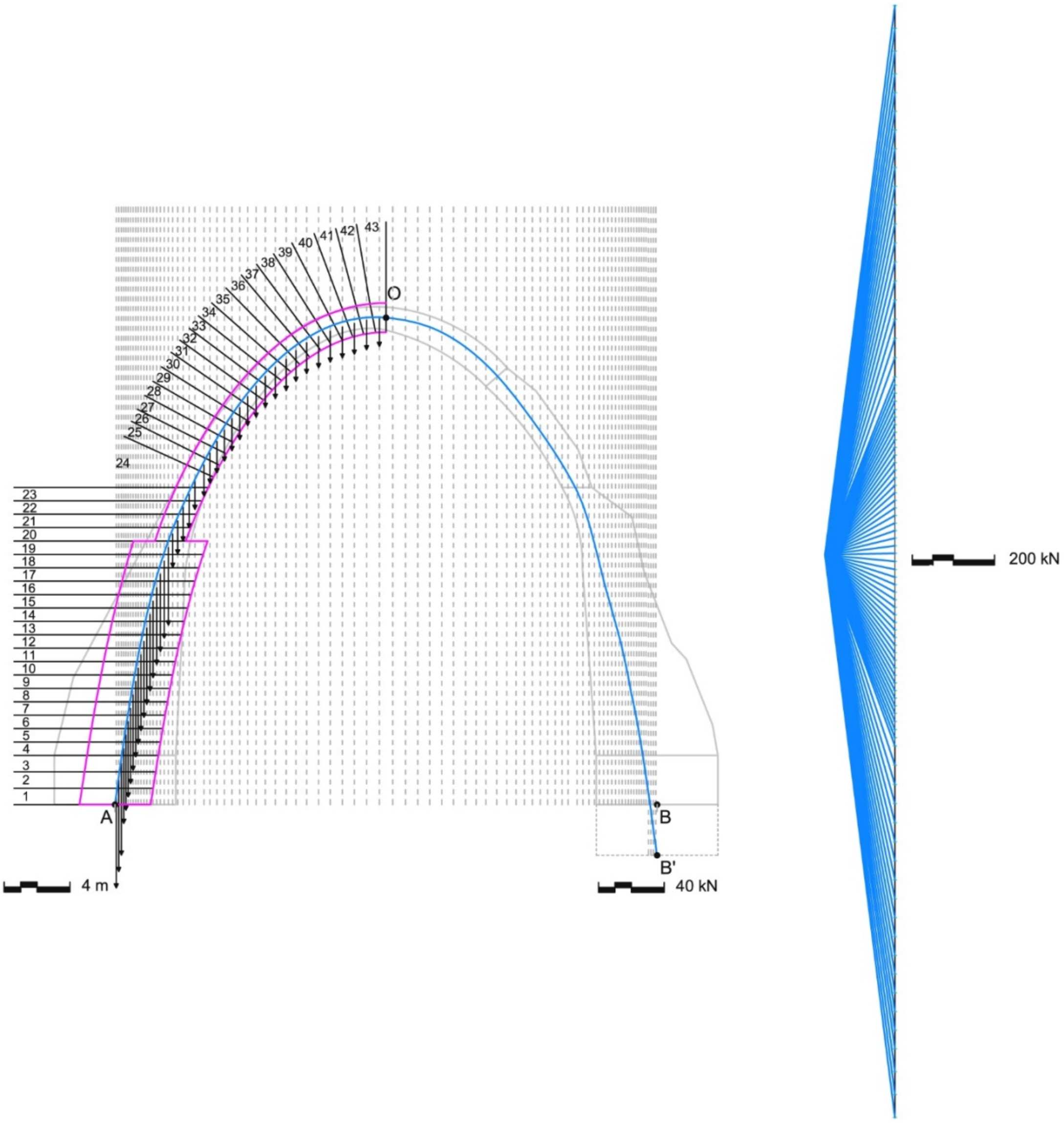


Figure 1.42. Force polygon (right) and funicular polygon (left) of the third step

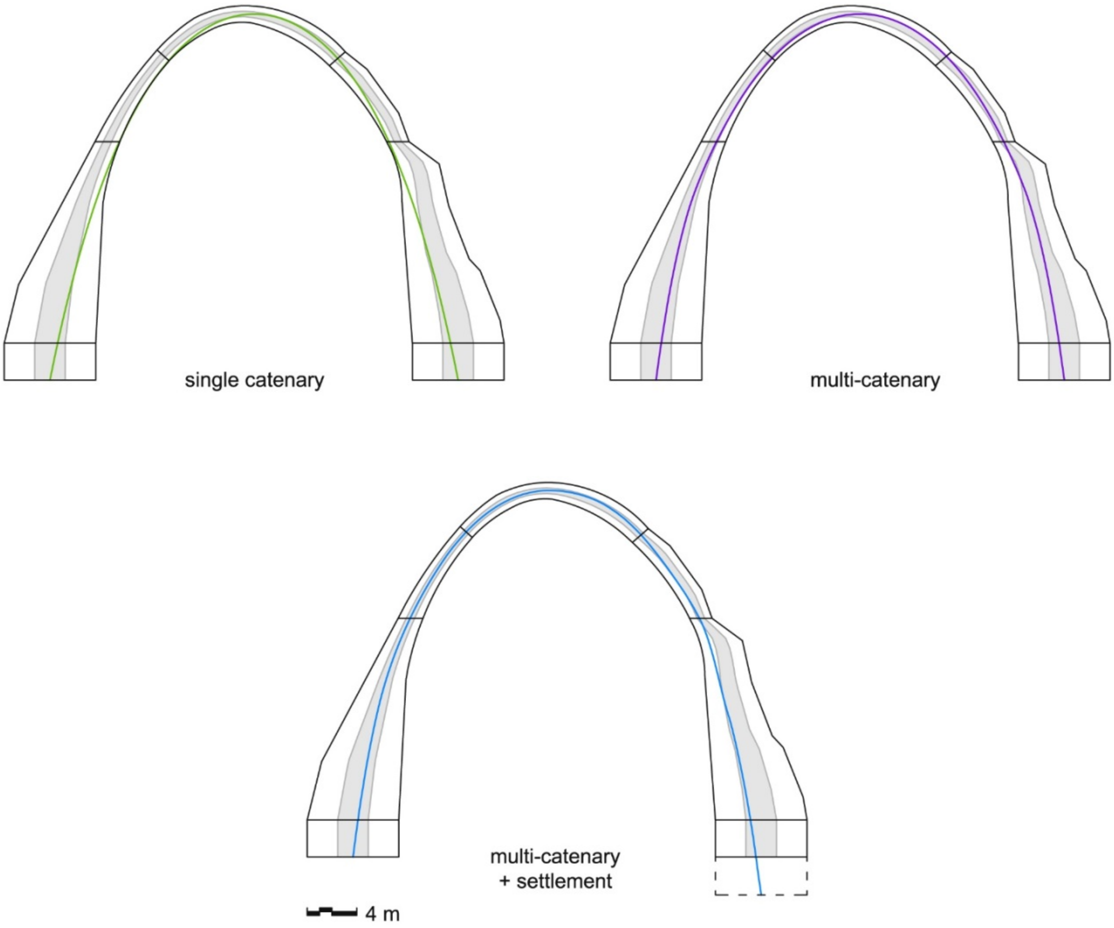


Figure 1.43. Summary of the funicular polygons

1.3.2.1.5.4. Ad hoc optimization Matlab program

The optimization Matlab program described in the previous section has been used to find the optimal value of the differential settlement of the supports of the Arch of Taq-iKisra, which is the one that minimizes the area between the funicular polygon of the loads acting on the arch and the axis of the arch, and to compare this value with that which is mentioned in the description of the building given in the “Shahnameh” (figure 1.44). In this example, the area is calculated only for the arch-zone, that is above y = 19.3 m.

The load system has been obtained by following the same steps used for the analysis with graphic statics. Table 1.4 summarizes the positions and values of the loads used to calculate the funicular polygon

The position of the right-hand support that minimizes the area between the line of thrust of the loads and the axis of the arch is y = –240 cm (figure 1.45). This is lower than the value mentioned in the *Shahnameh* (7 cubits, ca 310 cm), but it clearly indicates that the shape of the arch derives from a major differential settlement of the supports. Thus, it is very likely that the asymmetric shape of the arch was designed by the architect after the differential settlement occurred and was measured.

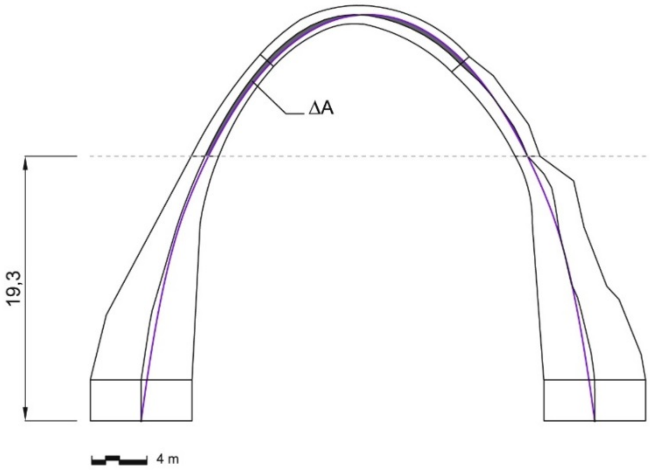


Figure 1.44. Area between the funicular polygon and the axis of the arch, above y = 19.3 m

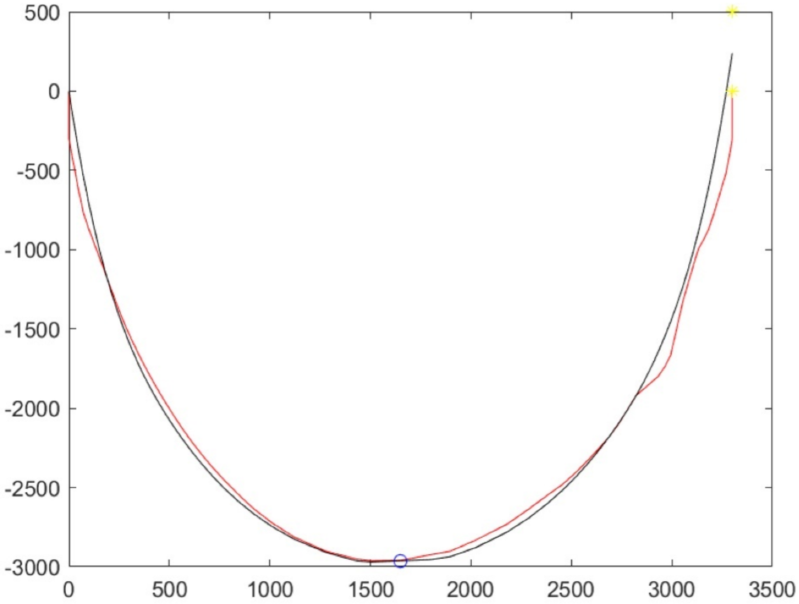


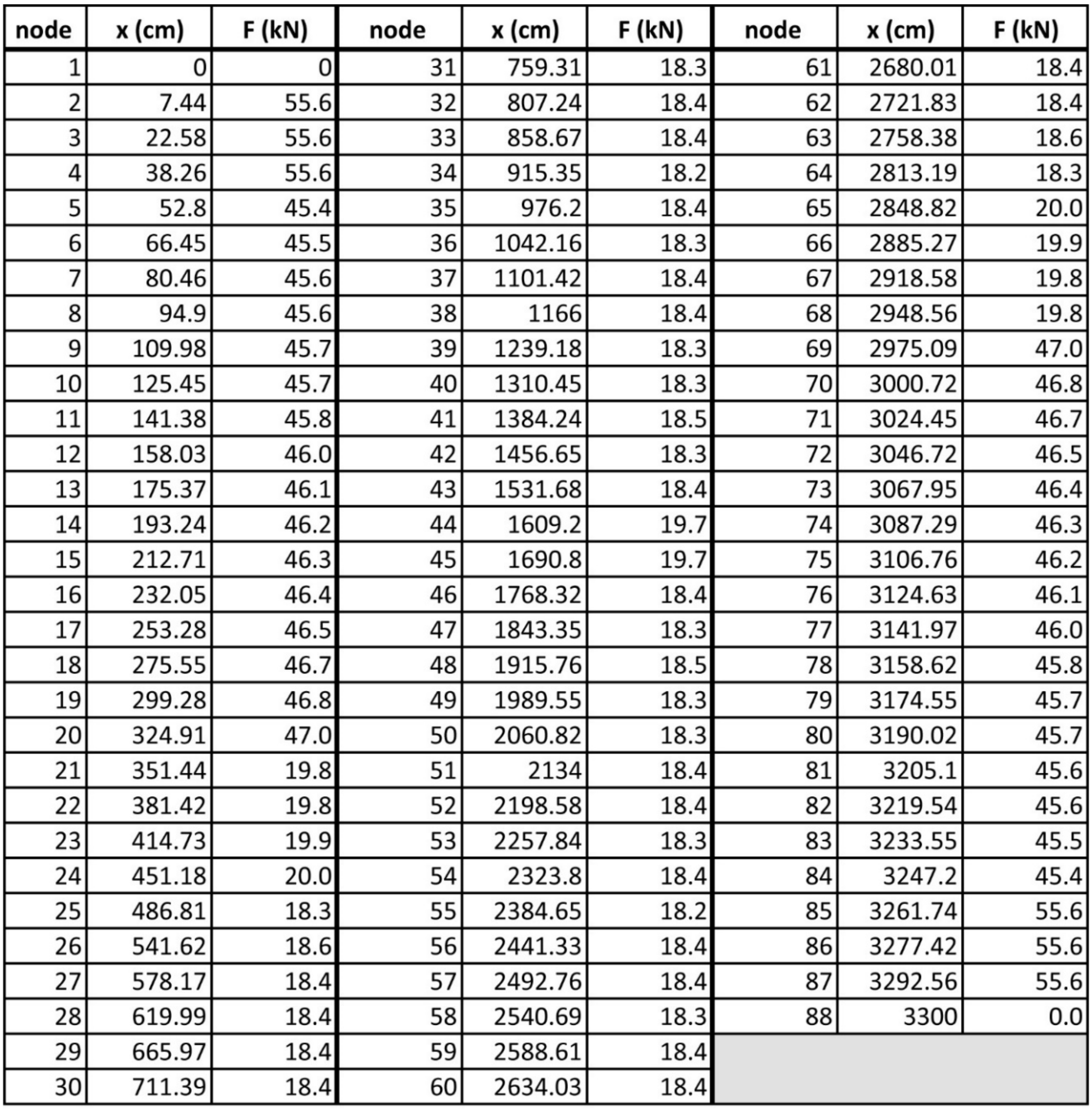
Figure 1.45. Result of the Matlab program applied to the analysis of the shape of the arch of Ctesiphon. Red curve: actual shape of the arch; black curve: line of thrust of the loads applied to the arch. The position of the right end minimizes the area ΔA

1.3.2.1.6. Conclusions

The historical record found in the poem *Shahnameh* by Ferdowsi has provided some evidence for the hypothesis about the shape of the Arch of Taq-iKisra by Hernandez-Montes et al.: the asymmetric shape of the arch comes from a differential settlement of the foundations, and the designer of the building was aware of the problem that such a settlement might have caused for the building. Therefore, he probably knew that there is a link between form and forces and that a change in the boundary conditions has an influence on the form. Not only did he know this, but he was also able to control it: the shape of the arch must have been designed prior to its construction. The most likely way to obtain such a funicular form, without the tools provided by graphic statics, would have been through the use of hanging models. This result is surprising for the history of structural engineering, as it predates the knowledge of catenaries and of the link between the form of a hanging cable and that of a rigid arch, first published by Robert Hooke, by 1000 years. The use of hanging models for design purposes was also present in the reconstruction of St Paul’s Cathedral in London by Christopher Wren and Robert Hooke (1690) and the analysis of the dome of St Peter’s Cathedral in Rome by Giovanni Poleni (1748). The Arch of Taq-iKisra also predates these constructions, even though the use of hanging chain models is not clearly specified in the poem *Shahnahmeh*.

Taq-iKisra is an example of modern structural design, many centuries before the first theories of structure appeared during the seventeenth century. This building deserves to be remembered and preserved for many reasons: it is the most important monument of the Sasanian Empire, it is relevant to the history of architecture, and it has been a symbol on various occasions: of the power and strength of King Khosrow II; of the superiority of the Arabs, who managed to defeat the Sasanians; and of the Islamic religion, both in ancient times and during the religious revolution in Iran in the 1970s. These reasons alone establish its importance, but it also deserves a place in the history of engineering, as the way it was designed is surprisingly modern. We do not know much about the architect of the building - only his name, Farghán, and his Byzantine origins, as found in the *Shahnameh*. Nevertheless, we can imagine that, even though he must have been exceptionally talented to have been chosen for such an important task, he was not the only savant of his time with knowledge about catenaries and designing a structure based on models. If this is true, the history of structural engineering might need to be reviewed and updated.

Table 1.4. Positions and values of the forces used in the MATLAB program



node	x (cm)	F (kN)	node	x (cm)	F (kN)	node	x (cm)	F (kN)
1	0	0	31	759.31	18.3	61	2680.01	18.4
2	7.44	55.6	32	807.24	18.4	62	2721.83	18.4
3	22.58	55.6	33	858.67	18.4	63	2758.38	18.6
4	38.26	55.6	34	915.35	18.2	64	2813.19	18.3
5	52.8	45.4	35	976.2	18.4	65	2848.82	20.0
6	66.45	45.5	36	1042.16	18.3	66	2885.27	19.9
7	80.46	45.6	37	1101.42	18.4	67	2918.58	19.8
8	94.9	45.6	38	1166	18.4	68	2948.56	19.8
9	109.98	45.7	39	1239.18	18.3	69	2975.09	47.0
10	125.45	45.7	40	1310.45	18.3	70	3000.72	46.8
11	141.38	45.8	41	1384.24	18.5	71	3024.45	46.7
12	158.03	46.0	42	1456.65	18.3	72	3046.72	46.5
13	175.37	46.1	43	1531.68	18.4	73	3067.95	46.4
14	193.24	46.2	44	1609.2	19.7	74	3087.29	46.3
15	212.71	46.3	45	1690.8	19.7	75	3106.76	46.2
16	232.05	46.4	46	1768.32	18.4	76	3124.63	46.1
17	253.28	46.5	47	1843.35	18.3	77	3141.97	46.0
18	275.55	46.7	48	1915.76	18.5	78	3158.62	45.8
19	299.28	46.8	49	1989.55	18.3	79	3174.55	45.7
20	324.91	47.0	50	2060.82	18.3	80	3190.02	45.7
21	351.44	19.8	51	2134	18.4	81	3205.1	45.6
22	381.42	19.8	52	2198.58	18.4	82	3219.54	45.6
23	414.73	19.9	53	2257.84	18.3	83	3233.55	45.5
24	451.18	20.0	54	2323.8	18.4	84	3247.2	45.4
25	486.81	18.3	55	2384.65	18.2	85	3261.74	55.6
26	541.62	18.6	56	2441.33	18.4	86	3277.42	55.6
27	578.17	18.4	57	2492.76	18.4	87	3292.56	55.6
28	619.99	18.4	58	2540.69	18.3	88	3300	0.0
29	665.97	18.4	59	2588.61	18.4			
30	711.39	18.4	60	2634.03	18.4			

1.4. The role of the structural engineer in the definition of the architectural space

The buildings by Pier Luigi Nervi, Eduardo Torroja, Riccardo Morandi, Felix Candela, Heinz Isler, and Oscar Niemeyer mentioned in section 1.1 are usually associated with and remembered as the work of a single designer. This designer was usually an architect, but sometimes an engineer. It is as if the design of a good structure depended solely on the ability of the individual and not on the collaboration between architects and engineers. In recent years, however, there have been numerous examples, many of them in Switzerland, of buildings created through collaboration between architects and engineers, in which the structure plays an important architectural role (figure 1.46). For example, the buildings designed by the engineer Jürg Conzett from Chur with the architects Miller & Maranta from Basel (Volta school in Basel, 1990; Markthalle in Aarau, 2002) (Conzett et al., 2006; Miccoli et al., 2021b), or the architect Gion Caminada (School in Duvin, 1994; Mehrzwerkhalle, Vrin, 2008) (Conzett et al., 2011) and the buildings designed by Christian Kerez and Joseph Schwartz (Apartment building in Fosterstrasse, 2003; Leutschenbach school, 2009). In order to design these buildings, the architects and engineers needed to share a common language.

Figure 1.46. Clockwise: Volta school, Basel; Markthalle, Aarau; School building, Duvin; Leutschenbach school, Zurich; Apartments on Fosterstrasse, Zurich; Mehrzwerkhalle, Vrin

1.4.1. The Volta school in Basel

The first example in figure 1.46, the Volta School in Basel, designed by architects Miller and Maranta and the structural engineer Jürg Conzett, was the result of a design competition for a new elementary school in the St. Johan district of Basel in 1996, and it was an opportunity for the architects and the engineer to experiment with a new structural typology, the wall-and-slab spatial system (Conzett et al., 2011). In the lot there was an old underground tank for fuel oil occupying an area of about 34x27 m, which the designers decided to exploit for the school gym (figure 1.47).

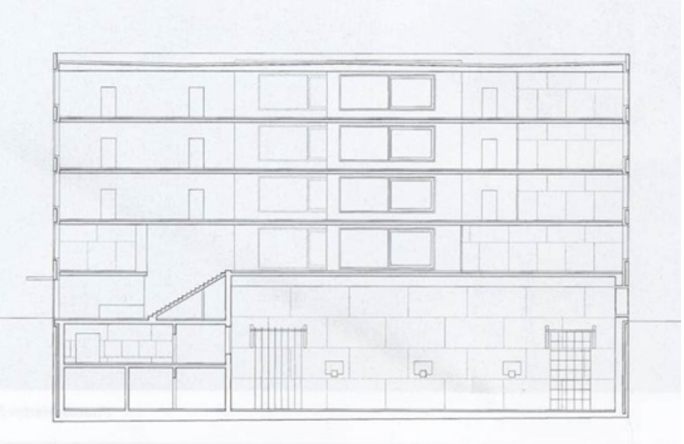


Figure 1.47. Cross section of the Volta School in Basel (drawing by Miller & Maranta)

The wall that separates the gym from the service areas is the only intermediate support on which the structure of the upper floors rests. Therefore, the structure needed to cover the smaller span of the gymnasium, equal to 27 m, using the only intermediate support available, and to enable a major structural change between the ground floor and the upper floors, for the classrooms. This change is also visible from the facade of the building, where it is evident that there is no continuity between the walls of the upper floors and those of the ground floor (figure 1.48).

Figure 1.48. Façade of the Volta school in Basel (photo by Ruedi Walti, Basel)

The principle behind the structural system is schematized in figure 1.49. In a system consisting of walls and floors, if the floors are rigid and horizontally fixed, then it is possible to support the walls on a single point.

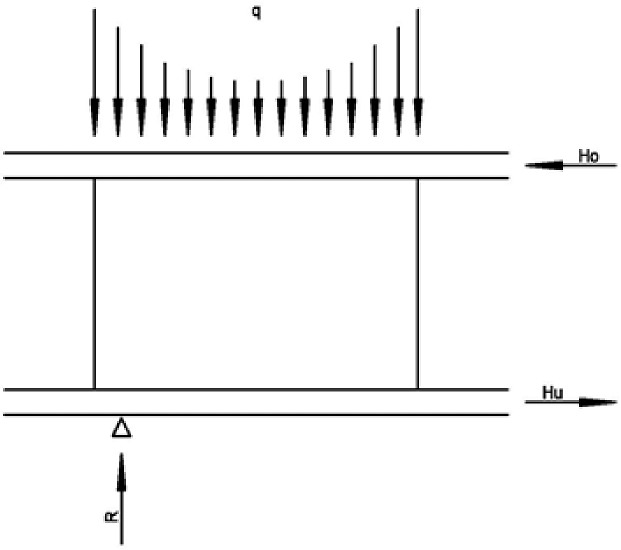


Figure 1.49. Schematization of the equilibrium of a wall supported eccentrically (drawing by Jürg Conzett)

The wall cannot rotate because of the horizontal stiffness of the floors that makes the eccentric support of the walls possible. In this way, a relatively free arrangement of the walls is possible, provided that the following conditions are met:

- each wall must be supported by another element;
- the floors must be fixed horizontally.

The following example shows the potential of this system in 3 dimensions (figure 1.50) (Conzett et al., 2006).

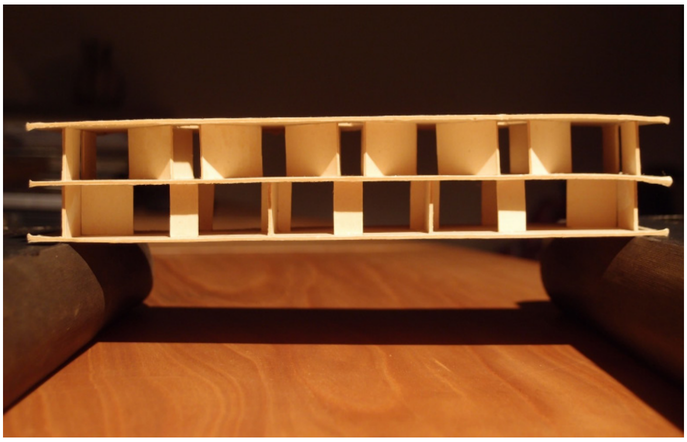


Figure 1.50. Study model for a bridge building (model and photo by Jürg Conzett)

The arrangement of the walls on the first and second floors is completely differerent but, by superimposing the plans of both floors, continuous lines are created, therefore each wall of the second floor is supported by the walls of the first floor, and the whole system is rigid. The structure of the Volta school in Basel is based on the same principle. The structure of the building is visible in the axonometry in figure 1.51. The walls that constitute the supporting structure of the four floors of the elementary school have a single vertical support, positioned in a totally eccentric way (walls supported by the external wall of the gym) or indicatively barycentric (walls supported by the internal wall of the gym). The floors, however, are held horizontally by the continuous walls that constitute the two side facades of the building.

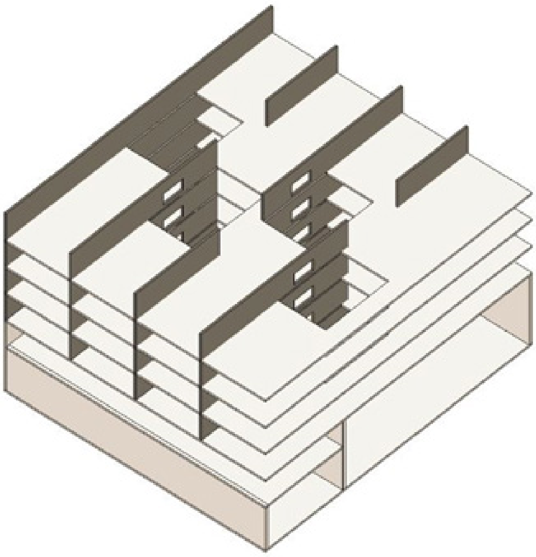


Figure 1.51. Axonometry of the structure of the Volta school in Basel (Miller & Maranta / Jürg Conzett)

Rotation of the walls of the four upper floors is therefore prevented by the action of the floors, in particular by the one covering the gymnasium and the one covering the building, which receive two equal and opposite forces, which the floors carry to the side walls, by using a system of prestressing cables (figure 1.52).

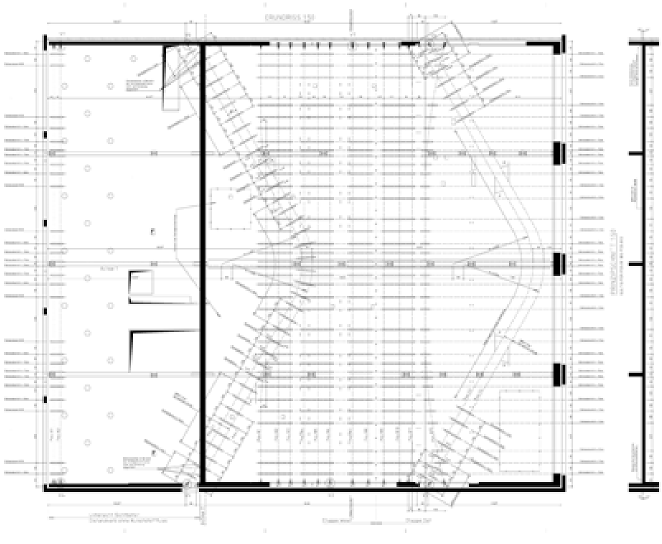


Figure 1.52. Plan of the gym roof of the Volta school in Basel (drawing by Jürg Conzett)

By making the walls and floors work together, the wall-and-slab spatial systems overcome the constraint of structural continuity in height. Moreover, these systems can change, sometimes drastically, the position of the vertical structure floor by floor. In the example of the Volta school in Basel, it is also evident that the distance between architectural design and structural design is considerably smaller than in more traditional structural typologies. The structural system is, in fact, extremely rigid, and each element is essential for the overall stability of the building. Close collaboration between architects and engineers is therefore required from the very early design stages.

1.4.2. The “Elena Cerio” retirement home in Giornico, Switzerland

The “Elena Cerio” retirement home in Giornico, Switzerland (figure 1.53) is another example of a building created using a wall-and-slab spatial system that came into being as a result of collaboration between the architects and the engineers.

Figure 1.53. the “Elena Cerio” Retirement home, Giornico, Switzerland (photo by Pedrazzini Guidotti sagl, Lugano)

The building is the result of a 2010 design competition won by the architects “Baserga and Mozzetti” from Muralto and by the engineers “Pedrazzini Guidotti” from Lugano, built in 2018. The structure of the building is a reinforced concrete wall-and-slab spatial system, chosen to completely free the perimeter band on the ground floor from any load-bearing element. The four blocks of rooms, arranged along the facades and spread over a height of 3-stories, are in fact cantilevered on the walls on the ground floor (figure 1.54, 1.55 and 1.56). In this way, the position of the structural elements in the basement is totally independent from that of the elements of the upper floors, thus ensuring greater freedom in the distribution of the spaces for different activities in the basement, which are not compatible with the spaces for the bedrooms. The supporting walls on the ground floor are located on four lines that form an inner ring and correspond to the walls between the rooms and the central distribution area of the upper floors. The concrete slabs are supported by or hung on the walls, and their thickness is derived from the verification of the maximum deformation at the Serviceability Limit State.

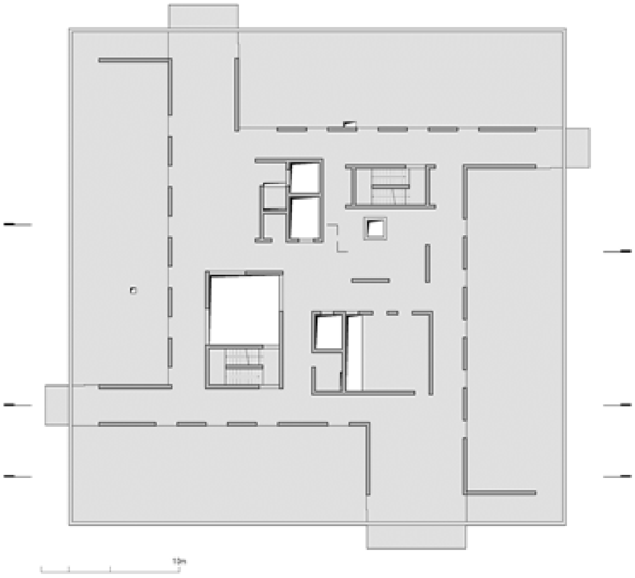


Figure 1.54. The "Elena Cerio" retirement home in Giornico – ground floor plan (drawing by Pedrazzini Guidotti sagl, Lugano)

Figure 1.55. The "Elena Cerio" retirement home in Giornico – first floor plan (drawing by Pedrazzini Guidotti sagl, Lugano)

Figure 1.56. The “Elena Cerio” retirement home in Giornico – Cantilevered room block resting on the walls on the ground floor (photo by Pedrazzini Guidotti sagl, Lugano)

The supporting structure of the cantilevered parts consists of the L-shaped walls of the rooms, the slab on the ground floor and those on the second floor (figure 1.57). After calculating the load acting on each slab, the quota loading the long wall of the "L" element is obtained. This long wall rests on the short one and is kept in balance by the membrane effect of the two extreme slabs. The force flow between the long and short walls can occur in three different ways: concentrated on the lower corner (figure 1.58a); distributed along the entire edge of the element (figure 1.58b) or with a combination of the two previous models (figure 1.58c). In the first model it is necessary to have enough reinforcement in the corner to "raise" all the force transmitted. In the second model, the force can go around the corner without being raised and therefore it is not necessary to have any vertical reinforcement in the corner. The disadvantage of this second option is that horizontal reinforcement must be distributed over the entire height of the element and that this reinforcement is greater than the one concentrated at the upper edge of the first solution. Despite this disadvantage, the second option makes it possible to significantly contain the thickness of the walls, since no space is required for the reinforcements in the corner. By doing so, the weight of the structural elements, which represents a large part of the total load, is highly reduced. Given the thickness of the walls, it is possible to define the maximum reinforcement that can be introduced into the corner, and, therefore, the third option arises (figure 1.58c). This option is the most rational and was chosen for the pre-dimensioning of the reinforcement. The reinforcement is almost always equal to the minimum level required by the codes, demonstrating the effectiveness of the chosen structural system.

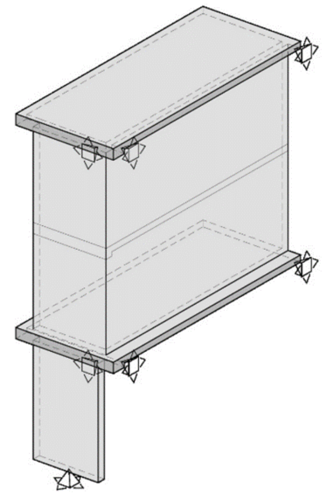
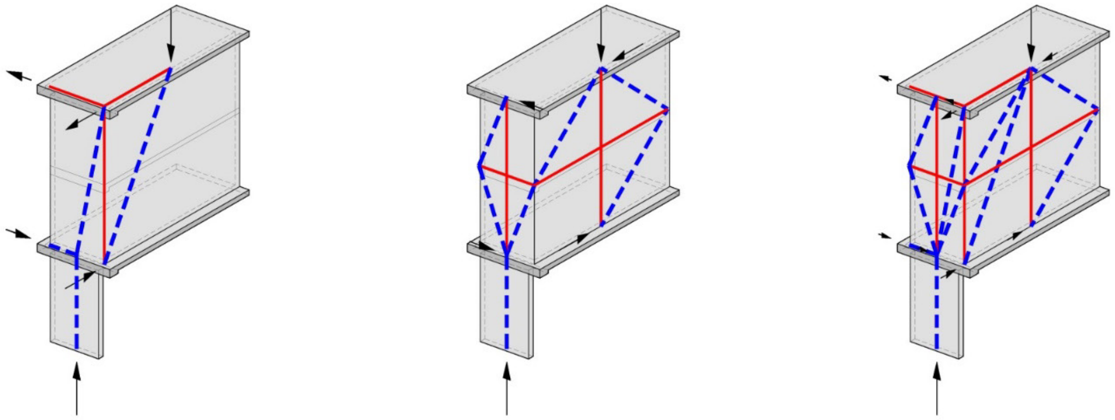


Figure 1.57. Load-bearing structure of the cantilevered part of the room blocks (drawing by Pedrazzini Guidotti sagl, Lugano)



a) b) c)

Figure 1.58. Different possible strut-and-tie models for the cantilevered part (drawing by Pedrazzini Guidotti sagl, Lugano)

As previously mentioned, the cantilevered elements introduce membrane forces into the slabs, which are partly balanced by those introduced by the block located on the opposite facade of the building. However, some of these forces are unbalanced because of the variable loads and the fact that the building is not completely symmetrical. It is therefore necessary that these forces are transmitted to the foundations by elements embedded in the base of the building (basement). The forces introduced into the slab above the second floor are the same, but in the opposite direction, as those introduced into the slab on the ground floor. Figure 1.59 and figure 1.60 show two possible strut-and-tie models for symmetrical and asymmetrical load conditions.

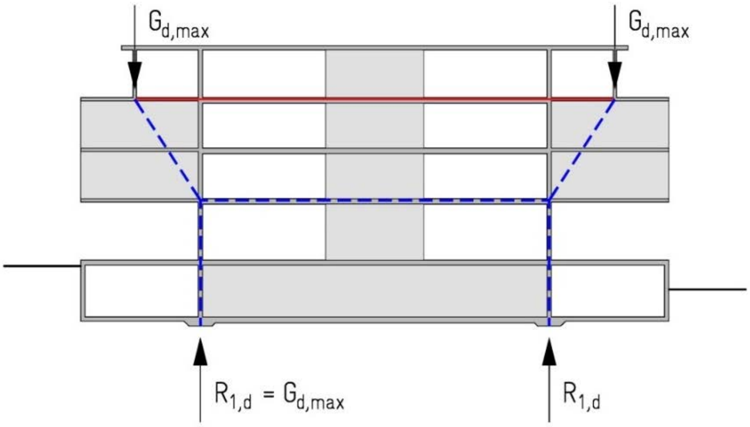


Figure 1.59. Strut-and-tie model for symmetrical loading (drawing by Pedrazzini Guidotti sagl, Lugano)

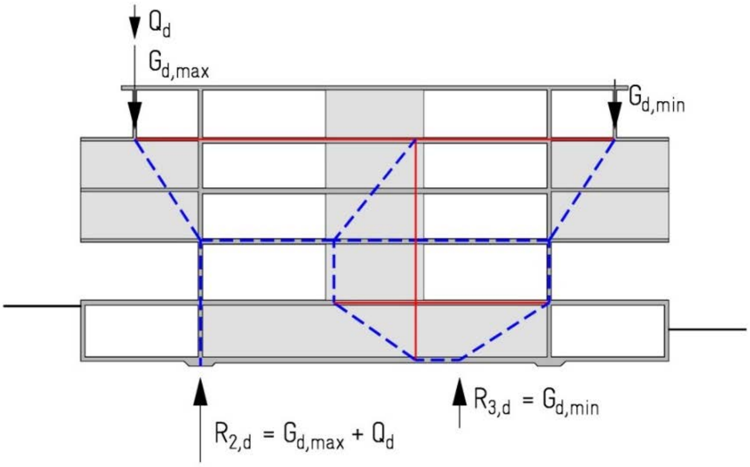


Figure 1.60. Strut-and-tie model for asymmetrical loading (drawing by Pedrazzini Guidotti sagl, Lugano)

Two different systems to transfer the horizontal forces of the slabs to the foundation have been considered. The first one considers only the vertical cantilevered walls consisting of the supporting walls on the ground floor plus the short part of the L-shaped walls of the rooms, fixed in the walls of the underground floor. The second system considers one whole side of the inner ring from the ground floor to the fourth floor. In fact, the wall on the third floor connects the cantilevered walls of the first system in pairs, making the system more efficient for the transmission of the horizontal forces (figure 1.61) and allowing the reinforcement in the walls on the ground floor to be reduced by 50%.

In order to avoid the premature cracking, and therefore a reduction in stiffness, of the slab above the second floor, prestressing cables have been placed, as shown in figure

1.62, while the cracks opening in the walls have been controlled by placing a minimum reinforcement. Furthermore, the rigid-plastic stress field models (RPSF) given by the strut-and-tie models have been checked and compared to the elastic-plastic stress field models (EPSF), finding that the behavior of the elements is almost elastic, and thus strong plasticization is avoided.

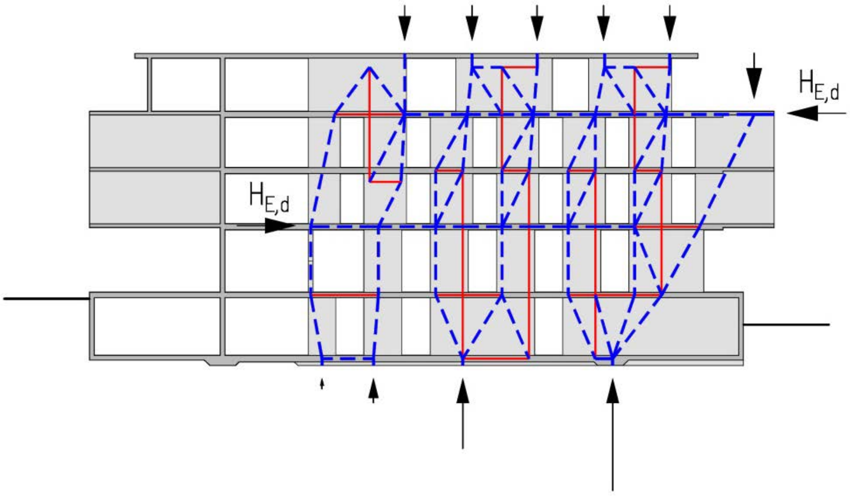


Figure 1.61. Strut-and-tie model for the transfer of the horizontal forces of the slabs to the foundation (drawing by Pedrazzini Guidotti sagl, Lugano)

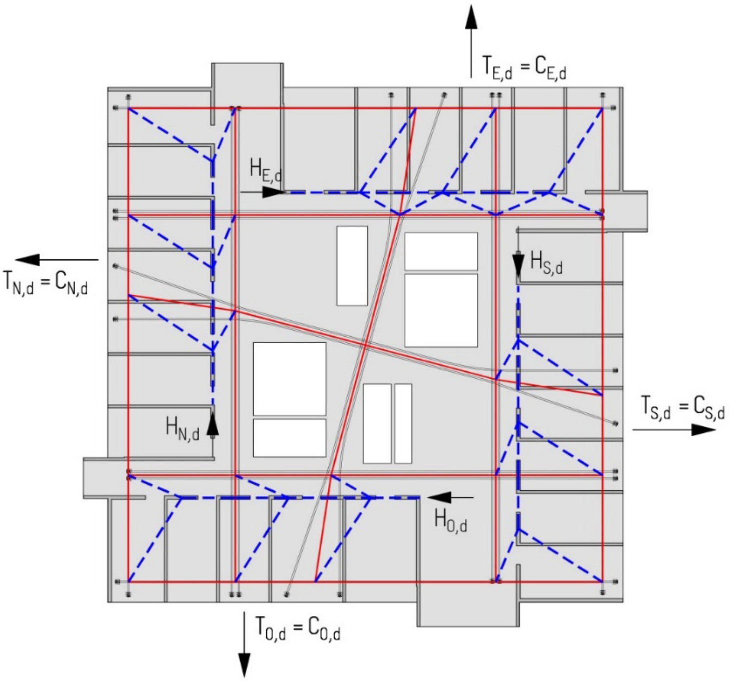


Figure 1.62. Placement of prestressing cables in the slab above the second floor and a possible strut-and-tie model (drawing by Pedrazzini Guidotti sagl, Lugano)

The global stability of the building is guaranteed by the cores in the central part of the plan. These elements, fixed horizontally at the level of the foundation slab and the level of the slab above the basement, transfer the horizontal actions up to the slab above the basement. The horizontal reaction at the level of the slab above the basement is then transferred to the inner ring of the basement level which, because of the high vertical load coming from the upper floors and the extension of this slab, can transfer the loads to the foundations.. As the stability of the upper floors is guaranteed by the two previously described systems (see figure 1.61), the internal cores can be used for other horizontal actions like seismic ones.

In this project, strut-and tie models and stress field models are used both tridimensionally (L-shaped walls of the rooms) and bidimensionally (walls in the longitudinal section and slabs) for the preliminary design of the structure. The executive design required some further considerations about the following issues: the behavior of the structure at the Serviceability Limit State and the optimization of the reinforcement.

The wall-and-slab spatial systems allow, by making the walls and floors work together, the constraint of structural continuity in height to be overcome, and these systems can change, even drastically, the position of the vertical structure floor by floor. In the two examples presented, the “Volta Schulhaus” and the “Elena Cerio retirement home” it is also evident that the distance between architectural design and structural design is considerably smaller than in more traditional structural typologies. In fact, the structural system is extremely rigid, and each element is essential for the overall stability of the building. Close collaboration between architects and engineers is therefore required from the very early design stages. But even in more traditional structural systems, a fruitful collaboration between the architects and the engineers can lead to better projects, or at least to projects where structure and architecture are in harmony with each other. In order to be able to collaborate and to communicate, architects and engineers need to share common interests and their own common language, which needs to be creative. The aim of this work is to formalize the creative aspect of structural design, to make it clear that this creative aspect does not depend solely on the personal talent of one designer, but it is an area in which individuals can be trained and educated. Moreover, both architects and engineers can be trained and educated in structural creativity, which can be the meeting point between the two professions. The second chapter of this thesis is dedicated to this area.

2. CREATING STRUCTURAL INTUITION AND A COMMON LANGUAGE FOR ARCHITECTS AND ENGINEERS

Structural engineering is undoubtedly a technical profession. In fact, structural engineers are professionals who make use of their knowledge of mathematics, physics, chemistry, and other specific disciplines such as statics, strength of materials, and dynamics. They apply this knowledge to technical procedures aimed at the design, construction, and management of buildings and infrastructures. It is therefore not surprising that being a structural engineer is not perceived as a creative profession. On the contrary, it is often thought that engineers are individuals who make calculations, devoted to the application of rules and formulas, provided by standards that leave no room for creativity. The curricula of civil engineering faculties only confirm this view of the profession.

However, in the first chapter we showed that there is a creative phase in structural design, that of structural conception, and that this phase can represent the meeting point between engineering and architecture, in which engineers and architects can share a common language. But how can the technical and creative aspects of structural design be reconciled? Education in engineering does not include courses on structural conception, and the creative aspect of the profession is not included in the curricula. How then can an engineer be creative? Is it just a matter of talent and personal interest? Is it a type of creativity developed by the technical and scientific education of engineers?

An engineer's job is to ensure that the structures they design are safe and efficient. A structure is safe when, for each statistically relevant load condition, the maximum stresses in the structural elements are less than the resistance of the materials of which they are made. A structure is efficient when, for each statistically relevant load condition, the deformations of the structure are less than the limits imposed by the regulations, or at least the structure guarantees that the building can be used satisfactorily.

There are many aspects that the engineer must consider to guarantee safety and efficiency: equilibrium, structural typology, shape, mechanical characteristics of the materials (in particular resistance and stiffness), geometry of the elements, position of the supports, slenderness of the elements, etc. However, all the aspects listed here are technical and do not seem, at least at first, to have anything to do with creativity. Yet these are precisely the aspects that allow for structural creativity. When designing a structure, there are various solutions that guarantee safety and efficiency, and it is not always possible to identify one that is obviously better than the others, at least when considering only the purely structural aspect. In order to select one solution from the many available, it is necessary to introduce other criteria, such as economic, environmental, logistic, and political criteria. And it is this variety of possible solutions that enables structural creativity to come into play.

The first requirement that a structure must satisfy is to be balanced. But once the architectural spaces have been defined and the acting loads have been evaluated, there are various structural solutions that guarantee balance. The first moment in which structural creativity comes into play is when a structural solution is chosen that responds to architectural needs and is balanced for the acting loads.

Once an equilibrium system has been defined, the type and position of the constraints that will control the entity of the stresses and deformations can be chosen. At this point, structural creativity also comes into play. In fact, once the link between the type and position of the constraints and the stresses and deformations is known, it is possible to find an optimal solution that considers space and/or the use of the material.

The shape of a structure and the geometry of the sections of the structural elements also come into play in structural creativity. In fact, the type of stress of the structural elements (axial action, shear, and bending moment) depends on the shape of a structure. The resistance and stiffness of the structural elements depends on the geometry of the sections of the structural elements. The knowledge of the relationship between structure shape and stress type, and between section geometry and strength and stiffness, can be used to creatively design a structure.

But if structural creativity, as described so far, depends on the knowledge of the link between the different possible structural choices and the type and extent of the stresses, then structural creativity can be created and taught. This is also true for the link between the geometry of the sections and the strength and stiffness of the structure. As a result, the criteria for making creative structural choices are clear. And given that structural conception, i.e. the creative part of structural design, can be the meeting point between architects and engineers, the creation of structural creativity is an aspect that can become part of the curricula taught to both architects and engineers. This is the first moment in which architects and engineers begin to get to know each other and collaborate, through a sharing of interests and thanks to a common language.

Finally, there is a further, non-technical aspect that limits and guides structural creativity: that of the context. When designing a structure, its geographical position, which may, for example, exclude the option of choosing a certain material (in the high mountains it is more difficult to build with concrete for logistical reasons), the local building tradition, the building standards in force, and the political choices of the local authorities must be considered. All the contingencies that are not directly related to structural choices, but which can have consequences for them, contribute to guiding structural creativity, and therefore these contingencies can be included in training programs for both architects and engineers in the field of structural conception.

In the following sections we will see, by looking at examples of existing buildings, how balance, constraints and stresses, the shape of structures and the geometry of sections, and context can create structural intuition, and how they can be used as tools to conceive a structure.

2.1. Equilibrium as a tool for the creation of the structural intuition

There are physical intuitions that we all have just by being alive. Our body occupies a volume and has a certain weight, and for this reason it is constantly subject to forces that can be static, when we are still, or dynamic, when we are in motion. However, we do not have to constantly worry about the forces that act on our body. The experience we have of the effects of these forces on our bodies allows us to correct our posture and balance, without having to constantly think about it. This is not only true for our bodies, it also affects the objects that surround us. Everyone knows with absolute certainty that a rectangular table resting on four legs placed at the four corners is in stable equilibrium (figure 2.1).

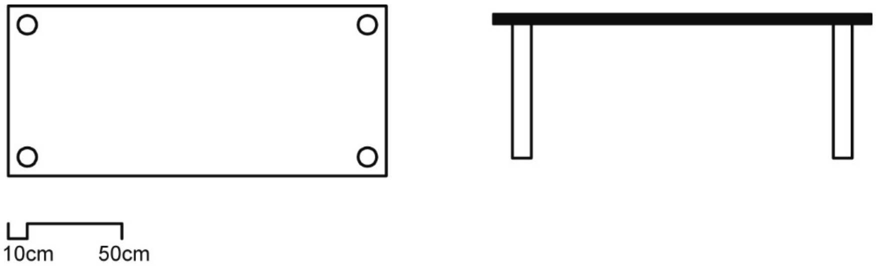


Figure 2.1. Table resting on four legs placed at the four corners is in stable equilibrium

While it would probably require some additional reasoning to answer the question "would the same table be in equilibrium with only three legs?". To answer this question, we need to resort not only to those innate physical intuitions that allow us to keep our body balanced. In fact, three-legged table is a situation in which balance is not evident, therefore in order to respond, it is necessary to draw on other resources, which are always linked to our own experience. For example, we could ask ourselves: "Have I already seen a table with three legs?", thus making use of our personal experience. If I have seen a table with three legs before, then it is possible. But at this point, the search for an exhaustive answer to the question would not have ended. In fact, at this point we should ask ourselves: "if the table can stand on three legs, can the legs be placed in any position?". Our innate physical intuitions would allow us to exclude, with certainty, some situations such as those shown in figure 2.2.

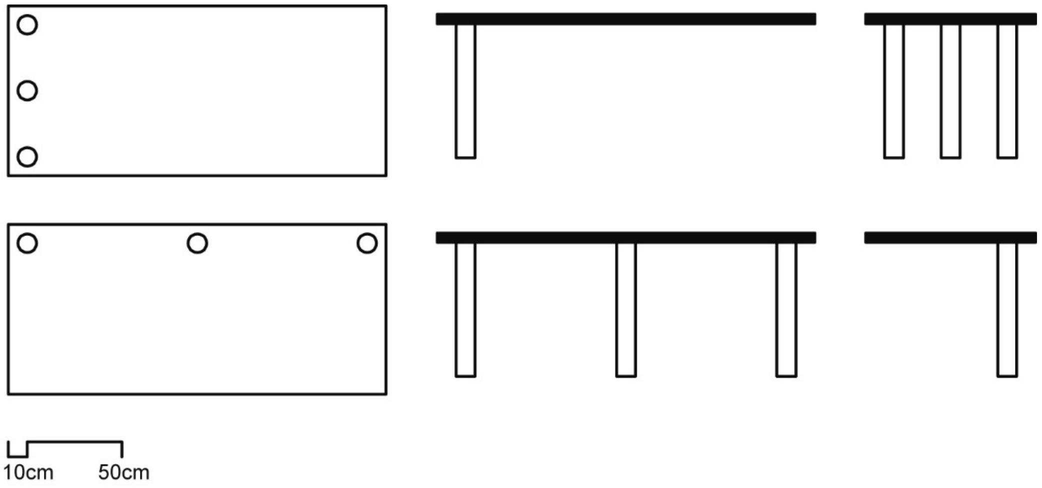


Figure 2.2. Examples of tables resting on three legs which are not in balance

Intuitively, one could therefore state that, for the table to be balanced, the three legs should not be aligned. But there are other situations that would not allow an immediate response that would be as certain, for example the situations shown in figure 2.3.

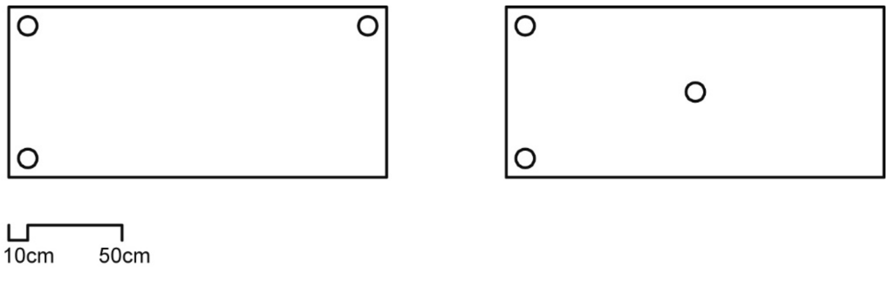


Figure 2.3. Examples of tables resting on three legs for which the equilibrium is not immediately clear

In the three situations presented, the three legs are not aligned, so can we say with any degree of certainty that the table is balanced? This question should be formulated in a more complete way: can it be said with any degree of certainty that the table is in equilibrium regardless of its characteristics? These include characteristics such as the dimensions of the top and of the legs, the materials they are made of, the shape of the legs, the maximum loads it must bear, etc.

Innate intuition allows us to confidently identify all the solutions that are undoubtedly balanced. But if we think of the example of the table, the solution with four legs placed at the corners of the rectangle certainly cannot be considered to be creative. Stable, safe, and efficient, but not creative. If we consider the tables shown in figure 2.4 instead, the way in which they are balanced is less evident, but more interesting for this very reason.

Figure 2.4. Tables in equilibrium in creative ways

The fact that the balance of the tables is not immediately evident gives rise to curiosity - "how does it stand up?", and it is possible to say that the chosen balance solutions are creative.

But how is it possible to make these more creative equilibrium solutions become more accessible? On the one hand it is certainly a question of talent, some people's intuition is more highly developed, and they are therefore able to identify less obvious equilibrium solutions. But since balance and stability depend on measurable physical quantities, this talent can be taught. In order to do this, it is necessary to show the physical parameters on which equilibrium depends, what the effects of these parameters are on equilibrium, and how to "play" with them to obtain interesting and creative equilibrium situations. All of this allows people to become familiar with these parameters in a way in which the range of solutions that can be identified with intuition can be expanded.

The project presented in this chapter, the APG Golf Club in Luque, Paraguay, demonstrates this type of process The architect, Javier Corvalán, created it using his intuition about balance. However, the project was built in a safer and less creative way.

The engineer Roberto Guidotti, of the Pedrazzini Guidotti engineering studio in Lugano, Switzerland, was fascinated by the architect's original idea and wanted to study the building. He demonstrated that the architect's original idea for the project was feasible. He then efficiently exemplified how an intuitive and creative idea can be formalized, showing the parameters on which it depends and, therefore, how formalized structural creativity can be an architectural design tool.

2.1.1. The APG Golf Club in Luque, Paraguay

The project analyzed in this section is the APG Golf Club in Luque, Paraguay, designed by the "Laboratorio de Arquitectura" studio led by the architect Javier Corvalán (figure 2.5).

Figure 2.5. The APG Golf Club in Luque, Paraguay (arch. Javier Corvalán, Laboratorio de Arquitectura). Photo by Leonardo Finotti

In an article published in the Swiss magazine "Archi" (Corvalán, 2015) entitled “Architetturaingegneria” ("Architectureengineering"), Corvalán questions the separation between architecture and engineering and identifies equilibrium as a field that is shared by the two disciplines, but they approach it from different perspectives. He says that "architecture is taught so that only external phenomena are imagined, while engineering can imagine internal phenomenology, tensions and deformations that are not appreciable at a simple glance. The two disciplines use different tools of observation and calculation as means of approximation, and both work with balance, gravity and geometry". Corvalàn then identifies a specific aspect that summarizes the difference in the vision concerning balance between architects and engineers: the Young module. When balancing systems, architects imagine rigid systems, not elastic systems, and this effectively excludes The Young module, and therefore the stiffness of materials, from their considerations. In fact, balance is often studied with representations on paper or in a digital format, or with models which do not give indications on how the structure works, as these representations lack the gravitational factor. However, there is another type of model which allows, in addition to a graphic representation of architectural spaces and volumes, structural behavior to be detected. Indeed, sometimes the main purpose of models is to study structural behavior. Think, for example, of the funicular models of Gaudì and Frei Otto (figure 1.4), or of the models of Heinz Isler used to determine the shapes of reinforced concrete shells, or of the models presented in section 1.3 to determine the shape of the palace of Ctesiphon. In Javier Corvalán's "Laboratorio de Arquitectura" they use this type of model, which makes it possible to obtain information for both the architectural project and the structural one. These models are generally made of wood on a 1:10 scale. In this way they cannot be assembled only with glue, but they need smaller scale construction that shows how they will be assembled on site. Moreover, in the case of the APG Golf Club in Luque, a structural model was used to verify preliminary structural intuition. In the next section, the project and the conception of this structural idea will be described.

2.1.1.1. The conception of the structural idea

The APG Golf Club project stems from a desire to build a line as a concept, a driving range for golf practice in a narrow plot (500x100 m) with a significant height difference on one of its long sides. For the practice of this sport, this line had to cross the ground, dividing it into two practice courses. The structure proposed is a response to the need for a horizontal line. It is in fact a beam or, to be more accurate, two rocker arms that stabilize each other (figure 2.6).

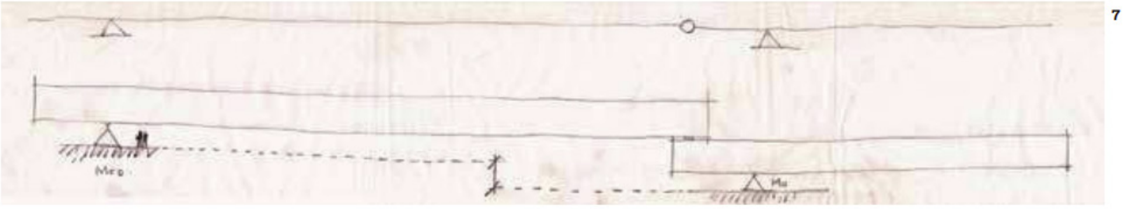


Figure 2.6. APG Golf Club, Luque, arch. Javier Corvalán. Sketch of the structure of the building. (Source: Pisani, 2014)

By using structural models, the architect studied various possible equilibrium situations to find the position of the supports, the length of the two rocker arms, and the overlapping area that best responded to the topography of the plot - in particular its height difference, the presence of a stream, and the function of the building (figure 2.7).

Figure 2.7. APG Golf Club, Luque, arch. Javier Corvalán. Structural models of the structure of the building. (Source: Pisani, 2014)

Once the most appropriate functional model had been chosen, the architecture of the building was defined: a golf driving range on three levels.

However, this project was not carried out as the architect intended. The engineers who were entrusted with the design of the structure were not prepared to create a structure consisting of two rods that balance each other. Instead, they decided to rigidly join the two rods together so that they worked as a single beam. This solution is certainly stable, but undoubtedly less interesting and less creative than the one proposed by the architect.

But would it have been possible to implement the idea proposed by Corvalán? Would it actually have been a structural risk?

The structural engineer Roberto Guidotti, from the Pedrazzini Guidotti engineering studio in Lugano, Switzerland was fascinated by Corvalán‘s structural idea and was disappointed that it had been written off in the executive phase in favor of a safer but less interesting solution. He analyzed the structure proposed by Corvalán wondering if, and under what conditions, it could be created. His analysis, which is presented in the next section, is a perfect example of how it is possible to formalize an idea that arises from structural intuition, showing the criteria and parameters on which it depends, thus transforming intuition into something that is formalized and can be used as a design tool.

2.1.1.2. The formalization of Javier Corvalán’s structural idea (Guidotti, 2015)

In the design phase, the structure of the APG Golf Club in Luque consisted of two rocker arms balanced one above the other. Their overlap would have made the system stable even in the presence of variable loads and there would have been no need to connect the two parts between them. In order to understand if and how this structural idea is feasible, it is necessary to highlight which factors equilibrium depends on and, in this specific case, how to evaluate what the minimum extension of the overlapping area is to guarantee equilibrium for any load condition. It is easy to understand that, for a given load - for simplicity we consider the case that only has permanent loads - there is a solution where the two arms are balanced without overlapping. This solution means that the point of contact between the two arms is exactly in the position of the zero-bending moment of the beam with the two cantilevers, as shown in figure 2.8.

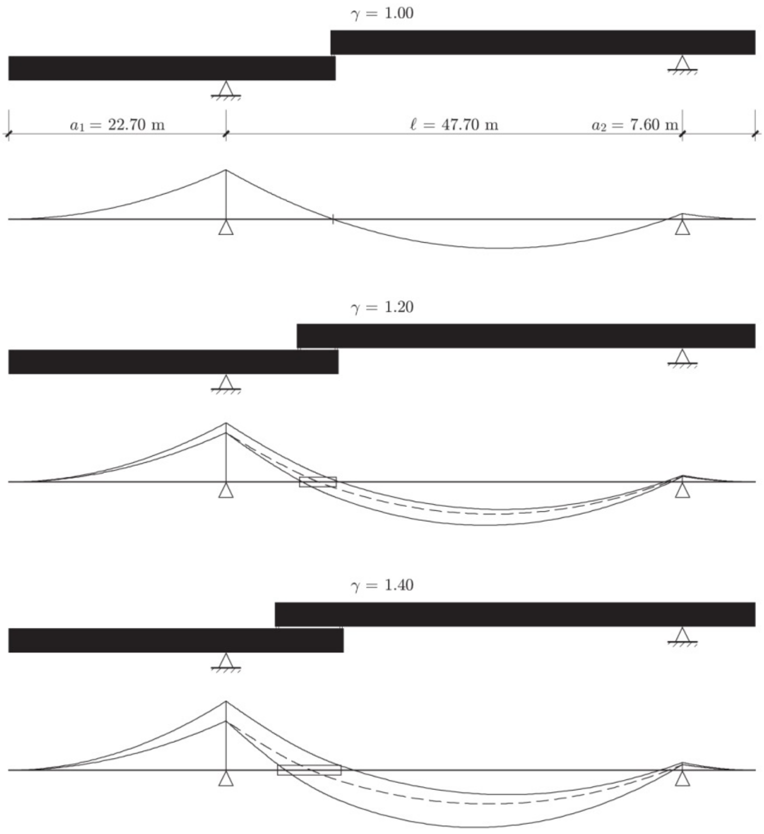


Figure 2.8. Solutions in limit equilibrium according to the variation of the ratio between maximum and minimum load. (Drawings by Roberto Guidotti – Guidotti, 2015)

Furthermore, since the two beams must not be connected to each other, the contact area must be stressed by a compressive force. For this reason, the point of zero moment in which the shear stress is negative has to be chosen.

The first objective and measurable aspects necessary to formalize Corvalán's intuitive idea already emerge from this first phase of the analysis. The equilibrium depends on the loads and the extension of the overlap zone on the bending moment and shear stress However, the situation described does not reflect the real one. In fact, the loads, and more generally the actions that stress the structures, undergo variations caused primarily by their use. Therefore, the solution in which the arms touch each other at a single point, which represents the limit between the infinite solutions in equilibrium and the infinite solutions not in equilibrium, does not satisfy expectations. This is because, a minimum variation of the applied load would cause the two arms to rotate around their respective supports. Therefore, it is necessary to extend the lower arm to the right and the upper one to the left. In fact, when the portion of the structure outside the supports has a greater load than the central part, the contact point moves towards the center of the span and vice versa. In fact, by unloading the portion of the structure outside the supports, the contact point approaches the left footing. In order to ensure the stability of the system even in these extreme situations, it is necessary to create an overlap and introduce supports at its ends which result in these load cases, one compressed and the other completely unloaded, as shown in figure 2.9. For all the other intermediate load cases – which also includes the load case that only has the permanent loads– the line of action of the resultant of the contact force between the two arms is located in the overlap area and both supports are compressed with different intensities.

Unfortunately, the configuration shown in the diagrams in figure 2.8, which explain how the structure functions, cannot be given by using the line of the moments or the envelope of the possible moment lines. In fact, the overlap modifies the load distribution by doubling the weight of the load-bearing elements in this area. The need to increase the other loads applied in the overlap area (dead weight of the non-load bearing elements and live loads) or the lack of this need, depends on the presence of one or two levels of slabs in this area. It has been assumed that these other two loads were doubled for all the analyses shown here.

It is therefore possible to explain more clearly the dependence of the equilibrium on the applied loads by stating that the equilibrium depends on the ratio γ between the total maximum load and the minimum load.

The minimum load combination is the one that considers only the dead loads, with a load coefficient $\gamma_{G,inf} = 0.90$ (limit state type 1 according to the Swiss standard SIA260), while for the maximum combination the variable load with the load factor for variable actions $\gamma_Q = 1.50$ must be added. The building has an estimated characteristic dead load of 52 kN/m for each of the two beams and a variable load of 6.0 kN/m, which corresponds to a variable load of 2.0 kN/m^2. The ratio that describes the maximum load variation on the structure is therefore $\gamma = 1.20$, the value shown in the graph in figure 2.10 with a dashed line. It can be seen how the influence of factor γ on the extension of the overlapping area is very important and how this area increases as the difference between the maximum and minimum loads increases. These considerations explain the previous use of the load coefficient for the favorable own weights, $\gamma_{G,inf}$, instead of the coefficient for the unfavorable ones, $\gamma_{G,sup}$. In fact, this consideration obtains a greater γ ratio, which is more critical for stability. Furthermore, the interest in reducing the variation between the maximum and the minimum load is clear. In this way, the γ ratio is kept as low as possible. Since it is impossible to reduce the variable loads which are defined by the use for which the building is designed, keeping the y ratio low is achieved by only increasing the permanent loads. In this case, the choice of a reinforced and prestressed concrete structure is therefore optimal. In fact, the heavy weight of such a structure, which in other cases could be a defect, is useful for guaranteeing the balance of the two arms in all the load situations by limiting the extension of the area of overlap.

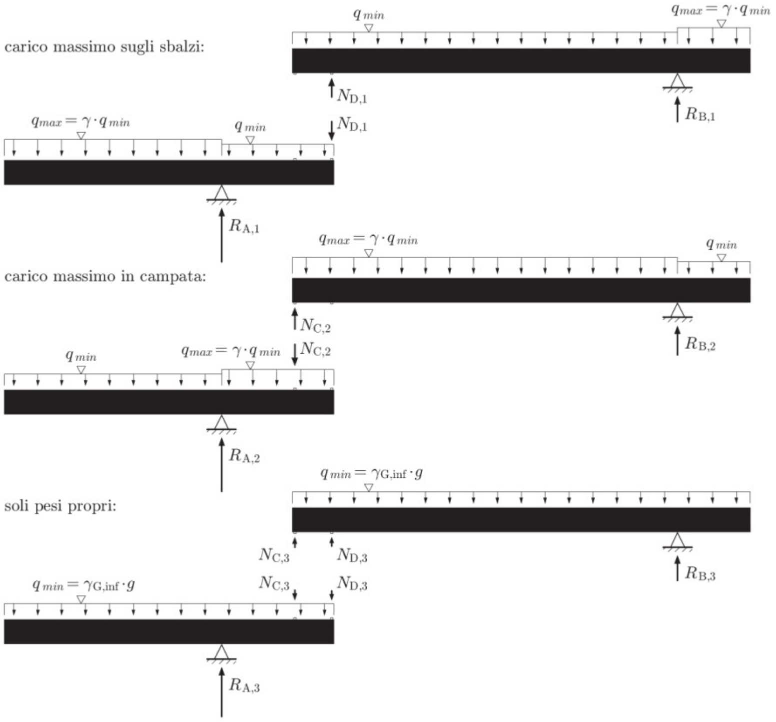


Figure 2.9. Balance of the two arms in the limit load situations and in the situation with only the permanent loads. (Drawings by Roberto Guidotti – Guidotti, 2015)

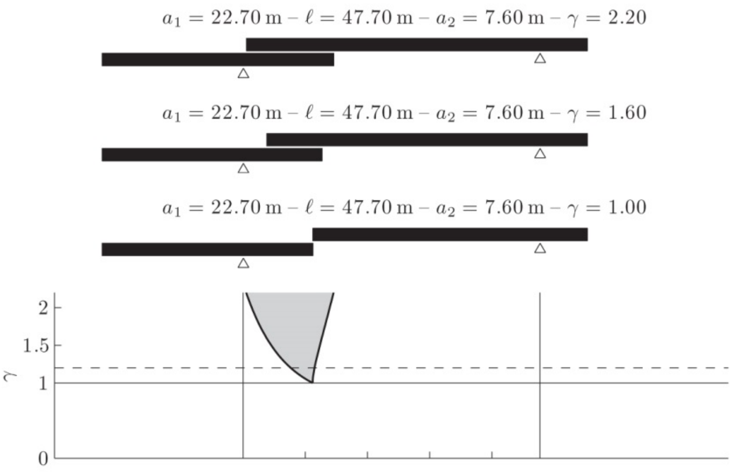


Figure 2.10. Analysis of the position and extension of the overlapping area as the ratio between the maximum and minimum loads varies (Drawings by Roberto Guidotti – Guidotti, 2015)

The analyses presented clearly illustrate how Corválan's initial idea would have been achievable with slight modifications to the geometry of the contact area between the two balance arms, without having to create a rigid connection. Figure 2.11 shows the overlap needed to maintain the total length and the position of the supports of the original structure: by comparing this structure with the one that was built, we can see how the small adjustments are probably compatible with the functional needs of the project.

Ratio γ between the maximum and minimum load acting on the balance arms is not the only parameter that influences the extension of the overlap zone, since the geometrical parameters are also responsible for its size. Therefore, once the section and the material that constitutes the load-bearing structure have been chosen, the position of the supports and the total length of the system that satisfy the project requirements need to be defined, then an overlap that satisfies the equilibrium conditions must be imposed.

Figures 2.12 to 2.14 show the solutions in limit equilibrium and the overlap zone as some geometric parameters vary. First, we can notice how the influence of these variations on the size of the overlap is very limited compared to that caused by the variation of the loads that has been previously analyzed. Furthermore, it can be seen that, given the length of the cantilever of the upper arm (figure 2.13), the variation of the lower one is mainly responsible for the position of the overlap zone within the central bay. Vice versa, by modifying the overhang of the upper beam, keeping the length of the other beam constant (figure 76), the extension of the overlap zone is defined. The previous considerations clarify how, by varying the position of the supports, it is possible to choose the position and extension of the overlap zone within certain limits defined by the lengths of the two arms, by the total length of the system, and, above all, by the ratio between the maximum and minimum loads.

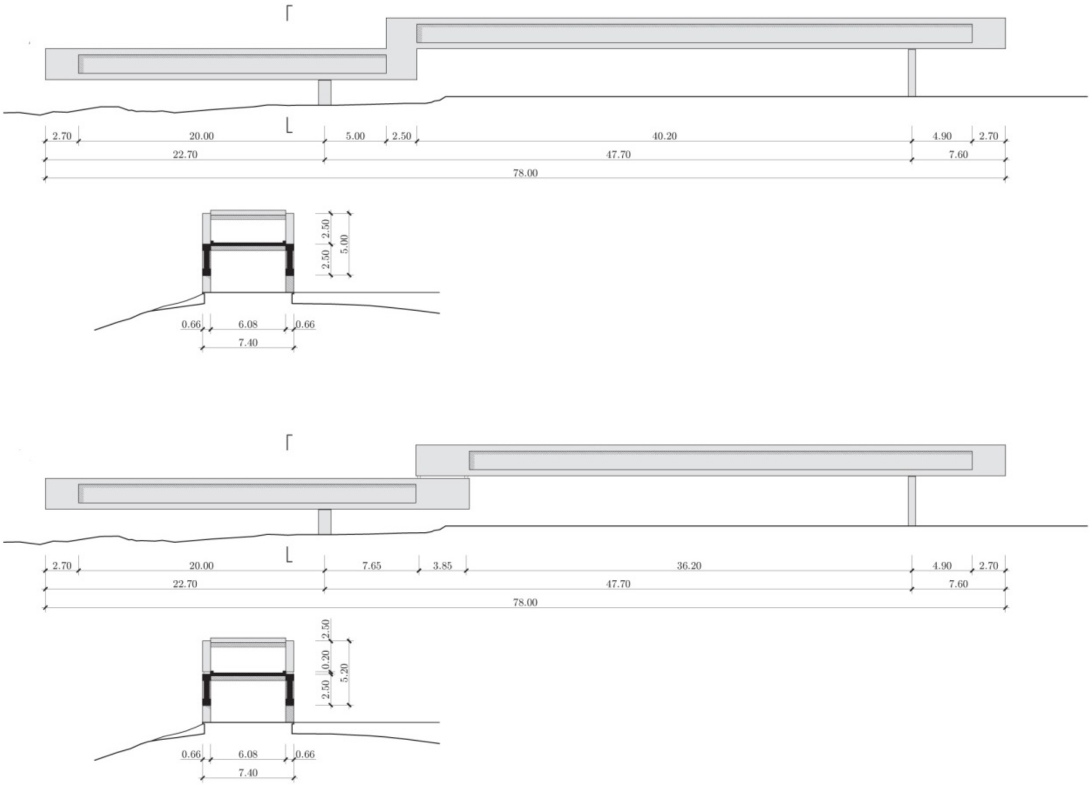


Figure 2.11. View and cross-section of the built structure, rigid connection between the two rocker arms (above). View and cross-section of the feasible structure in limit equilibrium while maintaining the dimensions of the overhangs and the central flow (below). (Drawings by Roberto Guidotti – Guidotti, 2015)

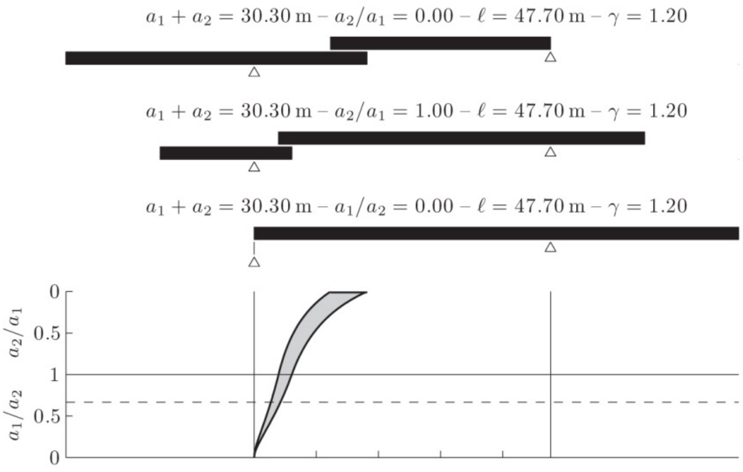


Figure 2.12. The Analysis of the position and extension of the overlap zone as the proportion between the two overhangs varies while maintaining fixed the total length of the structure. (Drawing by Roberto Guidotti – Guidotti, 2015)

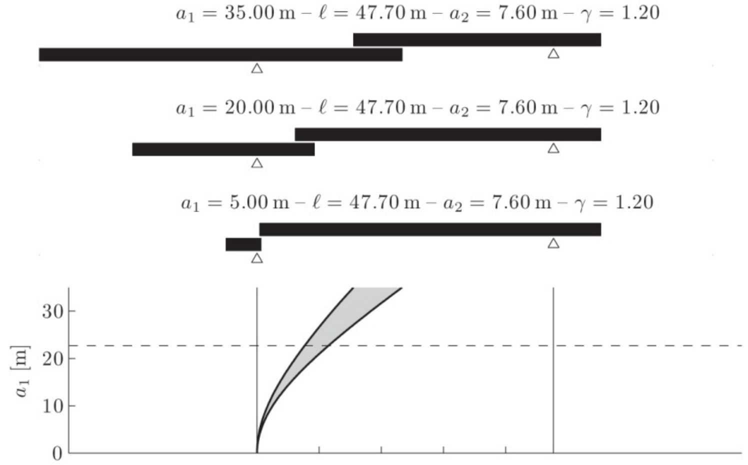


Figure 2.13. The Analysis of the position and extension of the overlap zone as the length of the lower arm overhang varies. (Drawing by Roberto Guidotti – Guidotti, 2015)

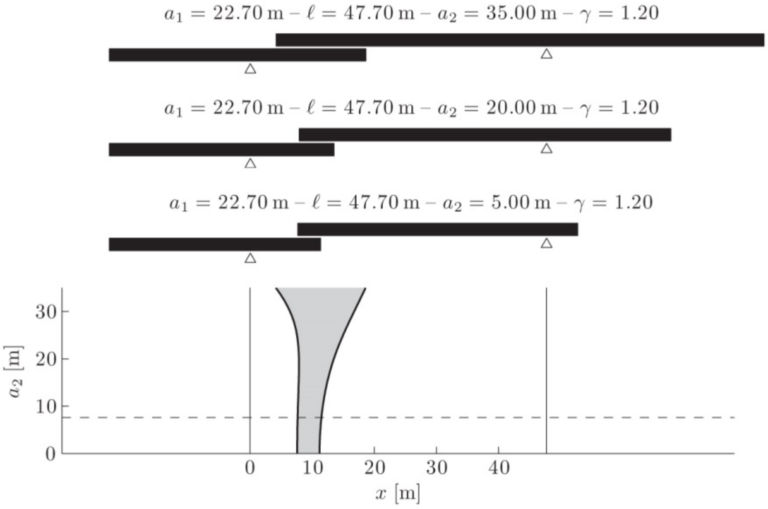


Figure 2.14. The Analysis of the position and extension of the overlap zone as the length of the overhang of the upper arm varies.(Drawing by Roberto Guidotti – Guidotti, 2015)

The analysis of this example shows the importance of equilibrium in the design process and how, by mastering the conditions that control equilibrium, it is possible to verify the feasibility of an intuitive idea. In other words, if structural intuition is formalized, it can become a structural design tool.

2.2. Constraints and stresses as a tool for creating structural intuition

The purpose of structural design is to provide a structure that is safe and efficient, i.e. a structure in which, for any reasonably foreseeable load condition, the maximum stresses are lower than the resistance of the materials of which it is made, and the maximum deformations are contained within acceptable limits. But generally, when a structure is conceived, tensions and deformations are not considered at the outset. The first priority of a designer, whether they are an architect or engineer, is to conceive a structure that allows the creation of the spaces and volumes required by the architectural project and which is, as we saw in the previous section, in stable equilibrium. The first factors that come into play when conceiving a structure are therefore intuition and experience. Intuition allows us to imagine a structural system that can be considered to be reasonably balanced. Experience allows us to go beyond intuition and to select less simple, more creative structural systems in equilibrium, thanks to the fact that we have already seen or designed them, and we know that they work. Awareness of the parameters on which balance depends - loads, position of the supports, and geometry, makes formalizing intuition and experience possible. This can be done in a way that makes it possible to use them with awareness to set up a balanced structure. However, this process can also be creative. Nevertheless, once a balanced structure has been set up, structural safety and structural efficiency still need to be addressed. Let's imagine a very simple design situation: the design of a structure to shelter two cars parked side by side. Imagine that you have to cover a square area of 6x6 m, as shown in figure 2.15.

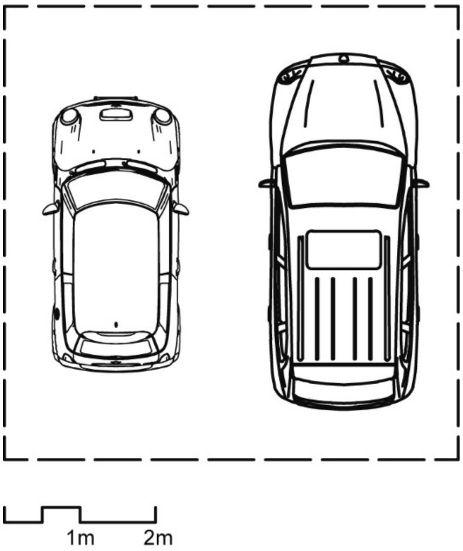


Figure 2.15. Design task: create a structure to shelter two cars parked side by side. Area of the project

Intuition allows us to state with certainty that four pillars placed in the four corners of the area to be covered would ensure coverage that is stably balanced (figure 2.16).

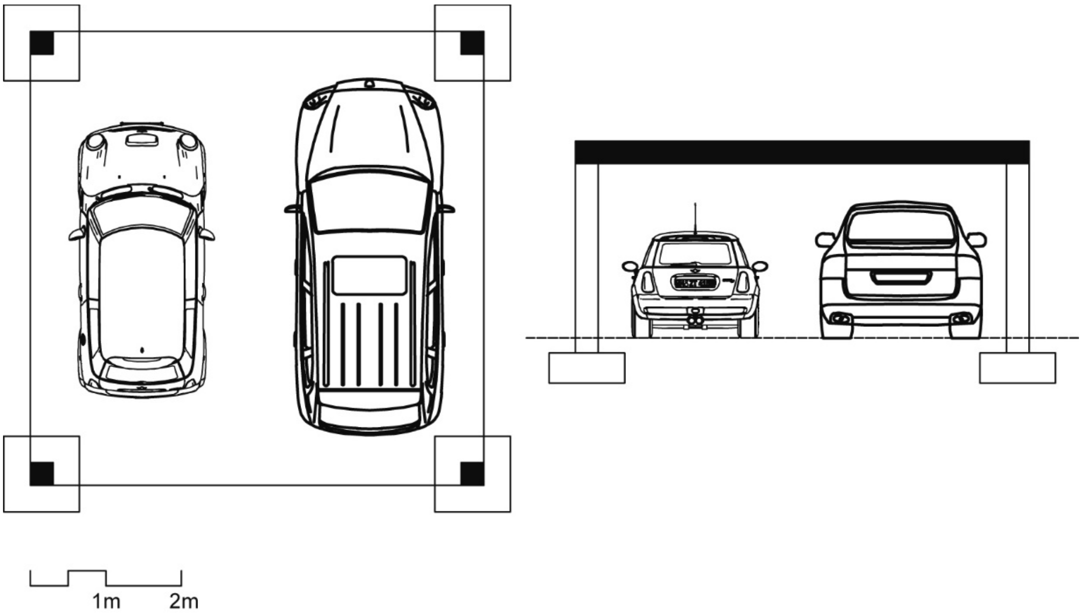


Figure 2.16. First design hypothesis: four columns placed in the corner sustaining a roof.

But from the perspective of safety and efficiency, do any other better structural solutions exist? And what criteria can we use to identify them?

As a second hypothesis, the roof could be built with timber, with two primary beams resting on the columns and four secondary beams resting on the primary beams, as shown in figure 2.17.

In this way, without considering the dimensions of the pillars, the static scheme of the secondary beams would be the one shown in figure 2.18.

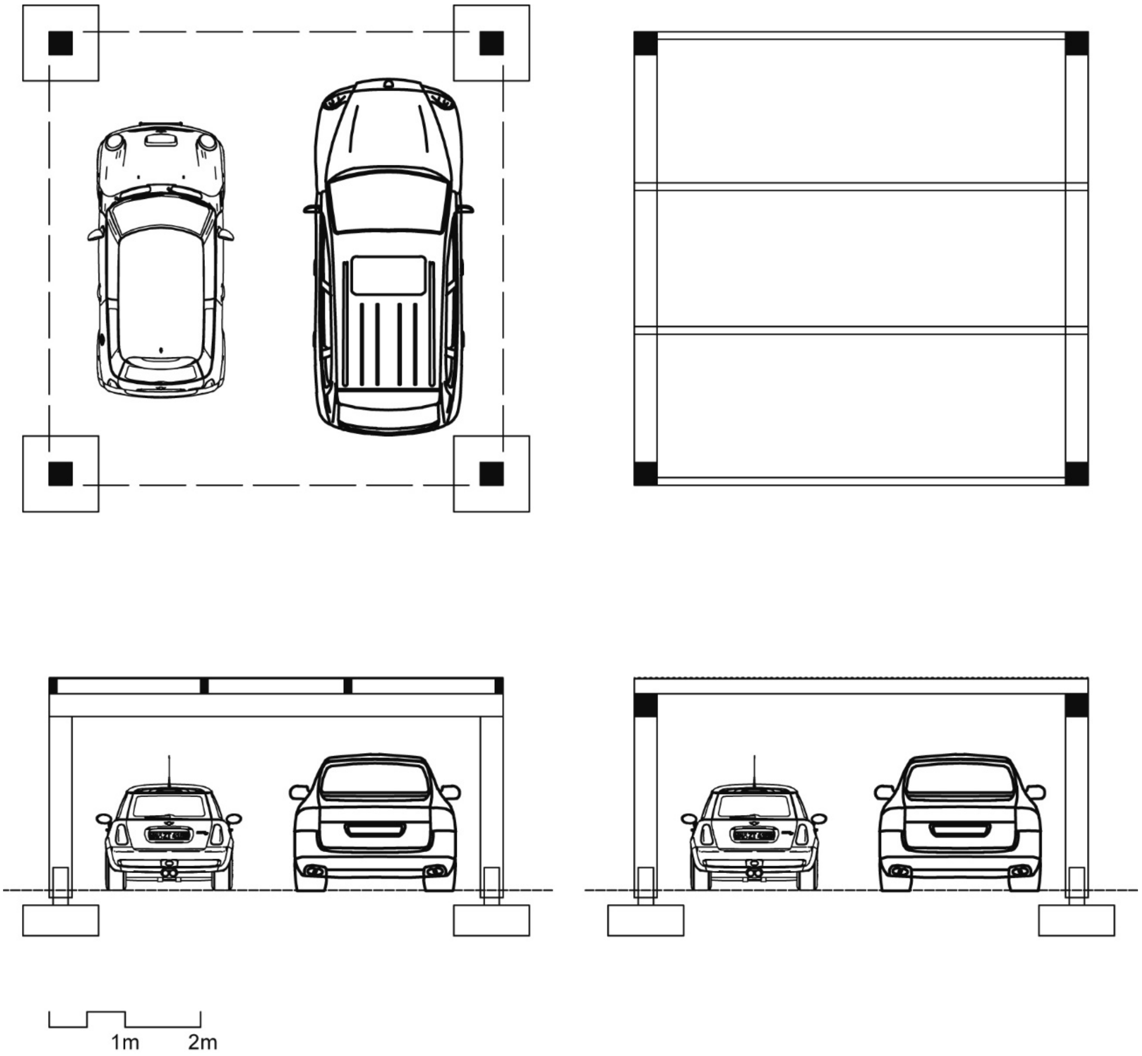


Figure 2.17. Second design hypothesis: timber roof with two primary beams resting on the columns and four secondary beams resting on the primary ones.

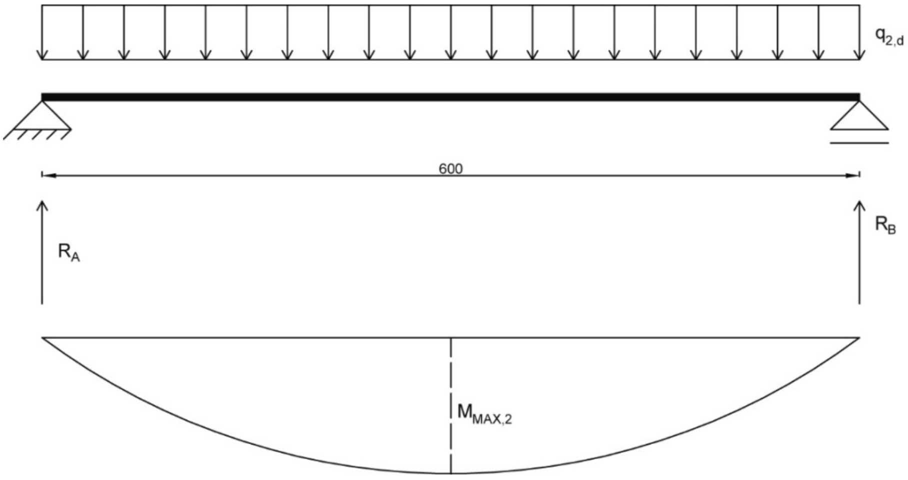


Figure 2.18. second design hypothesis: static scheme of the secondary beams and bending moment diagram

Considering, for the sole purpose of comparing the stresses, that the load on the roof at the ULS (Ultimate Limit State) is equal to q_d = 5 kN/m^2 then, given that the central secondary beams have an influence length of 2 metres, the load $q_{2,d}$ of the beam in figure 2.18 is equal to

$$q_{2,d} = 5\frac{kN}{m^2} \cdot 2m = 10\,kN/m$$

the maximum bending moment at the centerline of the beam would therefore be

$$M_{MAX,2} = 10\frac{kN}{m^2} \cdot \frac{(6m)^2}{8} = 45\,kNm$$

And the reactions at the supports would be

$$R_A = R_B = 10\frac{kN}{m} \cdot \frac{6m}{2} = 30\,kN$$

The static scheme of the primary beam is the one shown in figure 2.19

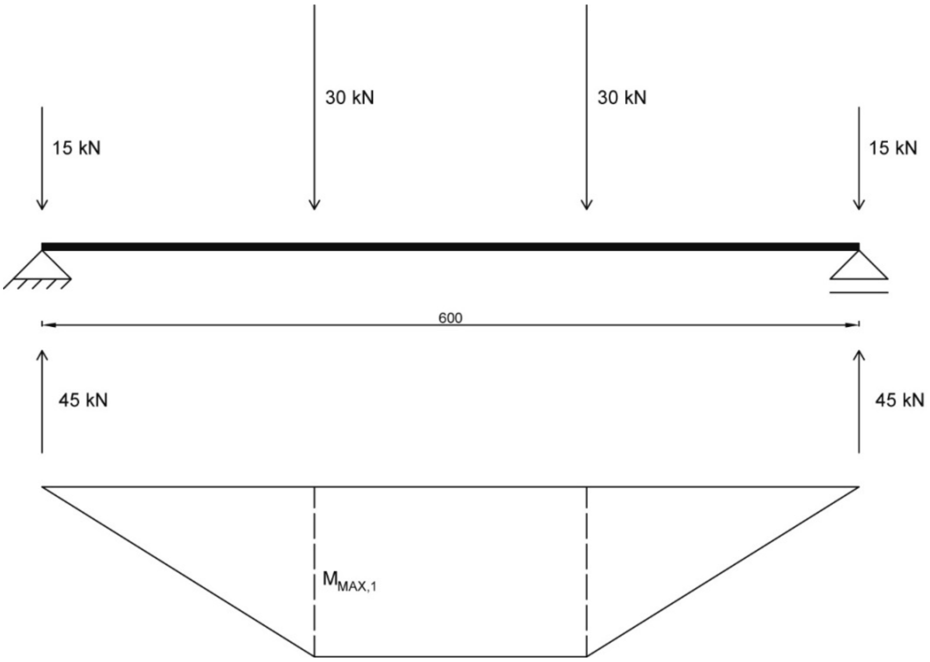


Figure 2.19. Second design hypothesis. Static scheme and bending moment diagram of the primary beam

and the maximum value of the bending moment is $M_{Max,1}$ = 60 kNm.

$M_{MAx,1}$ e $M_{MAX,2}$ would be the bending moment values with which the primary beam and the secondary beam should be sized, respectively. But can this static scheme be modified to reduce the maximum bending moment values without losing any of the space and volume for the parking lot?

The first step could be to replace the hinged supports of the static scheme of the primary beam with fixed joints, which would constructively correspond to creating rigid frame nodes between the columns and the beam.

The static scheme would therefore be the one shown in figure 2.20.

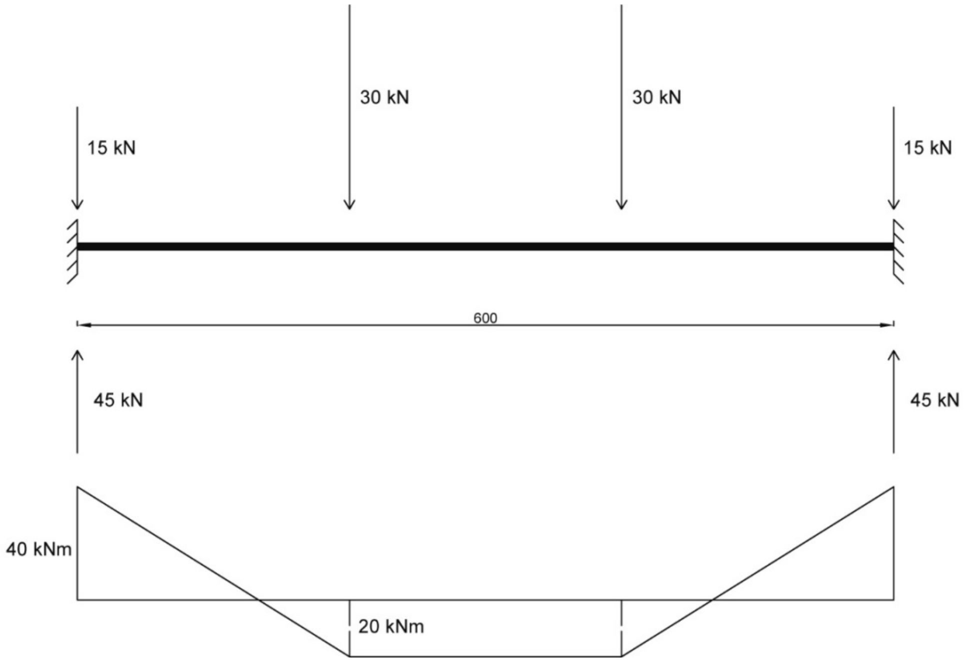


Figure 2.20. Second design hypothesis. Static scheme and bending moment diagram of the primary beams

In this case, the maximum moment would be equal to 40 kNm, with a reduction of more than 30% when compared to the previous solution.

If, in addition to creating frame nodes between the columns and the primary beams, the columns were moved inwards, as shown in figure 2.21, then the static scheme of the secondary beams would change, as shown in figure 2.22.

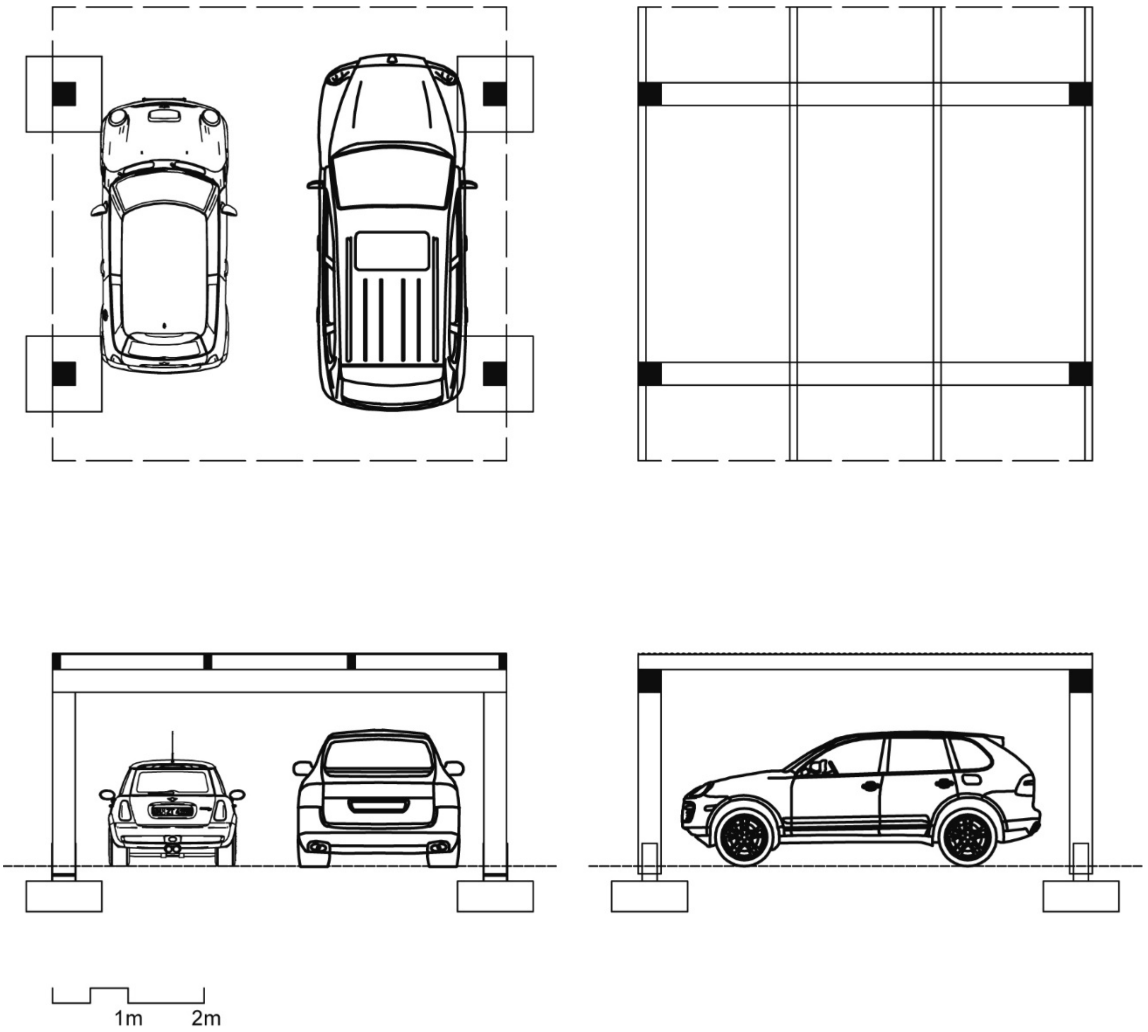


Figure 2.21. Third design hypothesis. The columns are moved inward

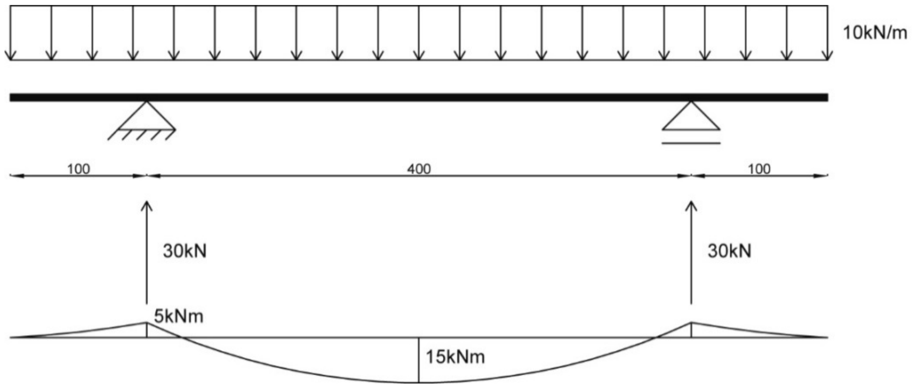


Figure 2.22. Third design hypothesis. Static scheme and bending moment diagram of the secondary beams

By displacing the supports, the maximum moment of the secondary beams would be reduced to a third. It is also easy to identify the position of the supports for which the moment at the support has the same value as that in the span, which would be obtained with a span of 3.52 m and cantilevers of 1.24 m. In this case the bending moment would be equal to 7.8 kNm. The situation is shown in figure 2.23.

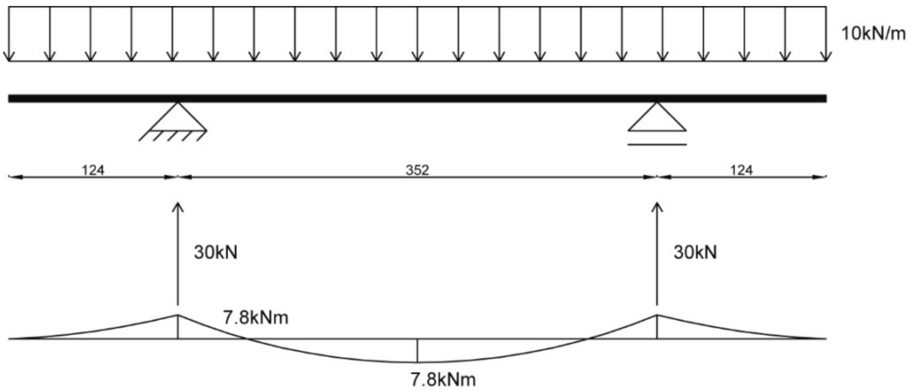


Figure 2.23. Third design hypothesis. Position of the columns to achieve equal values of bending moment at the support and at midspan

The position of the supports and the typology of the constraints have a major effect on the trend and on the entity of the stresses. The awareness and mastery of these effects can be used to design structures creatively, as shown in the project presented in the next section, the Ascona lido by the Swiss architect Livio Vacchini.

2.2.1. The Ascona Lido by Livio Vacchini

The Ascona Lido (figure 2.24) is a project by the Swiss architect Livio Vacchini designed and built between 1980 and 1986. It is a rectangular-plan building measuring 56.3x11.5 m, consisting of two floors above ground. On the ground floor there are all the closed service rooms for the activities of the lido: changing rooms, cash desk, restaurant, storage areas, caretaker's apartment. These spaces enable for a dense vertical structure that supports the slab of the first floor to be built (figure 2.25).

The locker rooms are located on the first floor and, as it is an open space – the facade only encloses the spaces on the ground floor and ends at the level of the parapet on the first floor. The architect thought it was appropriate to reduce the vertical support structure of the roof to only two points of support. What is the optimal position of these two supports, i.e., the one that satisfies all architectural requirements, but at the same time contains stresses and deformations? What criteria did Livio Vacchini use to choose the position of the supports for the roof of the Ascona Lido? Let's try to retrace the steps of structural conception, starting from the basic need for balance, and gradually adding increasingly restrictive architectural and structural criteria until we come to understand the reasons for Vacchini's structural choices.

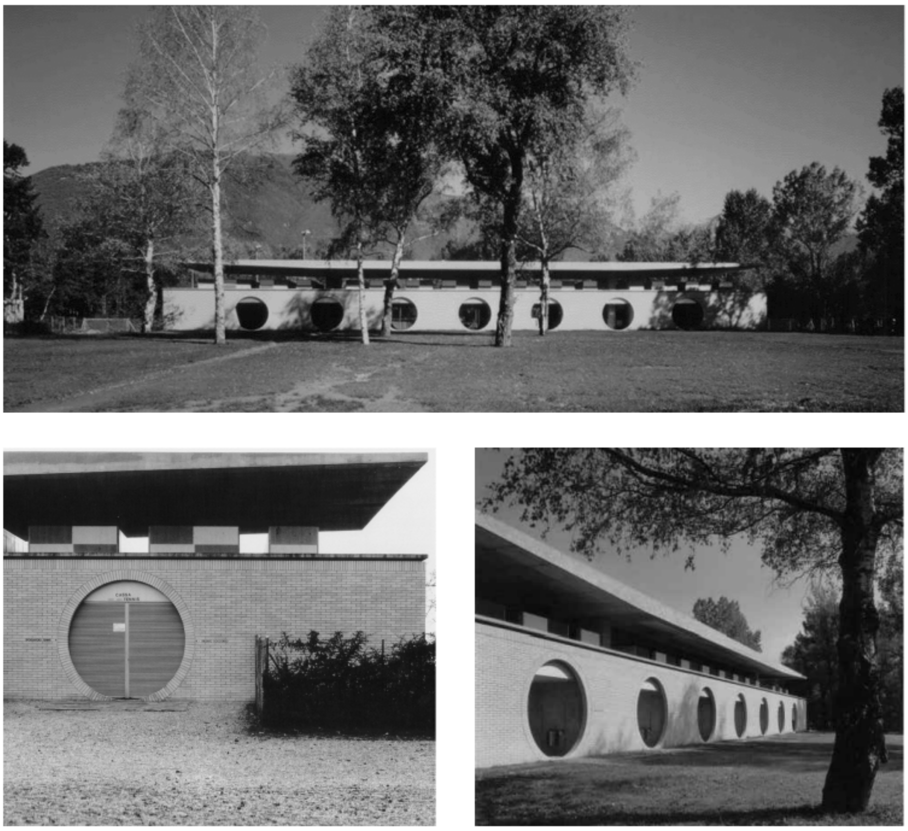


Figure 2.24. The Ascona lido by Livio Vacchini (1980-1986). (Photos by Studio Vacchini Architetti)

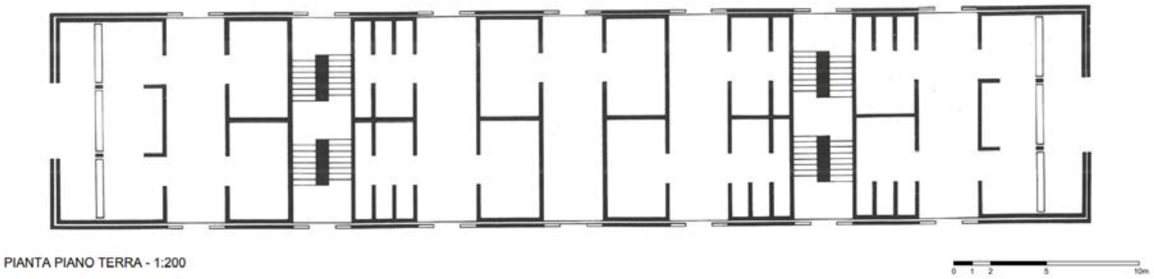


Figure 2.25. Plan of the ground floor. (Drawing by Studio Vacchini Architetti)

Putting architectural needs to one side and remembering the example of the table presented in section 2.1, the simplest solution for supporting a rectangular roof is to place four supports in the corners of the rectangle. However, at this point experience immediately comes into play. We are not dealing with a table, but with a large reinforced concrete roof with a free span of over 50 m, with supports placed at the ends. You do not have to be an engineer or an architect to know that, when dealing with a rectangular surface that is much larger on one size than the other , placing supports along the long sides is the best option, as the load is then transferred along the short one. An intuitive and structurally efficient solution would be to place several punctual supports along the long sides, as shown in figure 2.26.

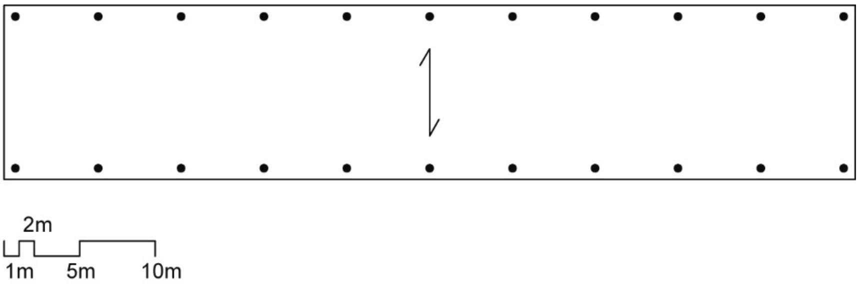


Figure 2.26. Structural conception – step 2. Columns along the long side of the roof

In this way, the structure of the roof would have to cover a span of 11.5 m, which is a considerable distance, but which is completely feasible.

Considering what we learnt from the example in the previous section, from a structural perspective, it would be even more efficient to bring the columns inwards, so as to reduce the bending moment stresses in the roof structure. For example, the columns could be positioned as in figure 2.27, creating overhangs of 2.3 m, equal to approximately 20% of the total span, the same percentage which, in the example in the previous section, guaranteed the equality of the moment at the supports with the moment in the midspan.

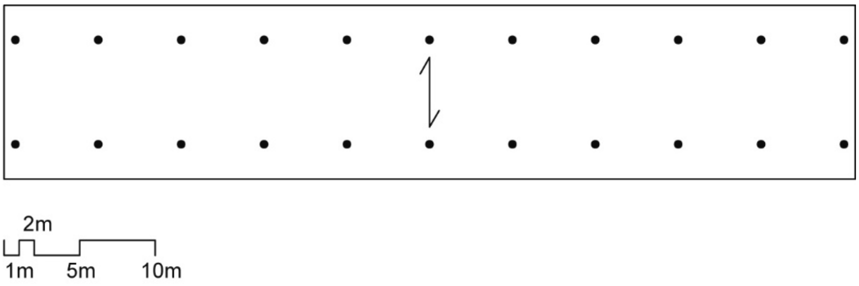


Figure 2.27. Structural conception – step 3. Moving the columns inward to create overhangs

However, we realize that this structural choice is not compatible with the architectural choices. In fact, in the built project there is a complete distinction between the vertical structure of the ground floor, which supports the slab of the first floor, and the vertical structure which supports the roof, for which the smallest possible number of supports were chosen, and these were positioned where the stairs are. In the solution in figure 2.27, the support structure of the roof invades the ground floor spaces, meaning that these spaces would have to be redesigned. Furthermore, the architectural role played by the roof would be considerably reduced. In order to highlight the architectural role of the roof, it was better to transfer the loads along the long side, and it was therefore necessary to find the position of the supports that was optimal both from an architectural perspective,-which did not interfere with the spaces on the ground floor, and from a structural perspective. As we have seen, placing the supports inwards and not at the ends is extremely beneficial for controlling the maximum bending moments. From what has been seen in the previous section, in the case of a uniformly distributed load, the optimal position of the supports is that for which the overhangs are equal to 20% of the dimension of the element. In this case, the optimal position would therefore be the one shown in figure 2.28.

Figure 2.28. Structural conception – step 4. Position of the columns to optimize the bending moments

However, if we position the supports in this way, we notice that it is necessary to considerably resize the volumes located at the ends of the ground floor. In order to not interfere with the spaces on the ground floor, the roof supports must be positioned where the stairwells are, and, consequently, the extension of the cantilevers increases to 14.30 m, and the span between the supports is reduced to 26.3 m.

The roof plate is made up of nine beams with a cross-section of 0.30x0.52 m, connected by an 18 cm thick slab whose position varies with respect to the beams, forming four pitches inclined by approximately 3%. Furthermore, at the ends, the floor tapers until it reaches the thickness of the slab (figure 2.29).

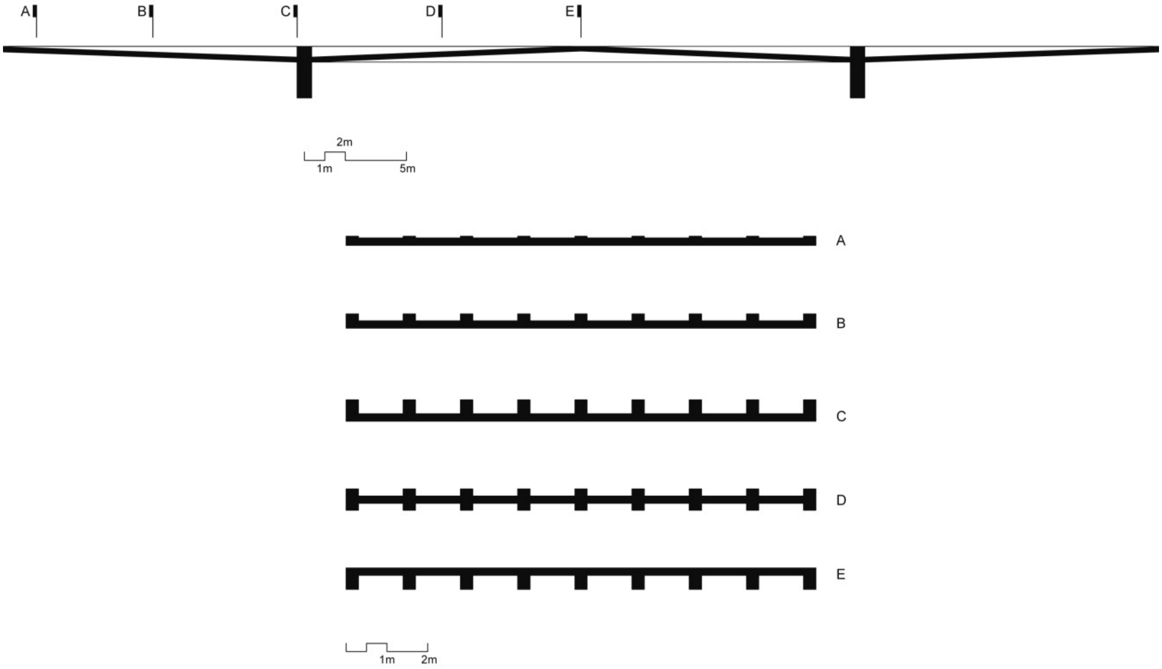


Figure 2.29. Longitudinal e cross sections of the roof

Four of the nine beams in the slab are interrupted at 4 m from the supports, therefore in the lateral portions of the cantilevers there are only five beams of decreasing height from 0.52 m to 0.18 m (equal to the thickness of the slab).

In order to understand the reasons for the structural choices, the loads acting on the structure, the load combinations at the ULS, and the shear and bending moment diagram are calculated below (figure 2.30).

$$q_{beam} = 0.52m \cdot 0.32m \cdot 25\frac{kN}{m^3} = 4.16\frac{kN}{m}$$

$$q_{slab} = 0.18m \; \cdot 25\frac{kN}{m^3} \cdot 1.4m + 0.1m \cdot 10\frac{kN}{m^3} \cdot 1.4m = 9.1\frac{kN}{m}$$

$$q_{snow} = 1.5\frac{kN}{m^2} \cdot 1.4m = 2.1\frac{kN}{m}$$

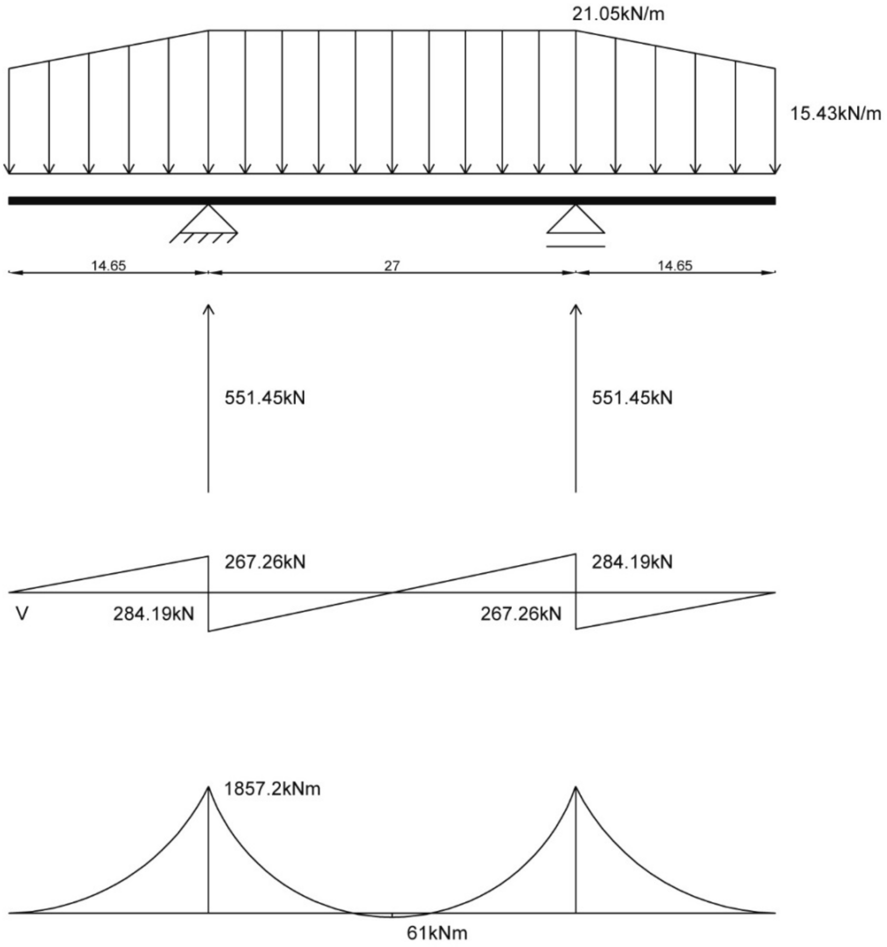


Figure 2.30. Shear and bending moment diagrams

Looking at the trend of the bending moments, it can be seen that the positive moment is practically null (61 kNm). The decision to place the supports at a distance of 27 m therefore allows for two almost independent systems. Columns placed at a greater distance would have made it possible to optimize the stresses (positive moment equal to the negative one). However, as previously shown, the layout of the ground floor rooms determined the choice of the supports. We are therefore faced with a building in which the architectural needs prevailed over the structural needs, and this led to having to select a non-optimized static system. So, what did the structural creativity of this project consist of? This question can be answered in various ways. First of all, despite the prevalence of architectural requirements, the main element of this building is certainly its roof, which defines the space and its size and the fact that it is supported only at two points are striking. But mainly, the creativity of this structure can be recognized in the elegance with which the structure responds to the stresses. In fact, the shape of the slab, follows the trend of the compressive stresses, which can be deduced from the bending moment.

With this example we have seen the fundamental role played by the position of supports in the trend of the stresses, and therefore the importance of knowing the effects of their position and knowing how to control these effects in order to make informed structural choices. But we have also seen that the optimal structural choice is not always the best from an architectural perspective. This is not a contradiction. In fact, in this example, we have seen how a non-optimized structure can be solved elegantly and creatively. In this project, in which structure plays a primary role, close collaboration between the architect, Livio Vacchini, and the engineers, the Andreotti & partners studio in Locarno, Switzerland, was fundamental.

2.3. Form and geometry as tools for creating structural intuition

In the previous section we saw how the position and type of supports have an influence on the extent of the stresses and, consequently, on the feasibility of a structure as well as on its dimensions. But there is another aspect which can be considered when a structural solution is chosen. This aspect is the typology, which comes before the choice of supports, and which affects not only the entity of the stresses but also, and above all, their typology.

For example, consider the task of building the roof of a gymnasium measuring 50x30 m. Without imposing any additional conditions beyond covering the area, there are a great many solutions that can be considered. Once again, as seen in the previous section, intuition and experience play a decisive role in choosing a structural system that responds to the requirements efficiently and even creatively. But, as mentioned in the previous section, intuition and experience can and must be taught to be able to make structural choices that are not dictated by personal talent and experience alone, but which derive from in-depth knowledge of the fundamental static structural principles.

One of the first structural aspects to be considered when conceiving a new structure is structural typology and, therefore, the shape of the structure. In fact, the method of load transfer and the type of stress of the structural elements depends on the structural typology chosen, and it is therefore necessary to know the consequences, advantages, and disadvantages of each typology to be able to make informed choices. There are basically three structural types to choose from, which are distinguished by the load transfer mode they use: shape resistant structures, vector resistance structures, and section resistant structures. The first structures transfer the loads through the adaptation of their shape, the second ones through the decomposition of the forces, and the third ones through the resistance and stiffness of the structural elements.

Here we try to solve the structural problem of providing a roof for the 50x30 m gymnasium using each of the three different structural types just introduced, highlighting the characteristics, dimensional limits, advantages, and disadvantages for each one. This process makes the structural parameters involved in the choices clear and evident.

As the purpose of structural design is to provide a safe and efficient structure, after talking about the shape, we will deal with the geometry of the structural elements. In fact, to guarantee safety, the area and inertia of structural elements must be big enough to ensure that the stress given by the acting loads is lower than the resistance of the materials. In order to guarantee efficiency, the elements must have a stiffness, and therefore a moment of inertia, that are big enough to contain the deformations within acceptable limits. In the examples presented, we will show the criteria which are used to choose the geometric parameters, in particular area and moment of inertia, so that informed choices can be made.

However, our aim is still to show how structural creativity can be formalized and used as a design tool, by knowing and being able to use the parameters which are used to make different choices .Therefore, we will present another project by the Swiss architect Livio Vacchini, the Losone gymnasium, to see the criteria shown in the examples applied to a real building and demonstrate how awareness of these criteria allows us to design a structure in a creative way.

2.3.1. Shape resistant structures

When we speak of shape resistant structures, we refer to the following structural types: cable structures, tent structures, pneumatic structures, and arch structures. For a detailed discussion of these structural typologies, see other publications (Engel 1997, Muttoni 2006, Allen et al 2010). In this section we simply want to discuss the advantages, disadvantages, and limitations of use of these structural types, show the selection and design criteria, and use these criteria to propose a possible solution for the structural problem of providing a roof for a 50x30 m gymnasium.

The main characteristic of shape-resistant structures is that they resist loads by modifying their shape to adapt to the funicular polygon of loads. Obviously, this feature is not suitable for a roof structure. If, in fact, structural safety could be guaranteed by adequately sizing the sections of the structural elements, it would not be possible to guarantee structural efficiency. And this is not the only limitation of funicular structures. Another characteristic that distinguishes them is that they transfer a pull force (in the case of cables) or a push force (in the case of arches) at the supports. This pull or push force, which can reach very high values, must be transferred to the foundations, meaning that major support structures are needed.

But does this mean that funicular structures cannot be considered for the roof of the gymnasium? Absolutely not. We need to know the problems involved in these types of structures and find solutions to overcome them.

Imagine, as a first hypothesis, that we want to cover the gym with a cable structure. Using experience, we know that suspension bridges, which are the man-made structures with bigger spans, are cable structures. So, we can say with some certainty that this type of structure can easily cover large spans carrying heavy loads. We therefore decide to position the vertical support structure of the roof along the short sides and transfer the loads along the long side. We refer to some examples of existing buildings that use the same structural typology, shown in figure 2.31: the Portugal Pavilion by Alvaro Siza (concrete roof), Hall 26 of the Hannover Trade Fair by Schleich and Begermann (steel roof) and the Grandview Heights Aquatic Center in Surrey, Canada, by HCMA architects (timber roof).

In all examples, we can see the imposing anchoring structures placed at the ends of the cable roof. In the case of the Siza pavilion, the roof is made of steel cables with virtually zero stiffness. Consequently, their shape is very susceptible to load variations. In order to solve this problem, the cables are weighed down by a concrete slab that contains the cables themselves. This has the dual purpose of covering the space of the pavilion and of increasing the weight of the roof so that the load variations caused by the variable loads - mainly those caused by wind, given that the snow load is negligible in Lisbon - are minimal compared to the dead load. However, in the other two buildings, the structural choice was to have light roofs, but more rigid funicular systems made up of steel elements in the Hanover Hall and timber elements in the Aquatic Center in Surrey. By assigning a certain stiffness to the cables, i.e. by assigning a geometric section with an adequate moment of inertia to them, the cables can respond to load variations without significantly changing their shape.

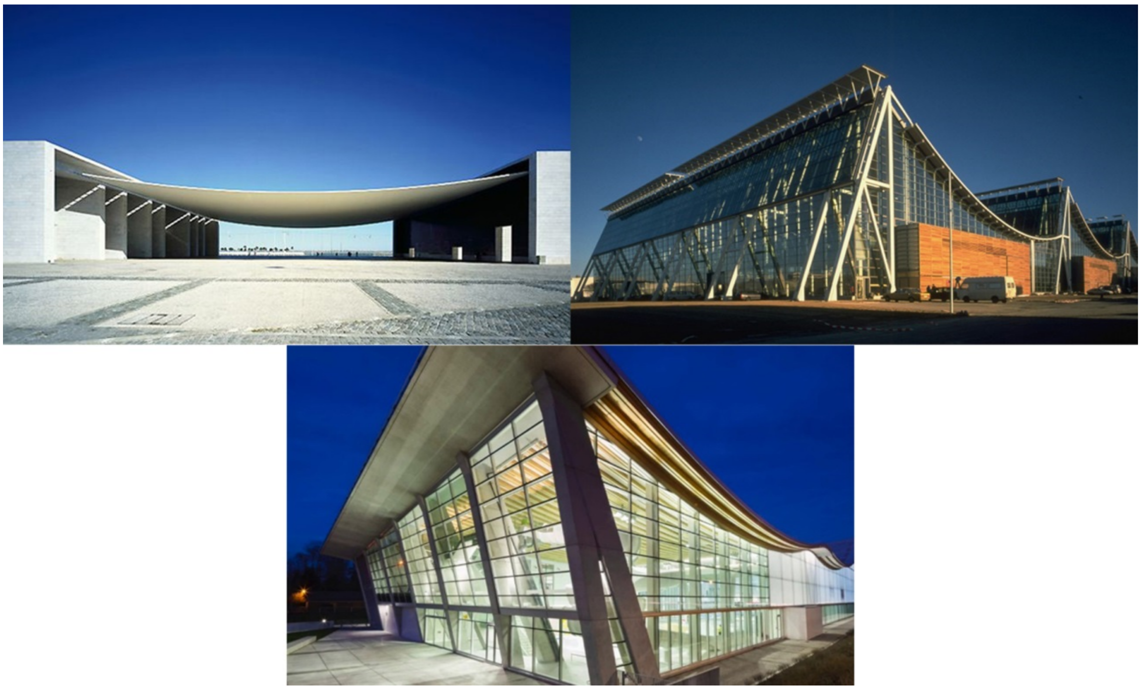


Figure 2.31. Portugal Pavilion, Alvaro Siza (top left), Hall 26 of the Hannover Trade Fair, Schleich and Begermann (top right) and Grandview Heights Aquatic Center in Surrey, Canada, HCMA architects (bottom)

Taking these buildings as a reference, we could decide to conceive a structure like the one in figure 2.32.

On one end, a reinforced concrete structure which, in addition to resisting and transferring the pull of the cables, could contain the service spaces for the gym (changing rooms, storage areas, bar/restaurant, etc.). On the other end, thirteen steel trusses, which would be able to transfer the pull force to the foundations. A roof made up of steel cables weighed down by a concrete slab, such as the roof of the Siza Pavilion. The advantage of this solution is that the two long facades would be totally free from structural elements, allowing total freedom from an architectural perspective.

In order to size the roof structure, it is necessary to determine its shape and the magnitude of the stress in the cable. As we saw in section 1.2, the search for the funicular polygon is an iterative process. The shape of the funicular polygon depends on the loads, and, in turn, the loads depend on the shape and length of the cables. In order to determine the loads used to calculate the funicular polygon, it is necessary to start from a first attempt cable, which we can determine mathematically by setting up the equation of a catenary passing through the connection points of the cables with the lateral structures (points A and B in figure 2.32) and a minimum point equal to the minimum desired height of the roof (point C in figure 2.32). Or, as we did for the analysis of the vault of the palace of Ctesiphon, it is possible to create a scale model of the roof and find the shape of the first attempt with a suspended chain passing through points A, B and C.

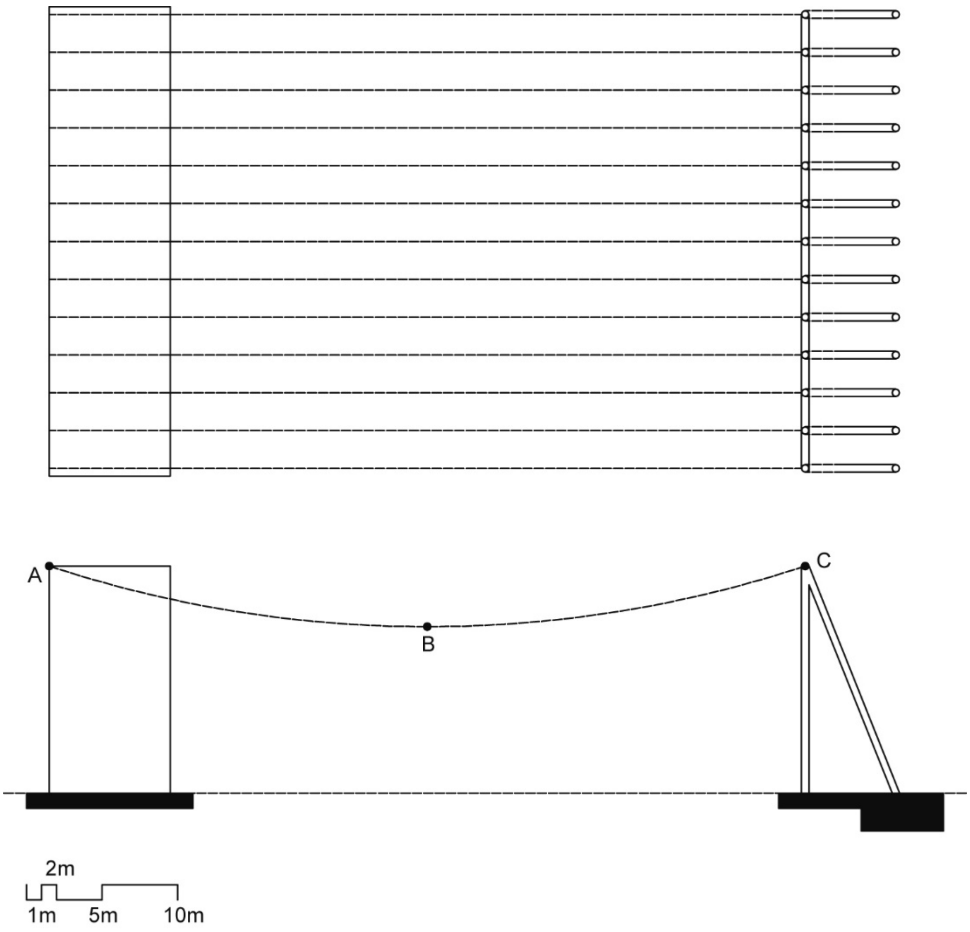


Figure 2.32. Structural conception for the gymnasium roof using a cable structure

Once the shape of the first attempt cable has been defined, the shape can be redrawn to scale, the chosen dimensions to scale (those of a 10 cm concrete slab) can be assigned and divided into segments with the aim of discretizing the distributed load into a chosen number of concentrated loads (the greater the number of loads, the greater the accuracy of the calculation of the funicular polygon). For example, a possible discretization of the cable is shown in figure 2.33.

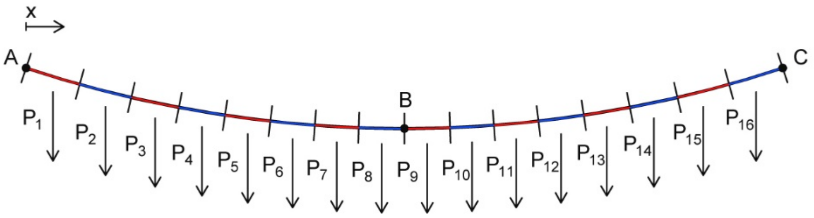


Figure 2.33. Discretization of the first attempt cable

For each cable segment, the weight and the position of the center of gravity (i.e. the point of application of the weight of the segment) are calculated, obtaining the values shown in table 2.1. In order calculate the weight of the segments, the number of the cables and distance between the cables need to have been established. Here we assume that we have a cable every 2.5 meters, as shown in figure 2.32.

Table 2.1. position and values of the loads for the first attempt cable

PIECE NUMBER	x-POSITION (m)	AREA (m2)	LOAD (kN)
1	1,77	0,372	23,25
2	5,25	0,355	22,19
3	8,52	0,324	20,25
4	11,62	0,313	19,56
5	14,65	0,299	18,69
6	17,61	0,298	18,63
7	20,53	0,288	18,00
8	23,49	0,305	19,06
9	26,51	0,305	19,06
10	29,47	0,288	18,00
11	32,39	0,298	18,63
12	35,35	0,299	18,69
13	38,48	0,313	19,56
14	41,48	0,324	20,25
15	44,75	0,355	22,19
16	48,23	0,372	23,25

With the Cremona diagram, the funicular polygon of the loads shown in table 2.1 is calculated, obtaining the result shown in figure 2.34.

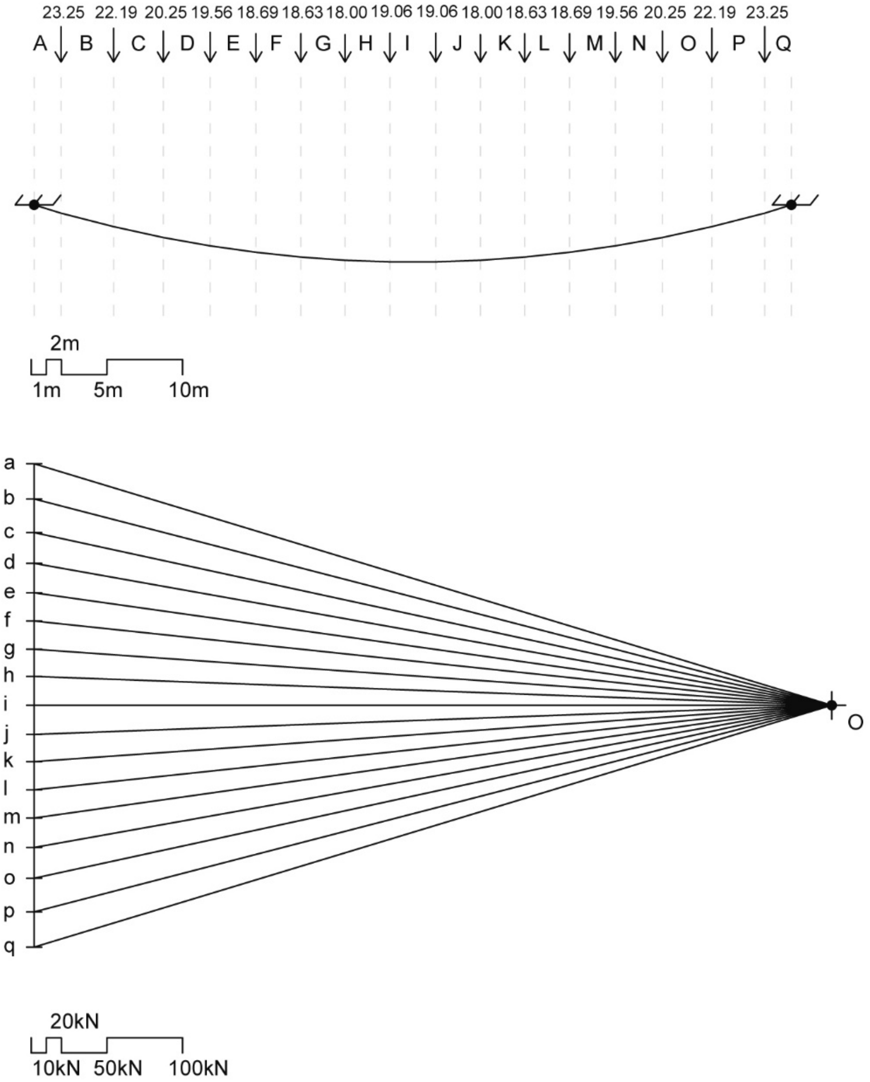


Figure 2.34. Funicular polygon of the loads in table 2.1

By comparing the funicular polygon of figure 2.34 with that of the first attempt, we can see that the curves do not coincide, but they are very close. So, we can assume that the shape of the roof is that of the funicular polygon in figure 2.34.

From the polygon of forces in figure 2.34, we obtain the maximum tension in the cables, which is equal to N = 550 kN. With this value we can size the cable with the formula

$$A_{MIN} = \frac{N_d}{f_{yd}}$$

Assuming that the cables are made of steel type ..., which has a resistance fyd = 1670 N/mm^2, then the minimum area of the cables is equal to A_{MIN} = 329,34 mm^2.

Given that the cables are only subjected to tension and given that, having weighed down the structure, the load variations given by the variable loads are minimal, we do not have to worry about the stiffness or the moment of inertia of the structural elements.

At this point, the structural project is not completely finished. We have not dealt with the foundations, the bracing, the connections between the cables and the support structures, the effects of the wind and earthquakes on the roof or the construction aspects. But we have conceived a structure which, thanks to the formalization of intuition and experience and the awareness of the structural parameters involved – such as shape, loads, span, geometry - and their effects on the type and extent of the stresses, represents a starting point for the structural design that will be defined, and not distorted, by detailed calculation.

2.3.2. Vector resistance structures

In the previous section we saw that the main limitation of shape resistant structures is their stiffness. In order to prevent them from changing their shape as loads vary, it is, in fact, necessary to weigh them down or stiffen them. This lack of stiffness comes from the fact that, given that their shape is the funicular polygon of the acting loads, the structural elements are stressed exclusively by tension or compression forces. If the problem of buckling of the compressed elements is not considered, providing sections, which have an area that guarantees the Ultimate Limit State, can withstand these types of forces is enough. When the shape of the structure moves away from the funicular shape, the structural elements are no longer only stressed in tension or compression, shear and bending moment stresses also come into play. In order to withstand shear and bending moment, it is necessary to increase the moment of inertia of the sections of the structural elements. The consequence of not using the shape of the funicular polygon, for example if we want to build a flat roof, is more rigid and, consequently, heavier structures.

But there is a structural typology that allows the stiffness of a structure to increase without losing the benefits of structural elements stressed exclusively by tension or compression actions: reticular structures. Before dealing with reticular structures, let's consider the stiffness of structural elements. When an element is stressed in tension, the characteristic to be dimensioned to verify the Ultimate Limit State is the area of the section, according to the formula

$$A \geq \frac{N_d}{f_d}$$

where N_d is the tensile action at ULS and f_d is the strength of the material reduced by the appropriate ULS reduction coefficients. However, if an element is subjected to bending stress, the characteristic to be sized for verifying the ULS is the section modulus, according to the formula

$$W \geq \frac{M_d}{f_{m,d}}$$

where M_d is the ULS bending moment and $f_{m,d}$ is the bending resistance of the material, which has already been reduced by the appropriate ULS coefficients. But the section modulus is a characteristic that indicates not so much the quantity of material of which the section is made up of (like the area), but how this material is distributed with respect to the center of gravity. The farther the material is distributed from the center of gravity, the higher the section modulus.

For example, consider the two sections represented in figure 2.35.

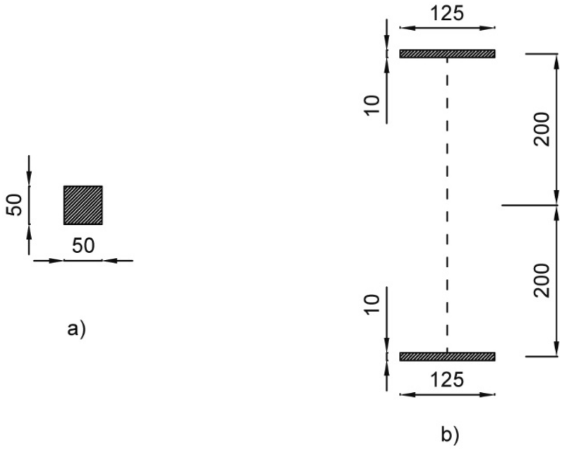


Figure 2.35. Comparison between two sections with the same area and a low section modulus (a) vs a high section modulus (b)

For both sections, the area is equal to A = 25 cm^2, while the section modulus varies considerably and is equal to:

$$W_a = 20.83\ cm^3$$

$$W_b = 500.1\ cm^3$$

Con W_b / W_b = 24

With the same area, section b) has a section modulus that is 24 times greater than section a). If we use a section like the one in figure 2.35b, in which, for simplicity of treatment, we do not consider the connection method between the upper and lower flange to resist a bending moment Md, the bending moment M_d generates a compressive force, $C_{d,}$ in the upper flange and an equal and opposite tensile force, Td, in the lower flange, according to the formula

$$M_d = C_d \cdot d = T_d \cdot d$$

Where d is the distance between the flanges. In this way we obtained a section made up of two parts, each of which is stressed only in tension or compression, but, at the same time, it is able to resist a bending moment because of the high section modulus.

In reticular structures exactly what has just been described happens. They are made up of elements that work exclusively in tension or compression in a triangular combination and form a stable composition which, if adequately supported, absorbs loads and transfers them to the ends.

For a complete discussion of reticular structures, see other publications (Engel 1997, Muttoni 2006, Allen et al. 2010). In this section, as we have already done for the shape resistant structures, we want to discuss the advantages, disadvantages, and limits of use of vector resistance structures, show the selection and design criteria and use them to propose a possible solution for the structural problem of providing a roof for a 30x50 m gymnasium.

First of all, we define which characteristics a structure must have to be considered a reticular structure. A reticular structure is a structure made up of rods (chords, and diagonal and vertical elements) connected to each other at articulated ends so as to form a stable load-bearing structure (figure 2.36).

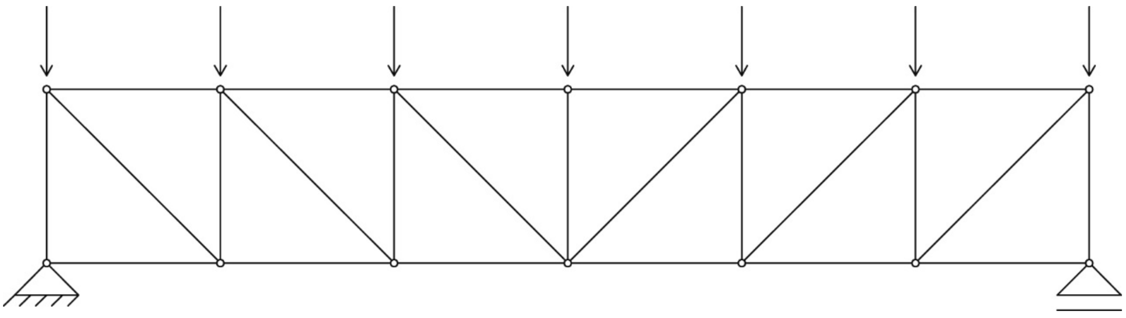


Figure 2.36. Example of a reticular structure

The axes of the members must be concurrent at the nodes and the loads applied at the nodes. If these conditions are met, the rods are stressed exclusively by tensile or compressive stresses. The transfer of the loads takes place through the decomposition of the forces at the nodes

But what are the criteria used to choose and conceive a reticular structure? First of all, reticular structures are a structural typology that is chosen when dealing with major spans, such as industrial warehouses, exhibition halls, gyms and sports halls, etc. For a parallel chords truss, the range of use goes from 20 to 50/60 meters when timber is used as a structural material, and from 20 to 80 meters in the case of steel (Engel 1997). Concrete is not suitable for this structural typology, even though it is potentially possible, because of the difficulties involved in constructing the formwork. Therefore, concrete would not be a good choice financially. Once this typology has been selected, and before carrying out detailed calculations, the height of the truss must be roughly defined, given that the entity of the stresses in the rods depends on it (figure 2.37).

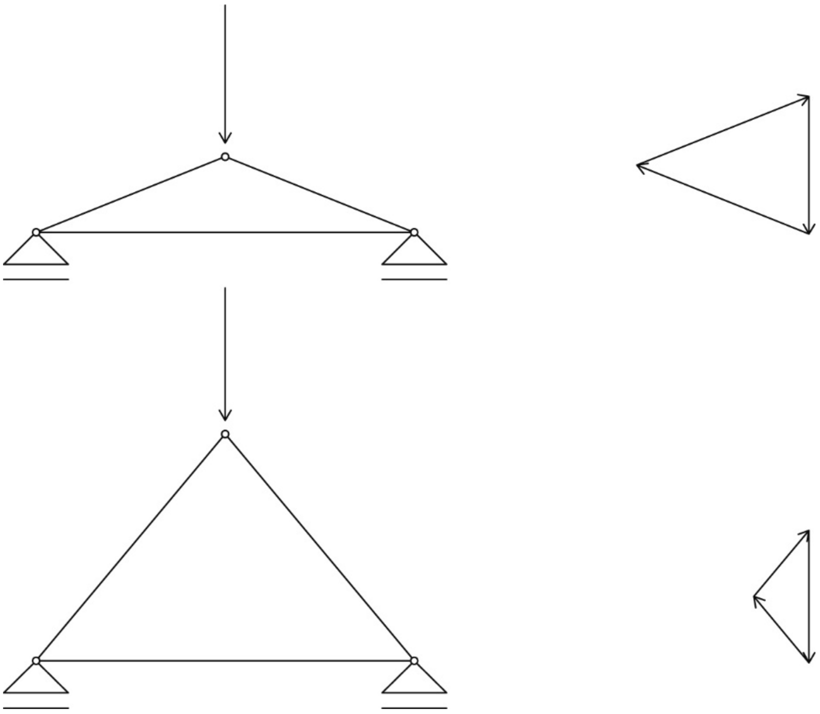


Figure 2.37. Variation of stresses as the height of the truss varies

If, in the presence of ordinary loads, the height of the trusses falls within the range of 1/15 ÷ 1/20 of the span it must cover, we can be reasonably confident that the stresses in the rods will be acceptable. The choice of the height also indirectly influences the number of fields into which the truss is divided. In fact, the diagonals must not be too inclined or too vertical to contain the internal stresses. In order to limit the number of fields, the diagonals must not be too vertical. The optimal range for the inclination of the diagonals is between 30° and 45°. At this point, it is necessary to decide in which direction to incline the diagonals to conclude the conceptual design of the trusses. In fact, the type of stress to which the diagonals are subjected depends on their inclination, which can be compression or tension. Given that, as can be seen in figure 2.36, the diagonals are the longest of the elements that make up the truss, and remembering that the compressed elements are subject to buckling, the best choice from a structural perspective, is that the diagonals are in tension. In order to determine how to arrange the diagonals so that they are in tension, the parallelism between lattice structures and funicular structures with compensated thrust, shown in figure 2.38, is used.

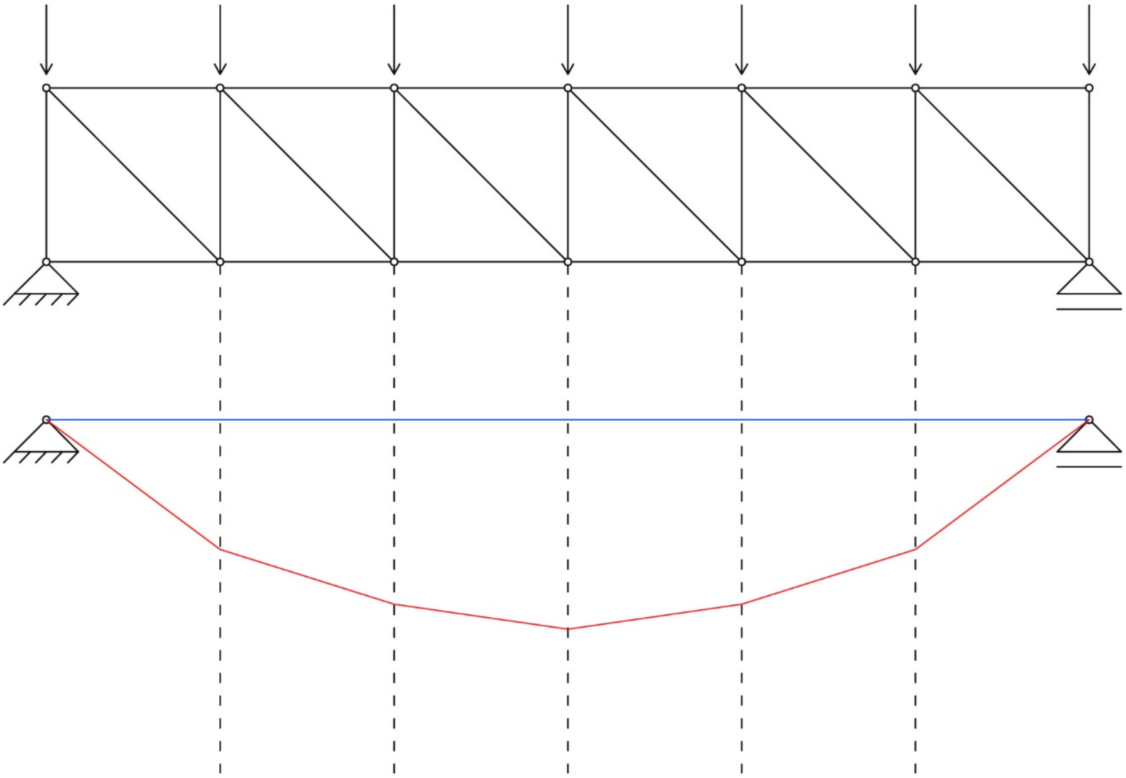


Figure 2.38. Parallelism between lattice structures and funicular structures with compensated thrust

The truss in figure 2.38 consists of six fields, and the diagonals are all inclined in the same direction. Imagine a funicular structure with compensated thrust carrying the same loads at the same supports (figure 2.38). The following information can be obtained from the comparison between the truss structure and the funicular structure with compensated thrust:

- since the strut of the compensated thrust structure is above the cable, then the upper chord of the lattice is in compression and the lower one in tension;
- the most stressed chords are those at the maximum distance between the cable and the strut, in other words those at midspan (where the bending moment is also greater);

- The most stressed diagonals are those that correspond with the fields where the cable has the steepest inclination, i.e., the first and the last diagonals (where the shear stress is greater);
- If the diagonals have the same inclination as the cable, they are in tesnion, otherwise they are in compression.

In the truss in figure 2.38, the first three diagonals are in tension, the others are in compression. From a structural perspective, it would be better to arrange them as in figure 2.36.

At this point, we have defined all the criteria that allow us to conceive and pre-dimension the roof of the 30x50 m gymnasium using vector resistance structures.

In order limit the height of the elements, we choose to carry the load in the short direction of the rectangle. The trusses will therefore have a free span of 30 meters, so a height of 30/15 = 2 m is chosen. We decide to divide the truss into ten 3-meter fields, obtaining inclined diagonals of about 33°, and we choose the inclination for which they are all in tension, at least under the permanent loads (figure 2.39).

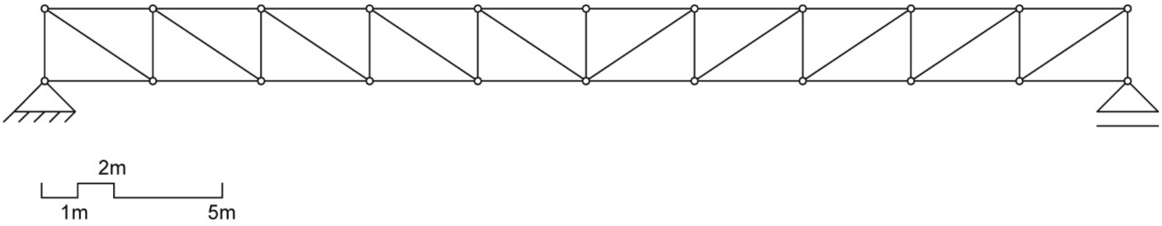


Figure 2.39. 30m-span truss for the roof of the gym

We decide to place the secondary roof structure under the trusses, so that they are visible from the outside. We then place a secondary beam at each lower node of the truss. In order to limit the span of the secondary beams, we set the distance between the trusses to 10 meters. We therefore obtain the structure represented in figure 2.40.

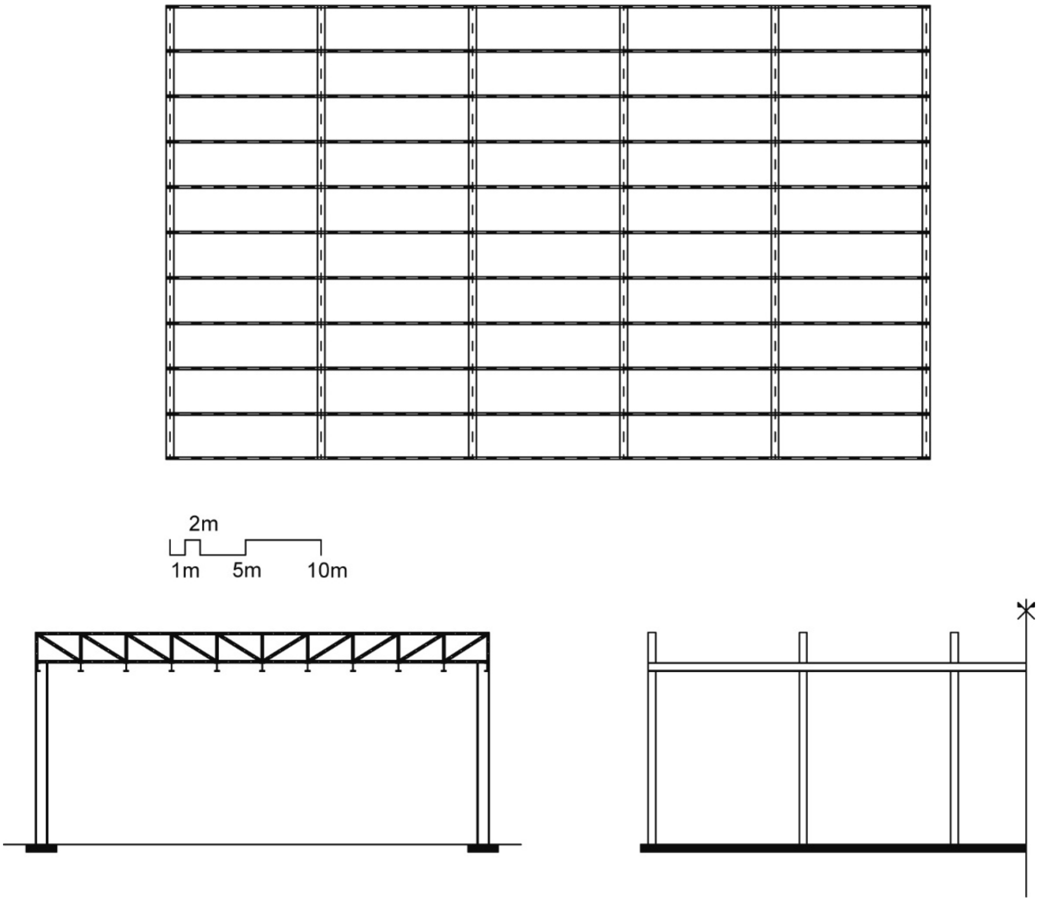


Figure 2.40. Conceptual design of the structure for the gym roof using a vector resistant structure

Therefore, we have conceived a roof structure for the gymnasium made up of trusses, using the criteria presented in this section to determine the height of the trusses, the distance between them, the number of fields, and the inclination of the diagonals. In order to complete the conceptual design phase, it is necessary to determine the indicative size of the truss rods, which will then be verified in the detailed calculation phase. In order to do this, we go back to the conclusions we drew from the parallelism between the truss and a funicular structure with compensated thrust, i.e. that the most stressed diagonals are those closest to the supports, and the most stressed chords are those in the middle. We can therefore decide to size all the diagonals in the same way as those at the supports, and all the chords in the same way as those at midspan, and we obtain a structure that is verified at the ULS.

We assume a load on the roof at the ULS of $q_d = 10$ kN/m^2 to carry out the pre-sizing calculations. Each node of the truss has an area of influence equal to $A = 3x10 = 30$ m^2, so the load for each node is equal to 300 kN for the central nodes and 150 kN for the lateral nodes. Therefore, the static scheme of the truss is that shown in figure 2.41.

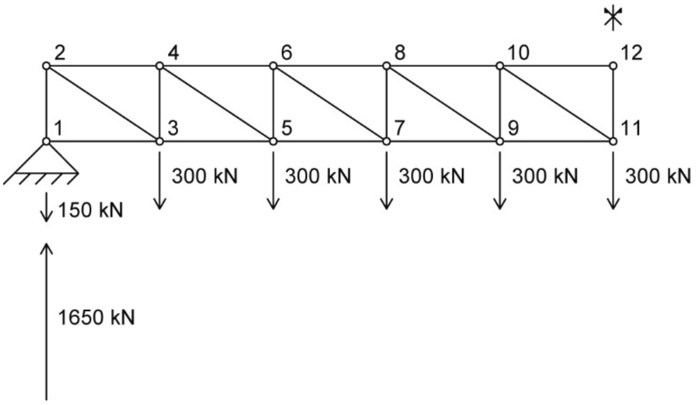


Figure 2.41. Static scheme of the truss

Only the equilibrium of node 1 and that of node 2 in order (figure 2.42) need to be solved to determine the stresses in the most stressed diagonal (rod 2-3).

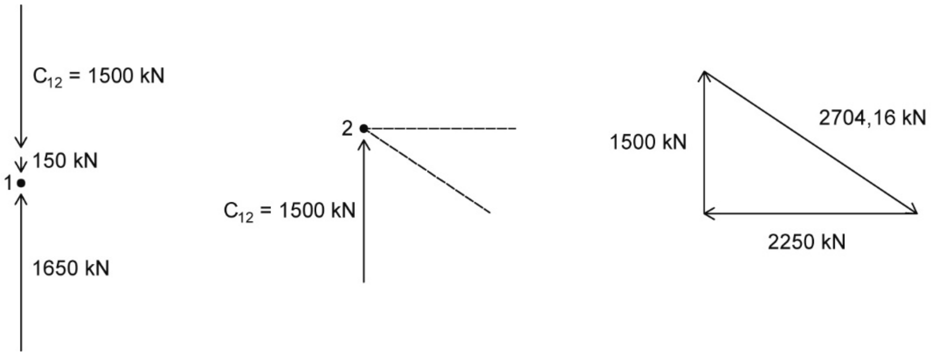


Figure 2.42. Equilibrium of forces at nodes 1 and 2

Therefore, the stress in the most highly stressed diagonal is equal to $N_{d,max}$ = 2704,16 kN. If S355 steel (SIA 263) is used, the diagonal section must have a minimum area equal to

$$A_{MIN} \geq \frac{2704.16 \cdot 10^3 N}{355\, N/mm^2/1{,}05} \sim 8000\, mm^2$$

For example, an area of 8460 mm2 is obtained if two UPN type 240 profiles are used.

The equilibrium of the sub-structure represented in figure 2.43 is set to determine the maximum stress in the top and bottom chords.

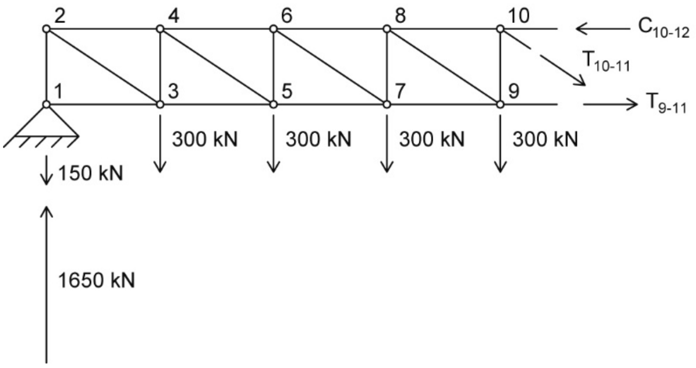


Figure 2.43. Equilibrium of the sub-structure to determine the maximum stress in the top and bottom chords

$$C_{10-12} = 6750\ kN$$

$$T_{10-11} = 540.83\ kN$$

$$T_{9-11} = 6300\ kN$$

The lower chord is subjected to tensile stress, therefore the following formula is applied to size it

$$A_{MIN} = \frac{T_{9-11}}{f_{yd}} = \frac{6300 \cdot 10^3 N}{355\ N/mm^2/1.05} = 18'633\ mm^2$$

We could, for example, assign two coupled HEB 240 profile to the bottom chord, which have an area of A = 21'200 mm^2.

Regarding the upper chord, given that it is a compressed element that is subject to buckling, we use a profile with greater inertia than that of the lower chord, for example two coupled HEB280 profile, postponing the buckling check to a later stage.

At this point, as in the case of the funicular roof conceived in the previous section, the structural project is by no means finished. We still have to deal with the foundations, the bracing, the connections between the truss rods, the connections between trusses and pillars and between secondary beams and trusses, and the dimensioning of the pillars. However, even at this point we have managed to conceive a structure by being aware of the parameters involved: loads, spans, resistance, and stiffness. We have also established criteria that allow us to make a choice of the static height of the trusses and the arrangement of the elements to choose the type of stress and control its entity. An in-depth structural calculation leads to the dimensions of the structure being verified all its details being defined, without its setting changing drastically.

2.3.3. Section resistant structures

In the previous section we saw how vector resistance structures allow the limits of shape resistant structures to be overcome, in particular those with low stiffness, while keeping the advantage of having elements that are stressed only in tension or compression. However, from a construction perspective, there is a downside to vector resistance structures. In fact, as they are made up of rods that meet at the nodes, they require numerous connections, so, in some cases, they may not be the best choice. Furthermore, requiring so many connections effectively excludes concrete as a building material for this type of structure. Although it is technically feasible to make a concrete truss, and it is possible to find built examples, the difficulty involved in making the formwork for casting vertical and diagonal elements makes trusses a structural typology reserved for timber and steel structures. The alternative to vector resistance structures, which keeps the advantage of being stiff, and therefore does not require the shape of the funicular polygon of the loads to be used, is that of the section resistant structures. When we talk about section resistant structures, we refer to the following structural types: beam structures, frame structures, beam grid structures, and plate structures. As in the case of vector resistance structures, given that the shape does not use that of the funicular polygon, the elements are stressed by shear and bending moment forces, so the sections of the structural elements must have a suitable section modulus. But unlike reticular structures, in which stiffness is obtained by spacing the upper and lower chords, in section resistant structures, it is necessary to increase the size of the section and/or optimize the distribution of the material around the center of gravity to increase the modulus of resistance. For example, consider the situation represented in figure 2.44.

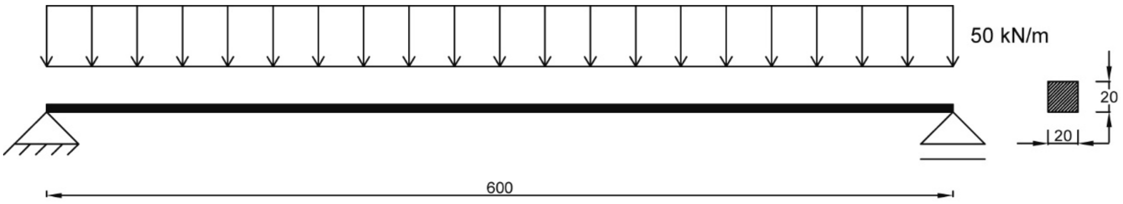


Figure 2.44. Structural scheme of a beam with a section 20x20cm

A 6-meter-long beam, subjected to a load of $q_d = 50$ kN/m, has a section of 20x20 cm in C25/30 concrete ($f_{cd} = 16.67$ N/mm2). The maximum moment in the middle is equal to

$$M_{MAX} = 20\frac{kN}{m} \cdot \frac{(6m)^2}{8} = 90\ kNm$$

The 20x20 cm square section has a section modulus W equal to

$$W = \frac{(200mm)^3}{6} = 1'333'333{,}33\ mm^3$$

Consequently, the maximum stress due to the bending moment is equal to

$$\sigma_{MAX} = \frac{M_{MAX}}{W} = \frac{90 \cdot 10^6 Nmm}{1'333'333{,}33 mm^3} = 67{,}5\frac{N}{mm^2}$$

which is much greater than the strength of the material. It is therefore necessary to modify the section to increase its section modulus, W. A first attempt could be to use a section with the same area, so as not to increase the weight of the beam but distribute the material further away from the center of gravity. For example, the section represented in figure 2.45 could be used.

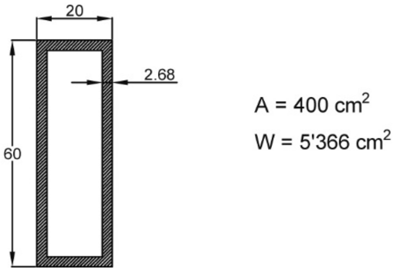


Figure 2.45. Possible section to increase the section modulus W, keeping the same area of a 20x20 cm section

With this section the maximum stress caused by the bending moment would be

$$\sigma_{MAX} = \frac{90 \cdot 10^6 Nmm}{5'366 \cdot 10^3 mm^3} = 16.77\, N/mm^2$$

which corresponds to the maximum strength of C25/30 concrete. However, a section of this type would be difficult, if not impossible, to create in concrete. The first problem would be the thicknesses, which would not be compatible with the insertion of reinforcement and the presence of the central void, which needs a formwork containing a void. In order to increase the strength of the concrete beam in the example in figure 117, its overall dimensions, especially its height, would have to be increased, which would also increase its weight. For example, a 20x50 cm rectangular section could be used, with area A = 1000 cm^2 and section modulus W = $20x50^3/6$ = 8,333.33 cm3. However, the bending moment would need to be updated as the self-weight of the beam would be greater. The ULS load that would need to be added is

$$q_{ADD,d} = 0{,}2 \cdot 0{,}3 \cdot 25 \cdot 1.3 \cong 2\, kN/m$$

The maximum bending moment is

$$M_{MAX,d} = 22 \frac{kN}{m} \cdot \frac{(6m)^2}{8} = 99\, kNm$$

and the maximum stress caused by bending results

$$\sigma_{MAX} = \frac{99 \cdot 10^6 Nmm}{8'333'33 mm^3} = 11{,}88 \frac{N}{mm^2} < f_{cd}$$

Section resistant structures exploit the strength and stiffness of straight linear members with full sections to transfer the loads. But since the sections are full, the elements are heavy, so the limitation of section resistant structures is their high self-weight.

In order to show the criteria for conceiving a structure resistant structure, we now analyze a building designed by the Swiss architect Livio Vacchini: the gymnasium in Losone. The plan dimensions of the gymnasium are 31.21x56.07 m, therefore approximately the same as those in examples 2.3.1 and 2.3.2. The structural solution chosen by Vacchini can therefore be compared with the examples in the previous sections.

2.3.3.1. The gymnasium in Losone by Livio Vacchini

The gymnasium in Losone (figure 2.46) is a project by the Swiss architect Livio Vacchini in collaboration with the engineering studio Andreotti & Partners from Locarno, built in 1995-1996 after winning a design competition in 1990.

Figure 2.46. Gymnasium in Losone by Livio Vacchini (exterior). (Photo by Studio Vacchini Locarno)

It is a three-court gymnasium with an area of 56.07x31.21 square meters and a height of 8 meters. The entire service space (showers and changing rooms) is located in the basement, while the gym floor is located on the same level as the surrounding natural surface level. The roof is a 140 cm thick prestressed concrete grid slab supported by tapered pillars with a section of 43x70 cm at the base and 43x43 cm at the top (figure 2.47).

Figure 2.47. Gymnasium in Losone by Livio Vacchini (interior). (Photo by Studio Vacchini Locarno)

In this project, unlike in the hypothetical solutions in the previous sections, the designers decided to transfer the loads in both directions. In fact, the grid slab is made up of beams of equal height and thickness that cross perpendicularly, and the support pillars are positioned along the entire perimeter.

But what criteria were used to decide how to transfer the load in both directions? The spans in each direction are very different, about 30 m in the short direction and about 50 m in the long one. So, if the load were equally divided in the two directions, the beams in the two directions would have significantly different dimensions. In fact, the stresses in the beams, if the load is the same, depend on the square of the span and the deformations on the power to the fourth of the span. Given that the ratio between the spans is 56.07/31.21 = 1.80, given the same load, the maximum moment of the beams in the long direction would be equal to 1.8^2 = 3.24 times that of the short beams. Furthermore, given the same section, the deformation of the long beams would be 1.8^4 = 4 times greater than that of the short beams. Moreover, the range of use of the prestressed concrete grid of beams goes from 10 to 30 m (Engel, 1997), so the 30 meters of the short side of the gymnasium are already at the dimensional limits of this range. It is more coherent with the trend of stresses given by the bending moment and with the deformations to divide the loads so that the maximum stresses and/or the maximum deformations are equal in both directions. For example, by equating the maximum bending moments, the following subdivision of the loads in the two directions is obtained

$$q_1 \cdot l_1^2 = q_2 l_2^2$$

where q_1 and q_2 are the loads acting on the beam in the short direction and those acting on the beam in the long direction, respectively, and l_1 and l_2 are the spans of the short beam and the long beam, respectively. Ratio q_2/q_1 is obtained from the equation [...]

$$\frac{q_2}{q_1} = \frac{l_1^2}{l_2^2} = \frac{31.21^2}{56.07^2} = 0{,}31$$

The load transferred in the long direction would therefore be 31% of the load transferred in the short direction, which corresponds, with respect to the total load, to

$$\begin{cases} q_1 + q_2 = q \\ q_2 = 0{,}31 q_1 \end{cases}$$

By solving the system, we would obtain the following relationships between the loads

$$\begin{cases} q_1 = 0.76q \\ q_2 = 0.24q \end{cases}$$

By equating the maximum deformations, the following subdivision of the loads in both directions would be obtained

$$q_1 \cdot l_1^4 = q_2 l_2^4$$

So the ratio q_2/q_1 would be

$$\frac{q_2}{q_1} = \frac{l_1^4}{l_2^4} = \frac{31.21^4}{56.07^4} = 0{,}1$$

Load q_2 should be approximately 10% of load q_1, which, with respect to the total load, is

$$\begin{cases} q_1 + q_2 = q \\ q_2 = 0{,}1 q_1 \end{cases}$$

By solving the system, we would obtain the following relationships between the loads

$$\begin{cases} q_1 = 0.9q \\ q_2 = 0.1q \end{cases}$$

By setting the equality of the deformations, only 10% of the load would be transferred in the long direction.

However, the choice of how to divide the load in both directions is free. It is, in fact, a design choice which has consequences for the sizing of the structural elements. The criteria we have proposed, that of equality of moments and equality of deformations, are used to get an idea of how to divide the load to have beams of equal size in both directions. By summarizing the results of both criteria proposed, it is possible to divide the load as follows:

$$\begin{cases} q_1 = 0.8q \\ q_2 = 0.2q \end{cases}$$

At this point, it is necessary to establish a criterion for choosing the number of beams in the grid and the distance between them. If the roof were supported only on the long sides, then all the beams that span the short side would have the same type of support and would therefore be identical from a static perspective. Therefore, there would be no reason to differentiate their sections or to vary their distance from each other. In the case of the gymnasium in Losone, however, the roof is supported on all four sides of the perimeter, and there are also beams along the long side, which have a binding effect, albeit with a yielding constraint, on the beams along the short direction. Moreover, this restraint is greater near the supports of the long beams, and it decreases to a minimum at the midspan of the long beams.

In other words, in the vicinity of the supports of the long beams, a share of the load that is greater than the 20% assumed would be transferred along the long beams, as a direct result of the proximity of the supports. Consequently, the short beams would have lighter loads and be more rigid, because of the presence of the support given by the long beams. It would therefore make sense to use the same section for all the short beams and differentiate their distance from each other according to the size of the loads they have to carry - increasing the distance moving from the supports of the long beams towards their midspan (figure 2.48).

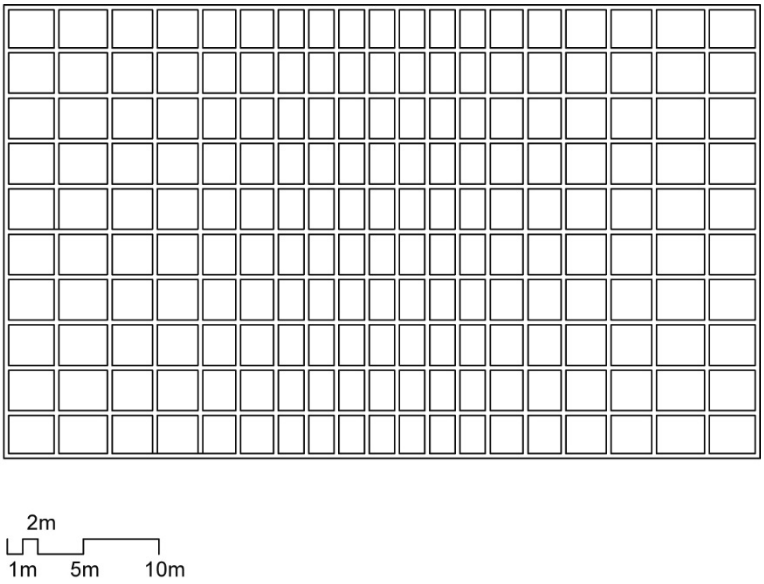


Figure 2.48. Possible layout of the short beams. The distance between the beams decreases from the ends to the midspan of the long beams

Another option could be to use constant spacing between the beams and vary their sections, increasing the section from the support of the long beams towards their midspan.

In the case of the gymnasium in Losone, the designers chose to have constant sections and spacing (figure 2.49).

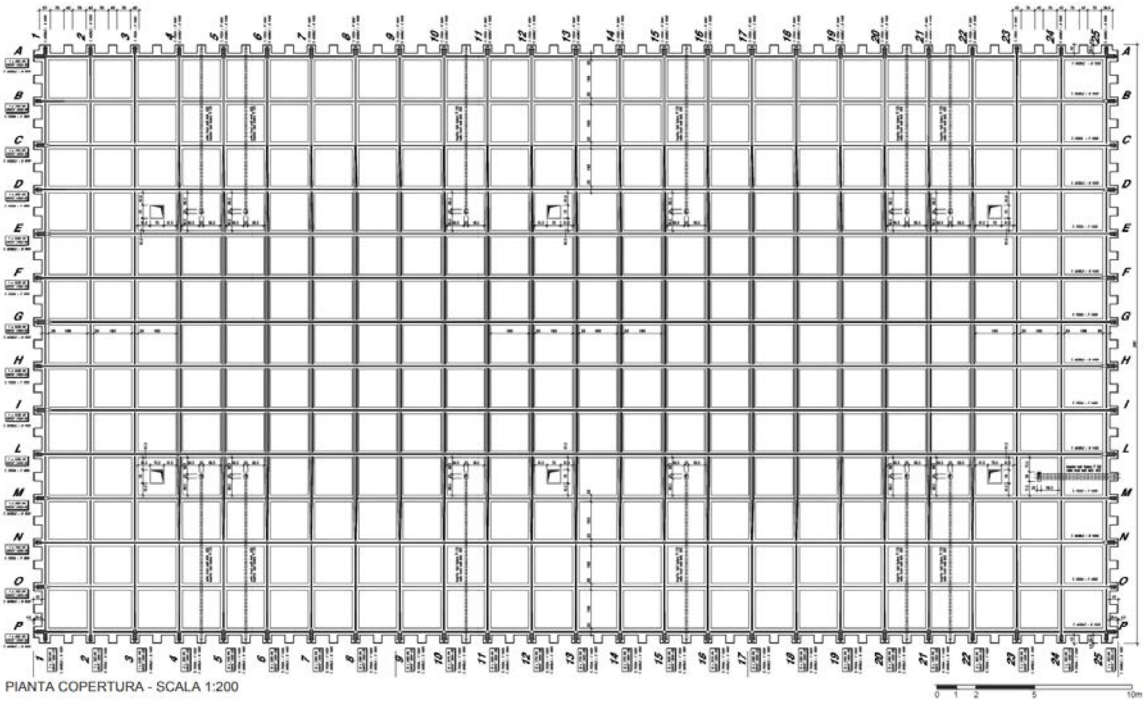


Figure 2.49. Structural plan of the roof of the gymnasium in Losone. (Drawing by Andreotti & Partners, Locarno)

Both characteristics are connected to each other. In fact, greater spacing, means that each beam has a larger share of the load, larger stresses, and consequently larger sections. Normally the height of a roof is a parameter that is more binding than the spacing between the beams. The designers of the gym probably set the maximum acceptable height of the beams and obtained the necessary spacing based on that height. The section of the beams is shown in figure 2.50.

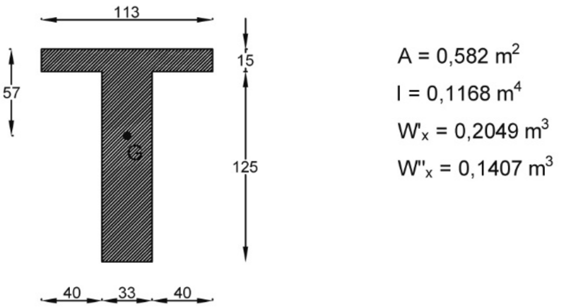


Figure 2.50. Gymnasium in Losone. Section of the beams

Part of the15 cm closing slab at the top of the beams was considered as part of the section.

The roof is made of C40/50 concrete, the strength of which is equal to f_{cd} = 26.67 N/mm^2. The resisting moment of the beam is therefore equal to:

$$M_{Rd} = 0{,}2059m^3 \cdot 26{,}67 \cdot 10^3 \frac{kN}{m^2} = 5464{,}7kNm$$

which corresponds to a load on the beam equal to

$$q_d = 48{,}57\ kN/m$$

The self-weight of the beam at ULS is equal to

$$q_{beam,d} = 1{,}25m \cdot 0{,}33m \cdot 25 \frac{kN}{m^3} \cdot 1{,}5 = 15{,}47 \frac{kN}{m}$$

Consequently, the load on the beam coming from the roof must be equal to

$$q_{slab,d} = 48{,}57 \frac{kN}{m} - 15{,}47 \frac{kN}{m} = 33{,}1 \frac{kN}{m}$$

Considering a load on the roof at the ULS of 12 kN/m^2, including the weight of the concrete slab, gravel filling, waterproofing, utility installations, any equipment hanging from the roof, and snow, the influence length of each beam, which also corresponds to the distance between the beams, would be equal to

$$\frac{33{,}1\, kN/m}{12\, kN/m^2} = 2{,}76m$$

The distance between the beams in the built project is equal to 2.26 m, smaller than the previously calculated distance, and therefore a distance that corresponds to a bending moment that is lower than the resisting moment of the section.

The analysis of the gymnasium in Losone has allowed us to show the parameters on which the structural choices for section resistant structures depend, and the criteria for conceiving these types of structures. First of all, we saw that the main limitation of this structural typology is weight, and this leads to a rather reduced range of use, with spans of up to about 30 m. We then saw that, it is possible to transfer of the load in both directions to limit the stresses, and we saw the criteria that make it possible to establish the subdivision of the loads in both directions of transfer: by setting the equality of the moments or of the deformations. Finally, we saw the criteria needed to size the section of the beams and their distance which, as in the case of shape resistant structures and vector resistant structures are still, as in span, loads, resistance, and stiffness. By mastering the use of these criteria, it is possible to conceive a section resistant structure and, since these criteria provide more structural choices, the structural conception of these structures becomes a creative process.

At the end of this chapter, the next section presents other non-structural criteria that limit and guide structural choices and favor creative design. Geographical location, political choices, local traditions and, in general, the contexts into which a structure is placed, can favor a material or a structural or constructive typology. We will see how context can influence structural conception and how context can be seen as a tool for forming structural intuition.

2.4. Context as a tool for the creation of structural intuition

Every building needs to respond to the spatial, functional, climatic, and aesthetic needs defined by its architectural project. Its structural needs are defined by the loads, resistance, and stiffness of the materials, as well as its shape and structural typology. In addition, every building is created within specific geographical, economic, and political contexts. If we want to build a timber building, the material must be available locally to avoid excessive transport costs. Advanced technical design and construction skills are needed to build extremely tall skyscrapers or incredibly long suspension bridges. The results of innovative research and the support from local authorities are needed for projects that use innovative materials. All of these factors show that context is a constraint that both architects and engineers have to deal with. And, like all the other structural constraints that we have seen in the previous sections, this too encourages and develops design creativity, including structural creativity. In fact, as a constraint, context limits design options, but, at the same time, it guides them. Once all the constraints imposed by a certain context have been overcome, multiple design options remain. Therefore, design creativity comes into play. Furthermore, context, unlike structural requirements, is not a fixed constraint, in fact context can be changed. For example, if city authorities want to prevent the construction of tall buildings, simply introducing a law limiting their maximum height is enough. In order to encourage the use of a specific material, incentives can be introduced for buildings that use it. These political interventions have immediate repercussions and should be part of a strategic development plan. However, it is sometimes possible to encourage the use of a material or a structural or constructive typology without political intervention, simply by creating awareness and enhancing some local characteristics. This section will present the results of a piece of research on this subject (Miccoli and Frangi, 2021), to exemplify how context can influence design choices, and how it must be taken into consideration for the formation of structural intuition. Specifically, we will see how the enhancement of the local tradition of timber buildings in the canton of Ticino, the Italian-speaking Swiss region south of the Alps, can encourage the diffusion of timber buildings in this region.

2.4.1. Timber constructions in Switzerland

Since 2005, and even more significantly since 2015, there has been a major increase in the number of timber constructions in Switzerland. This growth is mainly due to two factors:

- The new fire prevention regulations (AICCA 2005 and AICAA 2015) favour timber more than the previous regulations did. They have made the construction of multi-storey timber buildings possible, which the previous regulations did not permit.
- The sustainability of this natural material that can store CO_2 means that CO_2 emissions from the construction process can be reduced to a level that is lower than that of other materials, in particular concrete and steel. This is one of the main objectives of the "2000 Watt Society" (2000 Watt society), the climate and energy policy, signed by Switzerland in 2019, which aims to reduce energy consumption per inhabitant to 2000 W, to reduce greenhouse gas emissions from energy consumption to zero, and to use only renewable energy by 2050.

The increase in the number of timber constructions has been mainly concentrated in the Swiss regions north of the Alps (Selberherr J., 2017) and has mainly involved large projects in urban centres. This increase has been concentrated in these regions because of economic reasons; it has, in fact, been proved that the advantage of using timber is more marked in regions where rent is higher (Selberherr J., 2016). This concentration is also because the advantages in terms of environmental sustainability (reduction of grey energy and of greenhouse gas emissions), construction site planning, and cost control are more evident in large projects, especially when they are managed with the BIM procedure (Kunz M., 2019). As the rent in the southern regions of Switzerland is lower than those of the northern regions, and as the projects are generally smaller, the increase in the number of timber constructions has been smaller. Another aspect that has meant a lower level of growth in timber constructions south of the Alps is the lack of professionals with specific training for timber and companies specialized in timber construction in this area.

Therefore, we wondered how it would be possible to encourage the use of timber in a small, peripheral region that is dominated by small-scale projects and by private clients, such as southern Switzerland. Firstly, the reasons for the spread of materials in a specific geographical area was explored and compared to the situation in the region we are analyzing (§ 2.4.2). Then, some recent timber projects in this area were analyzed with the aim of identifying the unique features of the region regarding the use of this material (§ 2.4.3). The highlighted features are: i) a strong reference to traditional constructions and ii) a personal interpretation of the material by the designers, who use wood to convey a personal message. However, iii) a lack of full awareness of the potential of this material exists. Regarding this last point, various initiatives have already been activated to increase knowledge on the material at a university level (USI and SUPSI), at a level of continuous professional development (CPD), and at an informative level (specialized journals). These initiatives are presented and analyzed here (§ 2.4.2). Then, methods to make the most of the local features highlighted to encourage the spread of timber constructions were evaluated. Finally, the opportunities for applying the considerations made for the Swiss regions south of the Alps to other peripheral regions were evaluated (§ 2.4.4).

2.4.2. Reasons for the spread of timber constructions

There are three main aspects that favor the spread of materials: i) territorial availability; ii) political support, and iii) knowledge of the material and availability of trained and specialized professionals. In the following sections, the Swiss situation concerning the use of wood is analyzed by considering these three aspects.

2.4.2.1. Availability of the material

Forest resources in Switzerland are managed by the Federal Office for the Environment (FOEN), which is responsible for ensuring the sustainable use of natural resources in Switzerland, including forests. Every year, the FOEN publishes a brochure that provides information, with statistical data, on forest resources and, in particular, on how wood from Swiss forests is used (OFEV, 2019).

Forests cover 31% of the Swiss territory, with percentages that vary according to each area. In the region we are considering, this percentage reaches 50% (figure 2.51). Around 10 million cubic meters of wood grows in Switzerland every year and around 5 of these are harvested, of which 25% is used for energy production. The annual wood consumption in Switzerland is around 10.5 million cubic meters, a demand which could therefore be met almost entirely by timber from Swiss forests. The main softwood species present in the area are spruce (37%), silver fir (11%) and larch (5%). However, in the southern alpine region, over 20% of the timber is chestnut (hardwood), so experimental studies have been carried out on the use of chestnut wood in the construction field (Bernasconi, 2019). This use of a local resource further encourages the spread of timber usage in this region.

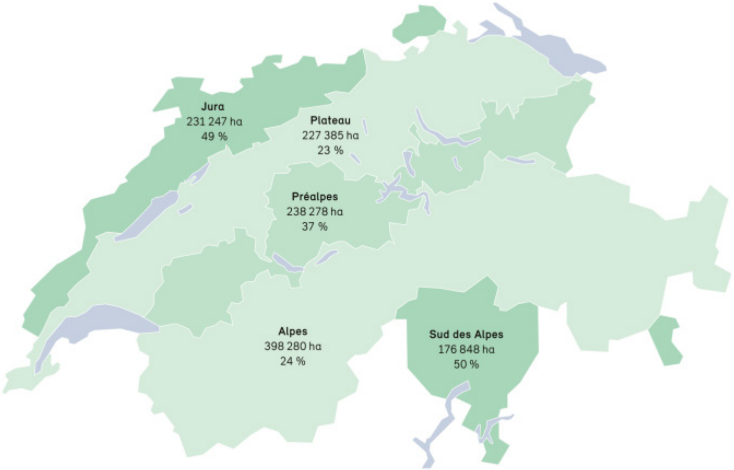


Figure 2.51. Distribution of forests in Switzerland. (Source OFEV, 2019)

2.4.2.2. Political support

The regulations on the limitations of the use of a material indicate whether its use is supported politically or not. The main problem with wood, or rather, the factor that has led to its almost total disappearance in favor of other materials, is the fact that it is a combustible material. Until 2004, the fire regulations in Switzerland limited the height of timber buildings to 2 storeys, with an exception for the areas with a tradition of timber construction, where the limit was moved to 4 stories, but with concrete staircase cores (AICAA 1993). In 2001, the organization Lignum - Swiss Wood Economy, and the FOEN, launched the "Brandsicherheit und Holzbau" project (fire safety and timber construction), to study and prove the safety of timber buildings against fire and, therefore, to allow it to be used in the construction of multi-storey buildings (DATEC, 1993). The project led to the modification of the fire regulations (AICAA 2005, 2015).

Today it is possible to build timber buildings up to 100 m high in Switzerland with timber staircases (provided that they are encapsulated with non-combustible material). First, the 2005 fire regulations opened up the field of medium-rise buildings to timber. The 2015 regulations eliminated any restrictions on the use of timber as a building material, even allowing the construction of tall buildings using timber.

2.4.2.3. Training of specialized professionals

Switzerland is one of the most pioneering countries in the field of scientific research on timber construction. The main educational and research centres on wood as a building material are the Bern University of Applied Sciences in Bienne (BFH) and the two Federal Polytechnics of Zurich and Lausanne. BFH brings together the faculties of Architecture, Civil Engineering, and Wood Engineering in one department. It offers a master’s course, which is one of a kind in Europe, on "Wood Technology", in which students are directly involved in innovative research projects that have a practical and industry-oriented focus; a niche area that is not extensively developed by the two Polytechnics (BFH Research projects). The chair of timber structures at ETH Zurich carries out research in the field of structural timber engineering through the development of projects that are currently divided into three thematic areas: fire safety of timber structures; basic research on glulam, cross-laminated timber (CLT), and connections; applied research through the development of new technologies in cooperation with industry. Some examples of the types of current projects are the research on the use of beech wood, which is widespread in the forests of central Europe; the development of novel timber slabs, and research into the robustness of tall timber buildings (ETH Zurich, Institute of Structural Engineering, Timber structures research). The iBois wood construction laboratory at EPF Lausanne, led by Prof. Yves Weinand, an engineer and architect, carries out research in the field of shell structures, digital design, and the use of new wood products (EPFL Lausanne, Ibois Laboratory, Research). The EMPA (Swiss Federal Laboratories for Materials Science and Technology) in Dübendorf also carries out research in the field of timber construction in the CWMI (Cellulose and Wood Materials Laboratory) and as part of the NEST project (EMPA, CMWI, Cellulose and Wood Materials Laboratory; NEST, exploring the future of Buildings). For all this research to have a practical application, including the regions south of the Alps, it is necessary for the results to be disseminated to reach all the actors involved in the construction sector. This dissemination work has been taking place for several years in southern Switzerland on different fronts. At a university level, the two schools for architects and engineers are the Mendrisio Academy of Architecture, part of the University of Italian Switzerland (USI), and the University of Applied Sciences of Southern Switzerland (SUPSI). In addition to leading the chair of timber structures at ETH Zurich, Professor Andrea Frangi teaches "timber structures" at the Mendrisio Academy of Architecture. He is therefore a direct link to the most recent knowledge on the material, derived from the research carried out at ETH Zurich, to future architects who are being trained south of the Alps. The course has been running since 2008 and receives excellent feedback from students. Each year there are about 90/100 students enrolled, in a school of about 700 students in total, and timber is given the same space as other building materials (2.5 ECTS - European Credit Transfer and Accumulation System, each academic year for concrete, steel, and timber construction courses). During the course, students are asked to analyze an existing building with a timber structure from an architectural and structural perspective and to create a scale model of the structure of the building (see section 3 and Miccoli et al. 2021c).

As for the SUPSI, the course on timber structures is given by Prof. Andrea Bernasconi, one of the leading experts in Switzerland in the field of timber constructions. Prof. Bernasconi is active professionally as co-owner of the Borlini & Zanini SA design office in Lugano, which has designed numerous timber building projects, including the Nordic Ski Center in Campra, presented in this chapter, and the residential project “Via Cenni” in Milan, which was the largest European construction site for timber structures in 2012; and at a university level, as a lecturer on timber structures at the University of Applied Sciences in Lugano and Yverdon-Les-Bains. In his article "Il legno nell’edilizia: si inizia dalla formazione" (Timber in construction: everything starts with training) (Bernasconi, 2019) he highlights how “timber construction is still often perceived as suitable only for small buildings, to be entrusted to the expert hands of a specialized craftsman, while buildings which are outside the "artisanal" category need all the design skills of the architect and all the technical skills of the structural engineer”. The SUPSI's civil engineering program requires all students to receive basic training in timber construction, as well as additional training for those taking the "building" option. Students can also choose to further explore the topic in their bachelor's theses.

Prof. Bernasconi also deals with the dissemination of information and training for professionals in order to fill the gaps for those who were trained before timber became a university subject and to make knowledge on a relatively new material accessible. The techniques and technologies for timber constructions have been developed over the last 40 years. Responding to the need to promote this material, every other year since 2015, the "Information and study days in Ticino" on timber constructions have taken place, in collaboration with different organizations: S-Win (Swiss Wood Innovation Network), Lignum (Timber Industry in Switzerland) and Federlegno. These events bring together various wood associations in southern Switzerland. During these days, aimed at architects, engineers and builders, the latest results of research in the field of timber and some recent projects that have been carried out in the region are presented (Bernasconi 2017, 2019).

2.4.3. Timber structures in Southern Switzerland

Even if the growth of timber constructions in this area is far smaller than that of cities like Zurich, there are still many timber buildings in southern Switzerland. For example, consulting the projects of reference from the main companies working in the timber construction sector (Laube SA, Veragouth + Xilema, Gandelli Suisse, Renggli), it is immediately obvious that timber constructions are widespread in southern Switzerland, but most of the examples are single-family houses, 2-3 story buildings, and roofs. The technical journal “Bulletin Bois”, published by Lignum, has dedicated two issues to timber constructions in the southern canton of Ticino (Bulletin bois, 2006(81), 2015(114)), but the projects presented in these issues are mostly small buildings. In the issue of “Archi” (the Swiss journal of engineering, architecture, and urban planning) on the topic "Building in timber south of the Alps" the curators, Stefano Zerbi and Stefano Miccoli, have discussed what the unique features of timber architecture in this region are. They have identified two main characteristics: i) tradition and ii) the personal interpretation of the material by individual architects (Miccoli, 2019; Zerbi 2019). Regarding tradition, in addition to the traditional massive use of timber constructions that is typical in the whole Alpine area, the architect Stefano Zerbi has identified an architectural current that is typical of the region which has made extensive use of wood: the Ticino architecture from the organic period, developed in the 1950s and 60s by various architects including Franco Ponti, Tita Carloni, and Giampiero Mina. This movement was inspired by international models, in particular Frank Lloyd Wright, and it interpreted these models according to the local context, by using, in particular, a critical reinterpretation of the construction tradition from the north of the region. An example of this movement is Giampiero Mina's Cinema-Theatre in Blenio (figure 2.52) (Graf, Buzzi-Huppert, 2017).

Figure 2.52. Cinema–theatre in Blenio, arch. Giampiero Mina, 1956-1958, Blenio

2.4.3.1. Methods for promoting timber

The two characteristics identified can be seen in the two projects presented here, which have recently been built in southern Switzerland: the Nordic Ski Centre in Campra, designed by the architects Durisch & Nolli in collaboration with Prof. Andrea Bernasconi (figure 2.53), and the house in Ludiano designed by the architects Tocchetti and Pessina (figure 2.54). The first example shows how the knowledge and technical skills of a structural engineer, and therefore the access to the most modern construction techniques and technologies, can lead to the best type of development of an architectural idea, which expands the range of design possibilities for architects. However, the second project shows how timber can be used to create a building that reflects tradition, while also exploiting the structural possibilities of “modern” wood.

Figure 2.53. Nordic Ski Centre in Campra, arch. Durisch & Nolli, 2019 (Photo by Durisch & Nolli)

Figure 2.54. House in Ludiano, arch. Tocchetti and Pessina, 2018. (Photo by Tocchetti and Pessina)

2.4.3.1.1. The Nordic Ski Centre in Campra

The structure of the building underwent a major change during the design phase. In the preliminary phase, a more traditional solution using timber trusses, which matched the skillset of a greater number of local carpenters, was chosen. The executive phase of the structural design of the timber parts was given to the structural engineer Andrea Bernasconi, who replaced the trusses with a CLT multilayer panel structure for both the walls and the floors, a solution that required the involvement of Austrian companies, as there were no local companies that were able to supply the necessary quantity of material. The CLT walls of the second and third floors exploit the supports of the walls and columns of the first floor to create an overhang on both sides of the building (fig. 2.55).

Figure 2.55. Overhanging CLT walls (Photo by Andrea Bernasconi)

At the support points, where the maximum concentrations of stresses are found, elements in beech laminated veneer were inserted (figure 2.56) both to guarantee resistance and to contain deformations, a choice that made it possible to avoid using any steel elements. The CLT walls allow the floors to be supported and to be hung, and the same walls are also used for the staircases, encapsulated on six sides for fire safety reasons. In the CLT panels that are used for the roof of the building, which remain exposed to the elements, the outermost layer is made of larch wood instead of spruce/fir wood, to ensure greater durability.

Figure 2.56. Beech laminated veneer inserts (Photo by Andrea Bernasconi)

2.4.3.1.2. The House in Ludiano

The main vertical load bearing structure consists of four C-shaped reinforced concrete elements, where the service areas of the house, and the central chimney, which is also made of reinforced concrete, are located (figure 2.57). The concrete elements, aided inside the house by two timber columns, the external light timber frame walls, and five steel beams support six glulam beams made of larch with cross sections of 200x400 mm (central) and 160x320 mm (lateral), which are longitudinal (figure 2.58).

Figure 2.57. Supporting RC elements (Photo by Tocchetti and Pessina)

Larch was chosen for its durability (some beams remain exposed) and for uniformity, matching the internal and external finishes Six longitudinal beams support the structural elements of the roof: straight solid timber beams made of class C24 spruce (not visible) with a cross section of 100x180 mm in the central part; lateral triangular trusses, the shape of which is more architectural than structural, and double beams in solid timber made of larch with a cross-section of 100x160 mm (figure 9). The connection between the steel beams and the internal longitudinal beams of the house is hidden in order to give the impression that the longitudinal beam that crosses the living area does not have intermediate supports. This is a solution that solves the structural problem of support, while allowing the creation of the desired architectural space. The house in Ludiano by Tocchetti and Pessina is a particularly successful example of harmony between architectural choices and structural choices. In fact, the structure cannot be discussed without mentioning the architectural ideas.

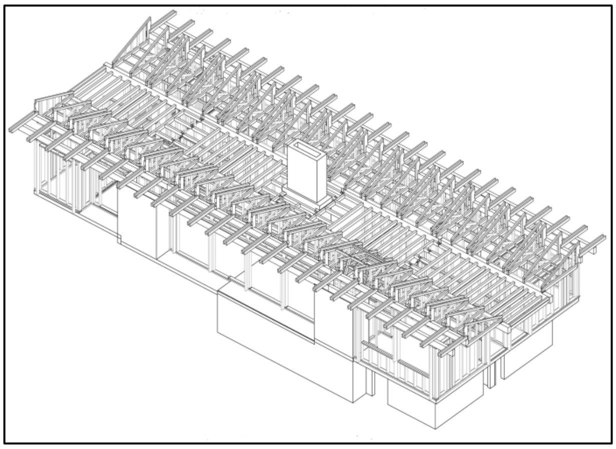


Figure 2.58. Axonometry of the structure (Drawing by Tocchetti and Pessina)

2.4.4. Conclusions

Numerous initiatives are underway in southern Switzerland to encourage the diffusion of timber constructions: the training of future professionals (architects and engineers) at the University of Italian Switzerland and the University of Applied Sciences; awareness raising and training for professionals working in the construction field, through the organization of “timber construction days” by the S-Win organization and other associations related to timber; the commitment of experts to the dissemination of knowledge on the material at a local level (in particular Andrea Bernasconi and Andrea Frangi); the identification of the unique local features of timber constructions (remembering tradition, architects’ personal interpretation of the material) to encourage regional timber architecture movement; awareness raising through the discussion of the topic in local journals (i.e. "Archi" journal) and national ones (i.e. “Bulletin Bois”); the publication of technical documentation in Italian, despite it being a minority language in Switzerland, to make knowledge on the material accessible in this area (Lignum, Città in Legno); the identification of the unique characteristics of the local forest, in particular the major presence of chestnut trees (20%) and the setting up of a research project on the opportunities of using the wood from this tree in construction; and finally, the involvement of local companies. These initiatives can also be applied to other regions, as they mainly consist of identifying unique local features and using these to encourage the development of timber buildings. The Italian situation, for example, is completely different in terms of geography and the availability of raw materials, as well as the fact that the peripheral and minority areas are less obvious to identify. However, it is possible to identify the north-east as an area where the growth of timber buildings has been more widespread, in particular the region of Trentino Alto Adige. This area can be compared to northern Switzerland, and other regions with many unique features that could be used to encourage local growth, which are similar to southern Switzerland. But it is perhaps at a European level that the Swiss model could find a more obvious application. If nations such as Austria, Germany, Italy (in particular the northern area), and the Scandinavian nations are compared to central Switzerland and the minority countries of the European community (Romania, the Baltic countries, and the Balkan countries) are compared to southern Switzerland, we can see that the initiatives that are underway in southern Switzerland could be implemented to encourage the development of timber constructions on a larger scale.

3. CONCEPTUAL DESIGN OF STRUCTURES: TRAINING FOR BOTH ARCHITECTS AND ENGINEERS

The purpose of formalizing structural intuition is to convert it into a design tool that architects and engineers can use to design structures creatively. Formalization takes place by showing the parameters on which structural choices depend in such a way that these choices can be used in a considered manner. This ensures that the structural creativity is not only the result of the talent or personal experience of one designer, but that it is something that can be communicated and taught. This is the direct consequence of the formalization of structural intuition, once formalized, it is something that can be taught. And, given that, as we have seen, structural conception, i.e. the creative part of structural design, can be the meeting point between architects and engineers, so training architects and engineers in structural conception can be the first moment in which these two professional figures get to know each other’s work and begin to collaborate.

In this chapter we present a research project carried out at the Mendrisio Academy of Architecture, part of the Università della Svizzera italiana, which has been taking place since the 2014/2015 academic year, on the teaching of structural design to students of architecture, which involves the courses on concrete structures, steel structures, and timber structures. The results of a survey on the perception of the relationship between engineers and architects and on the structural issues that interest architects will also be presented. The results of this survey were used to set up the teaching experiments of the research project (Miccoli et al., 2021c).

3.1. Introduction to the research project

Some new teaching experiments on the teaching of structural design at the Mendrisio Academy of Architecture have been taking place since 2014. The experiments have involved the courses "Timber structures" (prof. A. Frangi, ETH, Zurich), “Steel structures" (Dr. A. Bassetti, Lüchinger+Meyer, Zurich), and "Reinforced concrete Structures" (Dr. R. Guidotti, Pedrazzini Guidotti sagl, Lugano).

The teaching approach used before the experiments were carried out was mostly traditional: the study of the physical and mechanical properties of building materials, structural analysis and design of common structural elements, and a final written exam consisting of the design of a simple structure. This approach led to a lack of interest and participation from the students and unsatisfactory exam results.

Two questionnaires, one for students and one for professional architects, were prepared, using a piece of research on the structural engineer-architect collaboration carried out in New Zealand in 2009 (Charleson and Pitie, 2009), to investigate the reasons for this lack of interest and to understand how to improve and adapt the courses to the interests and needs of future architects. The results of the questionnaires highlighted some problems in understanding the language used by engineers, which is mainly analytical, and the usefulness of the course topics in the architectural field.

The planning of the three courses, and the corresponding exams, has since been changed, and three different approaches, which are presented in the following sections, have been experimented with. These approaches all involve an assignment to be worked on over the semester in groups of 3/4 students.

The experiments had an extremely positive outcome and helped to increase the awareness of the role of structure in the creation of architecture, and the importance of good collaboration between architects and engineers. The statistics of the exam results before and after the experiments, the results of the questionnaires, the course curricula, and the work produced - drawings, models, and photographs, by some students will be presented.

3.2. Structural design courses at the Mendrisio Academy of Architecture

The organization of the courses on structures on the Bachelor’ degree in Architecture at the Mendrisio Academy of Architecture is shown in Table 3.1.

Table 3.1: Courses about structures in the BSc at the Academy of Architecture, Mendrisio

Semester	Name of the course	ECTS
1	Introduction to load-bearing structures	7.5
2		
3		
4	Reinforced concrete structures	2.5
5	Timber structures	2.5
6	Steel structures	2.5

After three introductory semesters in which the students are taught the basics of load-bearing structures, semesters 4, 5, and 6 are devoted to structural design, applied to reinforced concrete structures, timber structures, and steel structures. From 2007 to

2014, the teaching of these three courses consisted of lectures on the physical and mechanical properties of materials and structural analysis and design of the common structural elements, practical exercises about the solution of some academic examples, and a final written exam with theoretical questions and some exercises on the design of a simple structure. Figure 3.1 shows the structure of the final exam of the "Reinforced concrete structures" course given in August 2015 and some of the questions asked in the exam are shown here:

- Determine the load combinations on the slab for the verification of ULS and SLS.
- Calculate the force acting in the tie rods at the SLS and ULS.
- Calculate the minimum pre-stressing force needed so that the tie rod does not crack at SLS.
- Determine the minimum pre-stressing reinforcement necessary so that the tie rod does not crack at SLS.
- Draw a truss model inside the beam with compressed struts inclined at an angle between 30° and 45°.
- Verify that the area of concrete provided for the top chord in the truss model can bear the maximum compression.

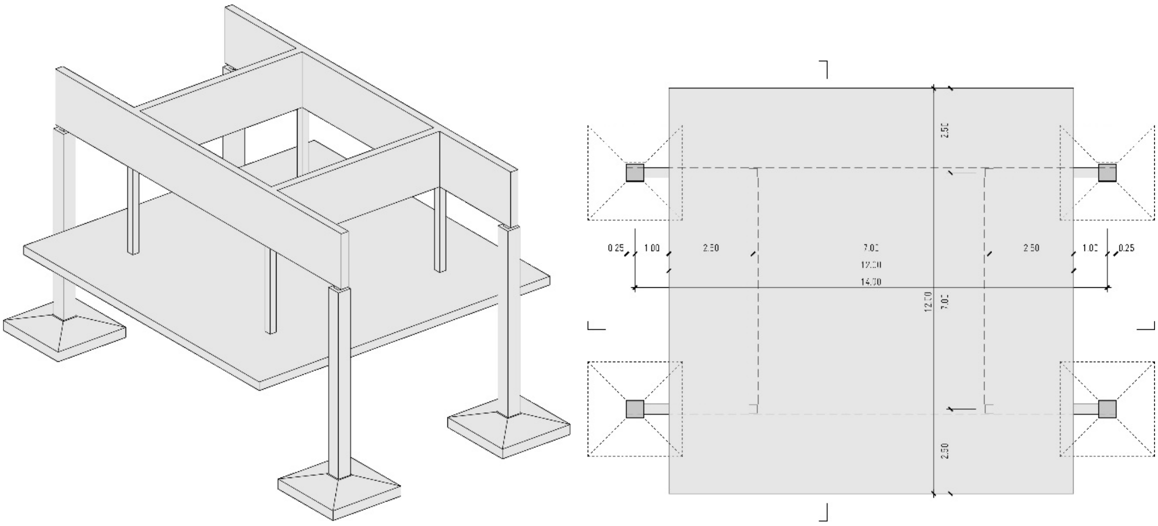


Figure 3.1: Structure for the final exam of "reinforced concrete structures", August 2015

We measured a lack of interest and participation from the students, by tracking student attendance and analyzing the comments given by the students in the course evaluations. The plot in Figure 3.2 shows, as an example, student attendance for the "Timber Structures" course during the first semester of the academic year 2012/2013.

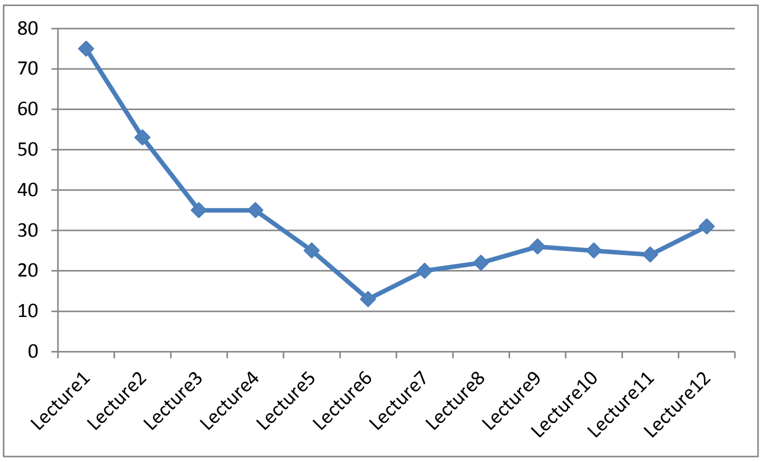


Figure 3.2: Number of students per lecture, Timber structure a.y. 2012/2013

Even though the number of students who took the final exam was 81, the number for class attendance was reasonably high only during the first class (75 students), then it continuously decreased during the semester, reaching the minimum number (13 students) during the sixth class (in this week the students had the mid-term review of their architectural design lab work), and it stabilized at about 20/25 students per lesson from week seven onwards. The comments given by the students were varied, but the following opinions can be taken as being representative of how they felt: “the exam was too long”, “too much work for only 2.5 ECTS”, “too theoretical”, “too much attention to specific norms and calculation that do not seem relevant to architects instead of more basic procedures that could be used in design”.

In order to investigate the reasons for this lack of interest and to understand how to improve and adapt the courses to the interests and needs of future architects, two questionnaires were prepared and given to students and professional architects. The results are presented in the following section.

3.3. Questionnaires for students and professional architects

The questionnaires, one for students and another for professional architects, had two objectives. The first was to investigate the relationship between architects and structural engineers, both in professional practice and how the importance of this relationship is perceived by students of architecture. The second was to identify which structural engineering topics are considered useful and important by both professional architects and by students, to get suggestions about how to improve the teaching of structural design to students of architecture. The two questionnaires share the same questions about the relationship with structural engineers (see Table 3.2) and about the interests and knowledge in the field of structural engineering (see Table 3.3), so the results can be analyzed together. Other questions were tailored to the different characteristics of the participants and were used to investigate their academic/professional status and the main professional activities being performed. Some questions were left open for comments, about the education received in the field of structural design and about the architect-engineer relationship and how to improve it.

120 participants took part in the survey, 80 students and 40 professional architects, all belonging to the Mendrisio Academy of Architecture. All the students, studying in the 3rd year of the Bachelor's degree or on the Master's degree at the time of the survey, have had at least one year of professional experience, in many different countries, which is a requirement of the curricula. This means that, even though it may only have been for a short period, they all have experienced a work environment.

The professional architects were professors, lecturers, and teaching assistants, with professional experience ranging from 1 to 33 years, and they were from different backgrounds and had worked in different countries. Table 2 and Table 3 show the results of the questionnaires from the two main sections. The analysis of the results in Table 3.2 leads to the conclusion that, generally their relationship with structural engineers is good and their contribution to the architectural projects is highly valued. Structures are considered to be an essential part of architecture and the answers show that there is a desire for a better understanding of structures, that there is a general lack of education in this field, and it is believed that the earlier they collaborate with engineers, the better the projects will be.

The results in Table 3.3 are more difficult to analyze. First the number of “I don't know” answers indicates that some of the questions were difficult to understand and, thus, the participants were not aware of some, if not many, of the structural engineering topics mentioned. Furthermore, in many cases, the range of the grades is not concentrated around the average. This is another sign that a shared opinion on the subjects does not exist and, probably, that the questions might not have been fully understood.

Table 3.2: Questions about the relationship with structural engineers. Scale 1 (not at all true) to 6 (definitely true)

QUESTIONS	VOTE
My collaboration with structural engineers is good	4.4
Structural engineers propose structural solutions in keeping with my design	4.6
Structural engineers generally appreciate the architectural requirements of	4.4
Structural engineers communicate structural requirements clearly	4.5
The most critical contribution of structural engineers to a design should be during the preliminary design phase, before the finalization of the architectural	4.9
Structure has an important role in architectural conception	5.3
I might consider reviewing my architectural choices in favor of a more efficient structural configuration	4.4
Structural conception is a task only for a structural engineer	2.0
In order to be able to conceive a structure, it is necessary to have good structural "creativity" in addition to specific technical knowledge	4.8
Structural "creativity" is innate and cannot be taught	1.8
Structural engineering is basically a technical profession and does not require	1.9
My personal knowledge allows me to set up the structural layouts of the	3.7
Better collaboration between architects and structural engineers would lead to	5.4

Table 3: Questions about the interests and knowledge in the field of structural engineering. Scale 1 (not at all true) to 6 (definitely true)

QUESTIONS	VOTE	I.D.K.
Vector representation of forces and equilibrium of forces in a 2D plan	4.1	6
Classification of structural typologies and their limitations of use	4.8	4
Loads on structures: types, entity, and effects on constructions	4.8	2
Representation of the static scheme of a structure (geometry, loads, and constraints) and identification of the degrees of freedom	3.9	6
Definition of forces, moments, stress, and strain	4.0	3
Internal actions in structures: tension, compression, shear, and	4.4	2
The funicular polygon and the force polygon: calculation of internal actions in funicular systems	3.4	13
Solution of statically-determinate schemes: calculation of the internal actions using equilibrium equations	3.2	13
The theory of elasticity, the Hooke law and the Young modulus: the elastic bond between stress and strain	3.2	21
Solution for redundant structural schemes: calculation of internal actions using equilibrium, compatibility, and constitutive equations.	3.0	23
The theory of plates and shells	3.2	26
Setting up of simplified models for the evaluation of internal actions	4.1	10
Physical and mechanical characteristics of construction materials	5.2	2
Area, moment of inertia, and resistance modulus: geometric	3.6	10
Sizing of structural members depending on the internal actions and mechanical properties of materials	4.3	3
Detailed structural design (reinforcement in reinforced concrete structures, connections in steel and timber structures, etc.)	4.1	9

Link between form and structural efficiency: finding the optimal	4.7	3
Computer aided structural design: the finite element method	3.2	27
Plastic analysis of structures: stress redistribution and detection of possible collapse mechanisms	3.3	18
The instability of structures: buckling of structural members	3.8	17
Dynamics of structures (behavior under dynamic loads)	3.7	18
Structural construction details and construction techniques	5.0	3
History of construction and of the theory of structures: historical evolution of structural layouts in constructions and anticipation of	4.3	3

However, considering the topics that received a mark higher than 4.5/6, it is clear that architects are interested in having some tools for setting up good structural layouts and for constructively communicating with engineers, without having to be involved in all the details and calculations.

It is also interesting to analyze the answers to one of the open questions, which requires mentioning the names of some structural engineers that made meaningful contributions to the field of architecture. The most frequently mentioned names are: Pier Luigi Nervi, Eduardo Torroja, Riccardo Morandi, Santiago Calatrava, Robert Maillart, Christian Menn, August Komendant, Peter Rice, Jürg Conzett. These engineers have a lot of things in common: some of them belong to the Italian school of engineering of the 20th century, and others to the Swiss school that began with Karl Culmann and is still connected with the ETH, Zurich. But the characteristic that unites them all is their devotion to conceptual design, which can be the meeting point between architecture and engineering and, therefore, should be the main subject of the structural design courses for architects. Another interesting open question required the participants to evaluate the education that they had received in the field of structural engineering. Even though a few participants were happy with their experiences, many highlighted a lack of education in this area with comments like: “not enough for the professional practice, too specific and not connected with practical application, based on static calculation rather than on the understanding of structural concepts”.

These questionnaires have been extremely useful for understanding how to improve the structural design courses at the Mendrisio Academy of Architecture and all the results have been considered. A review of the courses is presented in the next section.

3.4. Teaching experiments at the Mendrisio Academy of Architecture

When planning the teaching experiments for improving the teaching of structural design at the Mendrisio Academy of Architecture, not only have the results of the questionnaires presented in the previous section been taken into account, but also some issues about the most familiar ways in which students learn. Each semester at the Academy of Architecture is divided into 2 main activities: 15 ECTS are in the design laboratory and 15 ECTS to theoretical courses (each course is 2.5 ECTS) – 7.5 ECTS to historic-humanistic courses, and 7.5 ECTS to technical-scientific courses. So, most of the time, students are busy with their laboratory projects. The laboratory work is mainly practical, the search projects of reference is an important task, and students are often required to work in groups. These characteristics of the way in which students normally work have been integrated into the teaching experiments applied to the courses "Reinforced concrete structures" (dr. Roberto Guidotti), "Timber structures" (prof. Andrea Frangi), and "Steel structures" (dr. Andrea Bassetti) which have been taught since 2014. Three different approaches have been tested, all involving an assignment to be carried out during the semester in groups of 3/4 students:

- Analysis of an existing building focusing on the role of structure, through the construction of a scale model (course "Timber structures" from the academic year. 2014/15 to 2019/20 and "Steel structures" from the academic year 2015/16 and 2016/17). In 2016/17 this experiment for the "Steel structures" course were carried out in collaboration with the architecture studio Lacaton & Vassal, Paris;
- Design of a structure that responds to a precise architectural requirement, focusing on the conception and preliminary design of the structural members and joints ("Steel structures" course, academic year. 2017/18);
- Analysis of a building that exemplifies a selected topic (i.e. "cover a square") and the creation of a scale model to show, with a photograph, how the structure can create the architectural space ("Reinforced concrete structures" course, academic years 2017/18 and 2018/19).

The students were guided in their work throughout the semester and two mid-term reviews with the teaching assistant were planned. A detailed description of the revised programs and the setting of the experimental courses is given in the following sub-sections. Some of the work done by the students is also presented to show the outcomes of the experiments.

3.4.1. Analysis of an existing building and construction of a scale model

The first experiment involved the courses “Timber structures” and “Steel structures” and consisted of the analysis of the structure of an existing building chosen by each group of students, who focused on the following topics:

- Architectural description of the building, focusing on the aspects that constitute the starting point for the definition of the structural layout, such as: function of the building and its needs in terms of spaces resulting from this function, geographic location (this could exclude some materials or some structural typologies), construction period, and budget;
- Reasons for the choice of the material. The choice of the building material is a compromise between architectural needs, structural needs, and costs. The weight that each these three needs carried was required in the projects analyzed;
- Detailed description of the structure. The purpose of this part was to recognize, name, and describe all the structural types and the elements that they are composed of. These elements constitute the bearing structure of the building;
- Force flow and statics. The purpose of this part was to understand and explain how the structure works and how to model it by using structural schemes.
- Load analysis;
- Verification of the dimensions of the structural elements, using graphic and/or analytic methods to evaluate the forces acting in the structural members;
- Description of the structural joints;
- Development of one of the following topics in relation to the chosen building: construction techniques, historical references, architecture-engineering relationship, durability, fire safety, seismic resistance,;
- Construction of a scale model of the structure of the building.

The exam consisted of the presentation of the analysis with a written report and an oral exam during which the structure of the building had to be presented with the aid of the model. Figure 3.3 shows two of the models created by the students.

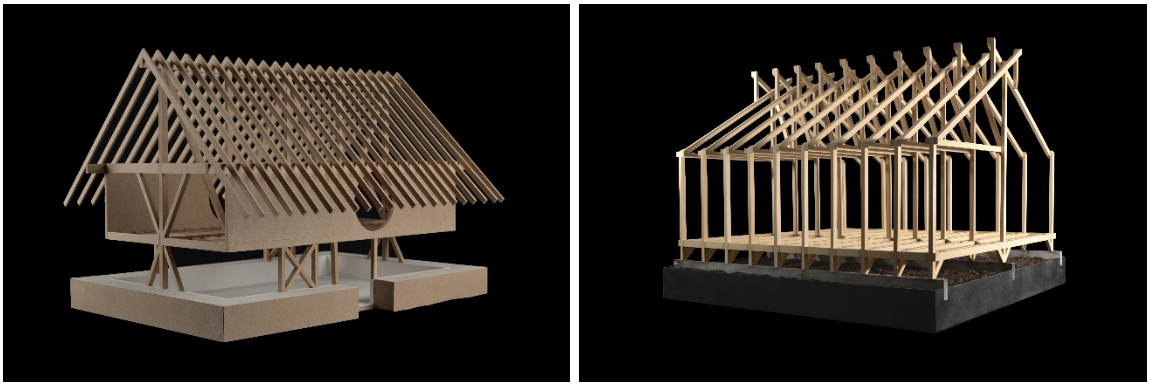


Figure 3.3: Scale models of two buildings with timber structures created by the students

3.4.2. Conception and preliminary design of a new structure

The second teaching experiment involved the “Steel structures” course, and it consisted of the conception and preliminary design of a new structure that would respond to a specific architectural requirement chosen and by the students. The students were required to focus on the following topics:

- Development of the architectural idea, which is the starting point for the structural choices;
- Structural conception (definition of a structural system responding to the architectural and static requirements);
- Preliminary dimensioning of the structures, by using geometrical rules or comparisons with similar existing structures;
- Load analysis;
- Static modeling of the structure and design of the main structural elements;
- Design of some structural joints.

The exam consisted of the presentation of the project with a written report and an oral exam during which the structure of the building had to be presented with the structural drawings. Figure 3.4 shows one of the structures designed by the students.

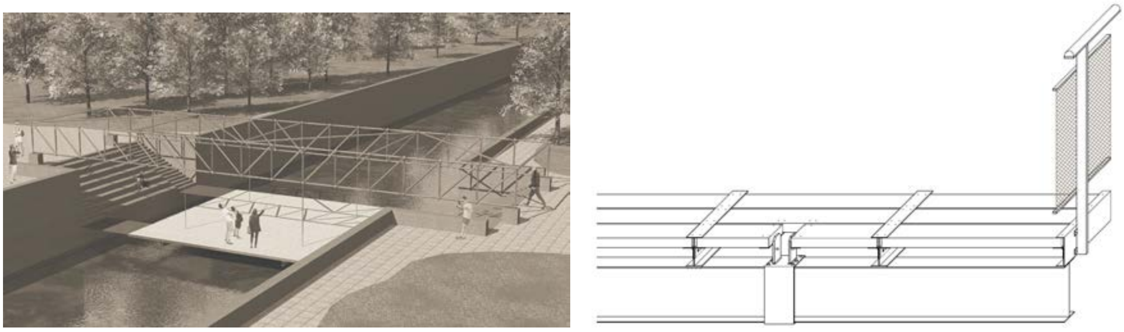


Figure3. 4: Design of a new steel structure responding to a specific architectural requirement

3.4.3. Create architecture with the structure

The third experiment involved the “Reinforced concrete structures” course, and it consisted of the analysis of an existing building that was chosen by the students, and exemplified a specific topic. The chosen topic for the academic year 2017/18 was “cover a square”, the topic chosen in the academic year 2018/19 was “the supporting point”. The main focus of the analysis was to understand how a structure can create the architectural space itself, and the following topics needed to be focused on:

- Short biography of the architect and the engineer who designed the building;
- Information about the construction site and a short architectural description;
- Detailed description of the structure of the building focusing on: structural typologies, materials, foundations, force flow, and bracing systems;
- Description of some structural details;
- Description of the construction techniques;
- Creation of a model of the structure and a photograph of the model that highlights the relationship between light and the architectural space created by the structure.

The exam consisted of the presentation of the project with: i) a written report; ii) the photograph of the model, and iii) an oral exam during which the structure of the building had to be presented using a poster containing the structural drawings and some sketches to describe how the structure resists vertical and horizontal forces. Figure 3.5 shows three of the photographs of the models created by the students.

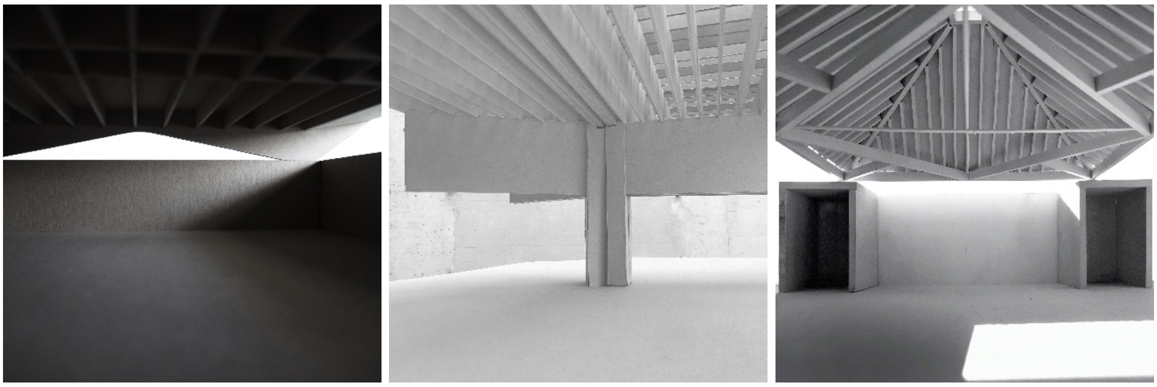


Figure 3.5: Three photographs of the models created by the students to show the role of structure in the creation of architectural space

3.4.4. Results of the experiments

The experiments had extremely positive outcomes, both in terms of increased interest from the students and in terms of the exam results The graphs in Figure 3.6 show the evolution of the students' exam results (on a 1 to 10 scale) and of the percentage of failed exams, from the academic year2011/12 to the academic year 2019/20.

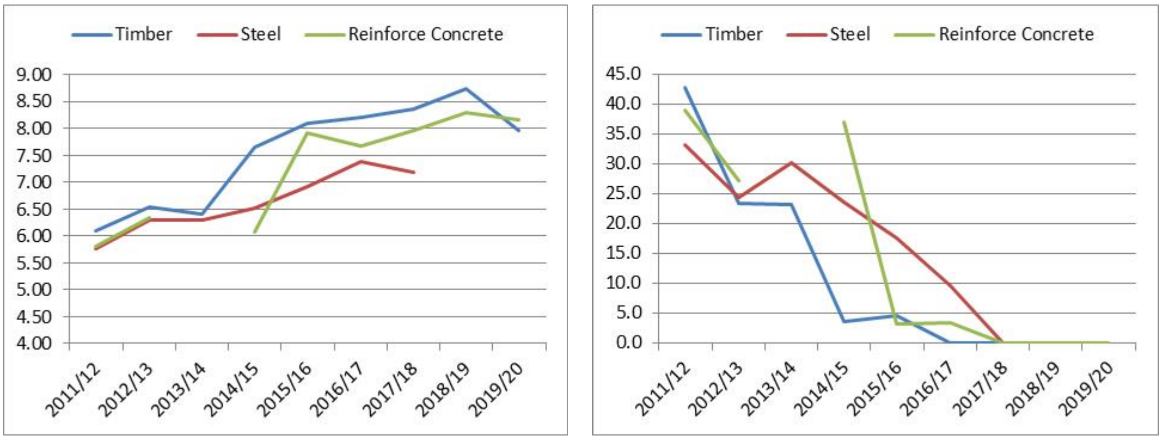


Figure 3.6: Evolution of exam results (left) and of the percentage of failed exams (right)

The graphs show that the exam results improved as soon as the experiments were introduced, that is the academic year 2014/15 for the "Timber structures" course and the academic year2015/2016 for the "Steel structures" course and the "Reinforced concrete structures" course. At the same time, the number of failed exams rapidly decreased to zero, showing the effectiveness of these methods for increasing student interest in structural design.

Figure 3.7 shows the evolution of the evaluation of the courses given by the students, on a scale from 1 to 10.

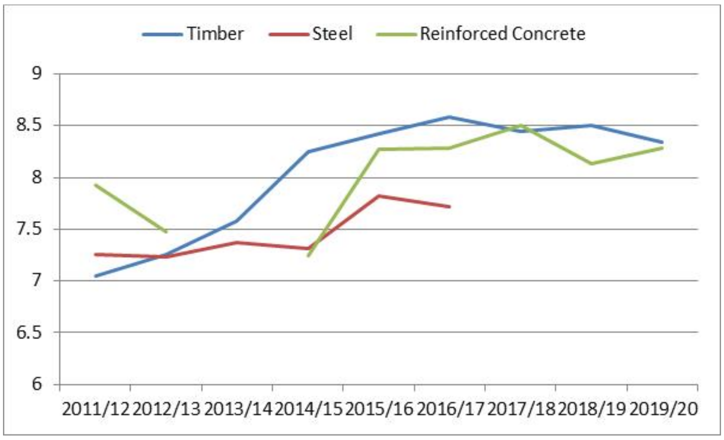


Figure 3.7: evolution of the evaluation of the courses by the students

The graph shows that there is an obvious increase in the grades given by the students when the teaching experiments began, which shows how much the students enjoyed the courses.

Other feedback on the experiments and, in general, on the enjoyment of the courses and how they are organized, can be obtained by analyzing the comments given by the students in the questionnaires for the evaluation of the courses. The comments given before the experiments highlighted that the students did not like the written exam and that they considered that they did not receive enough information during the course to properly prepare for the exam. Here some examples of their comments:

- The exam was too long and too difficult;
- The practical exercises given in class did not prepare us well enough for the exam;
- Not enough exercises were given during the semester;
- Too much attention is paid to norms and calculation, and this is not relevant for architects.

After the beginning of the teaching experiments, the comments given by the students became extremely positive. Here some examples:

- I really liked the exam method; I find it easier to apply what I learned in the lessons in a static analysis of an entire building than in a theoretical exam;

- The review sessions with the teaching assistant allowed us to understand the structure that we analyzed very well, and it also gave us interesting tips for our laboratory projects;
- I really liked the idea of working on a project that I could choose;
- The most interesting course in the whole year, we learned a lot and were given a lot of freedom.

These comments show that the changes carried out with the experiments have been understood and enjoyed, but they also highlight two aspects that had an important role in the positive outcome, but which are harder to measure quantitatively. The first of these aspects is the freedom to choose the project to be analyzed. The opportunity to work on a project which they have chosen themselves means that the students find it less boring and easier to carry out. The second aspect is the constant and continuous availability of the teaching assistant and the professors during the semester. One of the goals of the structural design courses at the Mendrisio Academy of Architecture is to teach the importance of fruitful collaboration between architects and engineers, which is exemplified by the guidance and counseling given to the students throughout the semester, and this has been received extremely positively.

3.5. Conclusions of the research project

The teaching experiments on the teaching of structural design at the Mendrisio Academy of Architecture have had extremely positive outcomes, which have been measured through the analysis of exam results and of the evaluation of the courses by the students before and after the experiments. The experiments have also given us some insight into how to improve the relationship between architects and engineers starting from their education and training at university. The questionnaires given to students and professional architects highlighted that understanding the analytical language used by the engineers could be difficult, but at the same time the answers showed great awareness of the importance of structures in architecture. The experiments carried out tried to solve this communication problem by adapting the programs and the teaching strategies to the interests and needs of the architects. Architecture is undoubtedly a creative profession that uses creative language. Engineering is mainly a technical profession, but the beginning of the structural design process is creative. Before it is calculated, a structure needs to be conceived, and this is a task that requires both technical and creative abilities. We think that this part of structural design can be the meeting point between architects and engineers and that the teaching of structural design to students of architecture should be focused on this creative part. Teaching should also encourage the growth of awareness of the importance of fruitful collaboration with the structural engineers, and this has been done in our courses through a constant and continuous exchange between the students and teaching assistants and professors, which has been received positively by the students. Finally, there is another aspect, which is less objective and more difficult to measure, that should be mentioned. The opportunity for students to make their own choice of the building to analyze has given us, professors and the teaching assistant, a different perspective on our profession. We were not aware of many of the projects chosen by the students, and their choices have given us a better understanding of their interests and their visions of the role of the structures. We have definitely gained a new perspective about our profession, experiencing the benefits that engineers can also enjoy from successful collaboration.

CONCLUSIONS

The idea of this research project came from a desire to rediscover and enhance the creative aspect of structural design. Structural engineering is not believed to be a creative profession nowadays. On the contrary, the role of the engineer is often seen only as being that of a technician who has the task of "making the architects' creations stand up", and who is therefore only involved when an architectural project is already defined. But if we look at the buildings of the past, we can see that structure has often played a predominant role, one that is difficult to distinguish from that of architecture. Who is not fascinated by the beauty of Gothic cathedrals, by the boldness of their vaults, by the momentum of the naves, by the light that enters through their large windows? And it is structure that has allowed the creation of spaces and volumes of such immense architectural value. However, Gothic cathedrals were built at a time when architecture and engineering had not been separated into two different professions, they were united in the figure of the master builder. Therefore, structural creativity was no different from architectural creativity. It was design creativity, which was mainly fueled by the experience of the builders. The technical and technological advances that began in the first industrial revolution gave rise to the need for a new professional figure, that of the engineer, and this led to the progressive estrangement between architects and engineers. This separation is expressed at different levels: those of interests, language, and involvement in the design process. When constructions were entrusted to the master builder, he was responsible for all aspects of design and construction. There was no clear distinction between structure and architecture, or rather, the structure was one of the aspects that the master builder had to deal with, and consequently the creative phase of the design also included the design of the structure. With the division of the professions, the phases of architectural design and structural design also divided. An architect is no longer directly responsible for the structure of the buildings he designs, this task is, in fact, entrusted to the engineer, but he still leads the project, he directs and coordinates all the phases from conception to construction. And since an engineer is not normally involved in the early design stages, the structure is not developed in the conceptual phase of the projects. With the advent of modern structural theories, the continuous advancement of engineering techniques and technology, and the development of ever more powerful calculation tools, the calculation tools used by engineers have also changed. The graphic methods were gradually replaced by analytical ones and manual calculation on paper by automatic calculation using calculation software. On the one hand, this has led to an increase in design options, but on the other, the visual link between form and forces which is encouraged by manual calculation with the use of graphic static methods has been lost. And analytical methods has also led to the diffusion of some structural typologies that are more suitable for automatic calculation, such as beams, frames, plates, to the detriment of other typologies such as arches, funicular structures, vaults and, in general, all shape resistant structures. However, there are still buildings in which a certain structural creativity can be recognized, and we have seen that there are basically two examples of these types of buildings: buildings whose structures arise from the specific talent and experience of the individual designer, architect, or engineer; and buildings whose structures arise from the collaboration between architects and engineers from the earliest design stages. We therefore wondered how to ensure that this structural creativity is not only the result of individual talent or collaboration, but that it is something that can be formalized. This would make it available to a greater number of designers. We have considered both the formalization of talent and how to foster collaboration.

In the first chapter we wondered about why the separation between architecture and engineering, and therefore between architects and engineers, occurred. We identified and analyzed some teaching approaches that have been experimented with since the 1980s in different European and North American universities, with the aim of promoting a rapprochement between the two professions (§ 1.1). We then identified graphic statics as a tool that encourages both structural creativity and collaboration between architects and engineers. Graphic statics has a fundamental role in the creation of structural creativity. In order to overcome the limitations that have led to graphic statics being abandoned in favor of analytical statics, i.e., the laboriousness of graphic constructions and the iterative nature of the process of researching the natural shape of the loads, we have proposed an original formulation of the Cremona-Maxwell method in matrix form. This formulation allows graphic statics to be used for form-finding purposes (§ 1.2). We then highlighted the important, but underused, role of the history of structures and structural engineering for the formation of structural creativity. After defining the characteristics of this hybrid discipline, which integrates historiographic methods with technical engineering methods, we have presented two original examples of research on the history of structures. The first of these examples is the importance of the palace of Ctesiphon in the history of structural engineering, and the second is the work of the Swiss engineer Henry Lossier (§ 1.3). These examples explain our thesis and also exemplify how a piece of research on the history of structures can be planned. Finally, the analysis and presentation of two specific projects, the Volta school in Basel, by the architects Miller and Maranta and the engineer Jürg Conzett, and the retirement home in

Giornico, by the architects Baserga and Mozzetti and the engineers Pedrazzini Guidotti, have shown how collaboration between architects and engineers from the early stages of design encourages structural creativity (§ 1.4).

In the second chapter, we wondered what intuition and structural creativity depend on and how it is possible to formalize them. First, we identified that the structural safety and efficiency requirements guide structural creativity, and therefore the formalization of structural intuition starts by meeting these two needs. In fact, there are many aspects that an engineer must consider to guarantee safety and efficiency: balance, structural typology, shape, mechanical characteristics of materials, geometry of the elements, position of supports, etc. All these aspects and the wide variety of solutions available that meet safety and efficiency requirements are the essence of structural creativity. In order to formalize this creativity, however, it is necessary to show which parameters creativity depends on and what happens to the characteristics that determine structural design when these parameters vary. This enables creative structural choices to be made. After highlighting the role of intuition and experience in the conception of a creative structure, in chapter two we dealt with the formalization of three technical aspects on which structural creativity depends: balance, the type and position of the supports, and the form, through the presentation and analysis of buildings that exemplify each of the three aspects. We analyzed the APG golf club building in Luque, Paraguay, by the architect Javier Corvalán, to show the role of balance in the formation of structural intuition (§ 2.1), while the roof of the Ascona lido by the architect Livio Vacchini was chosen to show the role of the type and position of the supports (§ 2.2). In order to show the role of form in the formation of structural intuition, we compared the structural solution chosen by Livio Vacchini for the roof of the gymnasium in Losone, a grid of prestressed reinforced concrete beams, with other possible structural solutions involving the use of shape resistant structures and vector resistance structures (§ 2.3). Finally, we analyzed the role of context - geographical, economic, political, and of tradition - on the formation of structural intuition, by presenting an original piece of research on promoting the diffusion of timber buildings in the Swiss region of Ticino, as a result of the enhancement of the local building tradition (§ 2.4).

If, as shown in the second chapter, structural intuition can be formalized, it can be taught. Therefore, in the third chapter we presented some educational experiments that we carried out at the Mendrisio Academy of Architecture, Switzerland, on the teaching of structural design, based on the results of some questionnaires specifically prepared and given to architecture students and professional architects to investigate the level of interest that architects have in structural issues and the state of the relationship between architects and engineers, as well as looking at on the formalization of structural intuition. The purpose of these experiments was also to show the advantages of fruitful collaboration between architects and engineers, which is why it would be useful to also teach these courses to undergraduate students in civil engineering faculties.

This research can be developed further, and we are currently planning another revision of the programs of the structural design courses at the Mendrisio Academy of Architecture as, despite the positive outcome of the experiments, we found some problems that need looking at. In particular, although the students enjoy the structural design courses and the exams, their attendance fluctuates and is generally low. We believe that this is partly due to the teaching methods used on the course, which now only includes lectures given by the professor. We would therefore like to introduce different educational innovations which could result in greater student involvement. The following ideas will be implemented :

- Introducing interactive elements into the lessons, which require the active student participation, using the digital tools offered by the university, for example:
    - Multiple choice tests on the topics covered in the previous lesson;
    - Quiz on technical/engineering nomenclature to improve their knowledge of technical vocabulary that could encourage the communication with engineers;
    - Short problems that students have to solve in class;
    - Open questions to be answered by expressing a personal opinion. The professor could then use the analysis of these answers to plan the lesson on the proposed topic on the spot.
- Part of the course will be taught in the "flipped classroom" mode. Some buildings will be selected, and material that is useful for understanding the criteria and methods with which the structure was designed will be prepared and given to the students before these classes. A period of time to study the material provided and the topics which will be explored and discussed in class will be defined. In class, the students will be asked to give presentations on the buildings according to the instructions provided, guided by the teacher.

These changes will be made in the 2023/2024 academic year, and, subsequently, we will measure the effectiveness of these educational innovations through the analysis of student assessments, exam results, and some feedback questionnaires specifically prepared and given to the students.

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APPENDIX A – SCRIPT OF THE MATLAB PROGRAM

```
%Variables definition%
x=input("Please insert forces position vector; make sure it's between squared
parenthesis");
y=input("Please insert cable starting positions vector; make sure it's between
squared parenthesis");
FF=input("Please insert forces vector; between squared parenthesis and in the
same order as ositions");
x=x';
y=y';
ystart=y;
FF=FF';
%Control on vectors length%
if length(x)~=length(FF) || length(FF)~=length(y) || length(y)~=length(x)
    disp('Input vectors length must be the same!')
    return
end
%Analytical problem definition%
%Since first and last points of the cable are already known, the problem
%concerns only the middle points. As we work this way to solve the problem,
%all vectors and matrix will have the dimensions of input vectors minus 2
%Matrix f definition%
l=length(x);
F=zeros(l-2,1);
for i=2:l-1
    F(i-1)=FF(i);
end
f=zeros(l-2,l-2); %Matrix f is already defined with its real dimensions, we
don't consider fixed points
for i=2:l-1
    for j=2:l-1
        if i==j
            f(i-1,j-1)=1/(x(i+1)-x(i))+1/(x(i)-x(i-1));
        elseif j==i+1
            f(i-1,j-1)=1/(x(i)-x(j));
        elseif j==i-1
            f(i-1,j-1)=1/(x(j)-x(i));
        end
    end
end
%Vector k definition%
K=zeros(l-2,1); %Vector K is already defined with its real dimensions, we don't
consider fixed points
K(1)=y(1)/(x(1)-x(2));
K(l-2)=y(l)/(x(l-1)-x(l));
%Solving method selection%
sel=input("Please choose solving method: choose by pressing 1,2,3,4");
if sel==1
    disp('First solving method chosen')
    H=input("Insert a value for parameter H");
    yy=f\(F/H-K);   %Solution for central points of the cable
    y=[y(1);yy;y(l)];   %Reconstruction of the y vector with fixing points too
    L=0;   %Initializing cable length
    T=zeros(l-1,1);   %Initializing tensions vector
    i=2;   %Initializing while index i
    while i<=l
        L=L+sqrt((x(i)-x(i-1))^2+(y(i)-y(i-1))^2);    %Rope length calculation
        T(i-1)=sqrt(H^2*(1+((y(i)-y(i-1))^2/(x(i)-x(i-1))^2)^2));    %Tensions
calculation
        i=i+1;
    end
elseif sel==2
    disp('Second solving method chosen')
```

```
    pos=input("Insert fixed y position");
    if pos>=length(x) || pos<=1
        disp('Position must be between rope fixed points!')
        return
    end
    yfix=input("Insert fixed y value");    %Definition of y value wanted
    H=0.0001;    %Starting H value
    yy=f\(F/H-K);   %Starting solution for central points of the cable
    y=[y(1);yy;y(l)];   %Reconstruction of the y starting vector with fixing
points too
    while abs(y(pos)-yfix)>1 %y position control
        H=H+0.0001;    %Iterative H value
        yy=f\(F/H-K);   %Iterative solution for central points of the cable
        y=[y(1);yy;y(l)];   %Iterative reconstruction of the y vector with
fixing points too
    end
elseif sel==3
    disp('Third solving method chosen')
    H=1;    %Starting H value
```