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Stefania Palaoro

ARCH BRIDGES
Design - Construction - Perception

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Design – Construction – Perception

Tutors: Enzo Siviero, Airong Chen
Cotutors: Bruno Briseghella, Tobia Zordan

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Prof. Antonio Tralli (University of Ferrara)
Prof. Bruno Calderoni (University of Naple)
Prof. Mariapaola Gatti (University of Trento)

SUMMARY

The arch bridges have an historical development, that is rooted in their ancient tradition, yet are also very successful to this day, a rediscovery of the earliest arched forms can be seen in the most recent innovations. After millennia of masonry arch bridges and almost two centuries of relentless development of iron, steel and concrete arch bridges, with different structural schemes and constructive shapes, there was a moment that this type of structure was bound to disappear.
The scope of traditional arch bridges, which refers mainly to the ones of small and medium span, was to become the uncontested role of the girder bridges. The reuse and the assertion of the arch bridge has been accompanied by a strong architectural emphasis on their structural design and constructive details. This relation, increasingly important during the design phase between the concept of FORM and of STRUCTURE, has ensured that many new projects link the strong relationship between TRADITION and technological and constructive INNOVATION.

SOMMARIO

I ponti ad arco sono quelli che presentano un’evoluzione storica che fonda le sue radici nella tradizione più antica, ma anche quelli che ricevono all’oggi il maggior successo, una riscoperta delle prime forme arcuate che ritornano quasi come una moda ma con l’impiego delle recenti innovazioni: dopo millenni di ponti ad arco in muratura e quasi due secoli di inarrestabile sviluppo di ponti ad arco in ghisa, di ferro, acciaio e di cemento armato, accompagnato da diversi schemi strutturali e di forme costruttive, sembrava che questa tipologia fosse destinata a scomparire. Infatti il campo tradizionale dei ponti ad arco che si riferiva soprattutto ai ponti di media luce era divenuto oramai dominio incontrastato dei soli ponti a travata. Il riuso e il riaffermarsi del ponte ad arco è stato accompagnato da una forte accentuazione architettonica della loro concezione strutturale e dei loro dettagli costruttivi. Il rapporto sempre più importante in fase progettuale di correlare il concetto di FORMA con quello di STRUTTURA ha fatto in modo che molte nuove opere d’arte di nuova realizzazione unissero in sé il forte rapporto tra TRADIZIONE e INNOVAZIONE tecnologica e costruttiva.

ACKNOWLEDGEMENTS

First and foremost, I wish to thank my tutor Prof. Enzo Siviero, who gave me the opportunity to carry out this study, giving me the right motivation for my choices and the useful and necessary help needed for my training and my scientific growth. I am grateful to him for his patience and his generosity but also for his enthusiasm, his cultural honesty and his teachings which have left a profound impression on me.
I came upon to the theme of bridges for the first time when I met Prof. Siviero during my university career. I was fascinated by the lectures in "Theory and Design of Bridges" at the University of Venice, where the main theme is the relationship between form and structure, a combination that is rare in a school of architecture. The research work started while I was writing the degree thesis that was based on historical and technical studies of Italian motorway infrastructures, paying attention to how the architectural shape of bridges and viaducts evolved over the years depending on the technological and constructive innovations and use of new materials.
I learned a lot from him especially regarding the fact that the two apparently remote worlds, one being artistic and the other technical, may overlap with one common goal of creating a good design. Through him I also learned how to communicate by means of a different reality from mine own. He is a very true Master.

I also want to thank prof. Airong Chen because not only has he contributed to my work with valuable advice, but showing great generosity he allowed me to stay and do research at Tongji University in Shanghai, where I spent a total of eight months This period of study abroad has allowed me to get in touch with a reality that is completely different from mine own, not only in terms of university life, research and design planning, but even from the human point of view..
He was always ready to listen to me, to advise me, to show me things with new eyes. The conversations I had with the Prof. Chen will forever remain in my heart because not only were they rich in scientific content but also in architectural content. I like to define him as an "architect" among engineers.

A special thanks also goes to Prof. Bruno Briseghella and Prof. Tobia Zordan, always present in their contribution through suggestions and for their constant encouragement and illuminating instruction during all the time of my research. Their scientific background, their diligence and their passion in research and teaching gave me the right incentive to complete this study.

Thanks to Michele Culatti who helped me a lot on the landscape perception.

I can't forget prof. Tullia Iori, for the friendly cooperation that began during the degree thesis and continued throughout the years of my PhD. She passed on her passion of teaching methodology and scientific research on to me, she advised me in every choice and helped me to pursue the right direction in the research. For me, she is a outstanding example to follow.

Finally, a particular and huge thanks to my family, whose support and patience allowed me to achieve my objective.

CONTENTS

INTRODUCTION

If the column is architecture, the arch is engineering;
Better still, if the column is art, the arch is technique …
Building an arch is not as natural as raising a column …
Eduardo Torroja

INTRODUCTION

Just like one hand clenching another a bridge embodies the sense of a connection, which unites two things that were once separated. Reaching and connecting with others in a common need of all people, bridge becomes an explicit expression of the human desire to connect and it is the union point between what is here and what lies beyond.

The design phase of any piece of architecture must take into account its entire lifespan from its inception, therefore, from primary need, to its implementation, from design to construction, and especially, as it will become part of the everyday life of the people that user it.

Architecture is an area of interrelations between people. A space becomes architecture with the continuous flow of people who live it, with materials and objects that it is made up of and with the surrounding environment that is in symbiosis with it: in a project all these factors must be considered, which interact among themselves. The individual person becomes an important component of the architectural reality when they feel integrated with the surroundings living their own daily lives through their own sensory experiences. Architecture becomes one unit with the environment, which is a complex system subjected to constant changes: from this point of view architecture, buildings, bridges and all artefacts constitute an factor of interrelation between people and landscape.

Bridges overcome artificial and natural obstacles, wide rivers and deep valleys, and open new communication paths. As work of architecture and engineering, the bridge has played a predominant role in the development of construction methods. The historical background of bridges shows us how construction methods have developed from their earliest application up to the present day and this evolution has been influenced by social, political and economic conditions of various time periods. Bridge structure particularly shows its typological progress much more than other man-made architecture and bridge designers play a main role in this development.

The choice, that lies at the basis of an architectural project, is mainly based on two geometries, apparently in contrast with each other: the clean and minimal line, that in its simplicity underlines the great design complexity, and the curved line, the arch, which defines the architectural form for excellence even more. History offers us many examples of arches, that are a symbol in the landscape design. The arch, more than any other architectural elements, is a geometric shape that in a natural way defines even its very structure. Therefore, the arch becomes the combination between form and structure and the arch bridge joins an architectural thought to an engineering one.

The choice of the arch bridge, as the object of analysis, comes from the importance this architectural shape has had in the history, for its long tradition and for its review

in recent years in bridge design due to innovations in both technique and architecture. After many years of arch bridge achievements, we had a long period of inactivity, during which traditional construction was replaced by the undisputed role of girder bridge, in steel, concrete, prestressed concrete, and it seemed that the arch shape was eventually going to disappear. It is only in recent years that arch bridge regained and reaffirms its importance thanks to a new structural design and construction details.
The arch structure, thanks to its shape, resists to external stresses through a mechanism, in which compression strain prevails, and in history it has been considered to be the most durable. Arch bridges meet their greatest difficulties during the construction phases: in fact, once completed the arch shape begins to function. The analysis of construction methods thus acquire the same value of the project phase. Despite the continuous and ever amazing architectural research of bridges built by means of modern and innovative methods of assembly, arch bridges never deny their basic structural principles.

AIM AND SCOPE

This PhD thesis aims to search the factors that influence the architecture design of a new project. Before people can live the arch bridge in their daily life, the bridge must answer first and foremost the basic requirements of necessity, to then be imagined, designed, and calculated. The life of the bridge is very complex, from its earliest design phase to its construction and use. In the doctoral research, titled **Arch Bridges, design – construction – perception**, I intend to retrace some steps of the arch bridge, from its project design through all the intermediate stages of site analysis, construction methods, up to when the bridge becomes a part of the human world, as persistent element in the area. Along this analysis, four issues will be discussed and studied separately, in order to answer several questions that will allow the designer to understand what the characteristics to consider are in the planning phase.
These four issues are:

-**DESIGN**
This section starts with an historical description of the arch and its use in the construction of bridges. This brief overview is to emphasize how the arch shape changed in history through the progress of construction techniques and use of new materials. Therefore, the bridge typology and its relation to history, its origins and developments, are to be considered as the first point in the analysis phase. Bridges have always tried to express the spirit of the period in which they were built.

Apart from the basic requirements of the bridge project, that must meet the exigency of functionality, design must also respond to the architectural question: structures must first be functional, but also have a pleasant form. Structural beauty can be considered as a subjective quality, but bridge as to possess the characteristic of completeness, must comprise two general non-independent elements: structural efficiency and unified appearance. With regard to structural considerations, these relate mainly to the materials used in the bridge, and how it should be designed and studied to ensure convenience, efficiency and durability.
The shape of the arch bridge itself has a characteristic of harmony. This principle is valid for both small and medium span bridges, but also of those with longer spans. In every period of the history the arch bridge has been an important landmark and has seen important developments and various architectural forms.
It is very important to consider the value of traditions during the project process, and more precisely with regards to the design of bridges: in fact it begins with a critical study of the existing works and an analysis of the factors that influence the design, so that they can propose alternative structures.

What are the formal characteristics of the arch bridge?

Architectural design must consider some important factors that define the arch shape: in this section were found to be: span, rise, rise/span ratio, arch typology (position of the deck). The chapter closes with considerations regarding the “good design”. The purpose of this step is to learn from what has already been done, in order to access future developments, and to define what are the main features that should be considered in the design of an arch bridge.

- human **PERCEPTION** and **LANDSCAPE PERCEPTION**

The architectural harmony does not require elaborate and false ornaments, but on the contrary the pleasure to live a work must be closely linked with the efficiency that it ensures: “beauty” is in fact related to the functionality of the bridge, that can be considered a good piece of architecture when it possesses these physical and psychological characteristics which reveal its character. These physical characteristics are proportion, symmetry, rhythm, repetition and contrast, and psychological characteristics one are those that give positive feelings to the observer. Structure should have a pure and clear shape and gives a feeling of stability.
With “originality”, the object will become a symbol of the place where it is located, and “harmony of form” is a concept closely linked to the “truthfulness” of the structure. These features are all to be considered during the design phase with particular reference to interesting places. The size of the structure must be linked to the human scale and to the need to integrate them into their environment, being a

natural or urban landscape. Even purely architectural features, as superficial texture and color, have fundamental roles in the integration of a work to its surroundings.

How are the feelings of the people that live the arch bridge?
What is the relation between the arch bridge and the landscape?

The aim of this chapter is to tell the designer that arch bridges, and any other types of architecture, are not only structural works, but are objects that comes into direct contact with the people who will cross it, who will see it from distance and recognize that place by its presence. The primary importance of design lies in its functionality and its goal is to become a “work for man”, an object to be lived. The relationship between the arch bridge and environment is of equal importance.

-**STATE OF ART**

This study will allow us to understand the design choices made in the recent past for bridge building and what the common characteristics are among a number of projects, taking into account both architectural aspects of shape, but also place and the obstacles to be overcome.

The comparison of what has already been done is useful and necessary. The statistical analysis of the world’s longest arch bridges includes a meticulous collection of data subdivided into length, construction method, structural typology, materials used and country of belonging. Through research filtered with appropriate parameters, graphics can be obtained, which allow us to understand the trends of arch bridges over time, to help guess future possible developments. A similar study will be done for the arch bridges over the Italian territory, with a distinction between concrete and steel works. There are many examples of important Italian bridges, that do not find classification on a national level. The analysis of these bridges permit us to see bridge development, from the first use of reinforced concrete in the mid 20th century to the latest steel achievements of the 21st century: this has involved, albeit in more modest measure, comparable evolutionary phases and construction techniques.

What are the methods most used for the construction of arch bridges?

The purpose of this chapter is mainly to give a complete overview of existing works, in the world and particularly in Italy, as to be able to define the historical evolution. In particular, I intend to perform a more detailed analysis for concrete bridges: this is done taking into account the characteristics that influence the architectural form of the arch, and subsequently looking at some architectural considerations seen in chapter 1 and the close relationship that there is between the bridge and environment, seen in chapter 2. These features are put in comparison with the construction methods adopted mostly for the construction of these works, successively analyzed in chapter 4.

-CONSTRUCTION

After the design phase follows the construction phase: bridges have always been at the forefront of technology, and create a union between architecture and engineering. The knowledge, about what are the advantages and disadvantages of one method respect another in advance, is of fundamental importance to comprehend what the issues effectively dictated by the site are. Over time the construction of arch bridges has created ever more examples which have span ever longer respect to any previous constructions: in fact, the record spans represent the evolution in construction technologies, the development of the tools used on the yard and the quality of the materials. However, a technological evolution does not necessarily mean a higher quality in the architectural design or more attention to construction design, which on the contrary, are often overlooked. The choice of the construction method and the verification of the preliminary project, that starts from the designer's creativity which is based on the past experience, cultural background and knowledge of the designer.

What are the positive and negative characteristics of each method?

The purpose of this final chapter is to define the methods mostly used in construction highlighting the advantages and disadvantages to be considered in the first phase of the project.

HOW TO PURSUE THE AIM

Chapter 1: Design
What are the formal characteristics of the arch bridge?

The evolution of the arch shape and the definition of its main architectural features have been pursued through a brief historical overview of the major and most influential works that have been made around the world.

Chapter 2: Perception
What are the feelings of the people that live the arch bridge?

Through visual perception, senses and personality psychology, the position that one has towards the object, their personal and cultural experiences and relative movement, some actual characteristics of the object and feelings of the person walking on it are defined.

By means of the Gestalt psychology methodology laws, figures and objects will be analyzed taking into account the separation from the background.

What is the relation between an arch bridge and the landscape?

Landscape is considered as a set of past experiences, human, historical, architectural, relational. The goal of this analysis is to be able to identify the concept of “design quality” and to achieve this a reading code of the Italian law is used, the DPCM 12th December 2005, which stipulates that the public and private management of the territory is authorized through an obligatory landscape report whose contents and purposes are determined by the decree. The use of the criteria listed in the DPCM does not constitute a scientific method but a discussion method of some concepts: this evaluation method of the landscape perception does not represent a technical manual, does not indicate mathematical models to follow but merely provides some evaluation elements that could be used as a base for a critical judgment to a given context. These elements have the aim of sensitizing the designers to the themes of landscape, emphasizing the importance of the quality in the design and land management.

Chapter 3: State of art

What are the methods most used for the construction of arch bridges?

By means of a in-depth analysis of modern artifacts that show the development of infrastructure networks through political, economical and social changes in the world, and especially in Italy, and by means of the analysis of the construction methods and the various stages of assembly, the factors that influence the design work mostly are considered.

Some 600 examples of arch bridges in the world were taken into account, with the two common characteristics of having been built after the year 1900 and with a span of more than 100 m. The analysis of the data (span, material, static scheme, construction method, year of construction, etc.) can determine the record lengths, the materials most used in the construction of arch bridges, the amount of bridges depending on their length and country and how the architectural features (span/rise ratio, environment, location and obstacle to overcome) can be arranged in relation to construction methods.

The analysis conducted on Italian arch bridges with a sample of about 120 bridges, built after the year 1900, shows the evolution of the infrastructures in Italian territory, and points out that there were some temporary pauses in the construction of arch bridges due to historical reasons and the use of different building materials. Through this study, the architectural typologies and construction methods applied mostly on the Italian territory, also in relation of what is happening in the world, are highlighted. Finally, some important examples of arch bridges built in history and in recent years are discussed. This data collected is still an ongoing process because the works carried out on our territory are not cataloged and unfortunately are often unknown.

Chapter 4: Construction
What are the positive and negative characteristics of each method?
Showing various types of construction methods, using examples of built arch bridges, enables us to define what are the advantages and disadvantages of each methodology.

CONCLUSIONS AND ACHIEVEMENTS

My personal contribution to the state of research analysis is to have collected a unique number of examples of arch bridges, catalogued in a database that gathers as much information as possible about each work (name, year of realization, main span, total span, construction method, country, location, designer). This collection defines a very wide overview of arch bridges.
The research of arch bridge projects lead to a very interesting investigation of Chinese achievements, because China is the country that has the highest number of arch bridge than any other country. My permanence there and the opportunity I had at the Tongji University of Shanghai under the guidance of the professor Airong Chen allowed me to broaden the study of Chinese bridges, both by direct observation and through the material that was given me.
Yet another study was carried out on Italian arch bridges. Although our country has a long tradition in the construction of arch bridges, as we will see later on, there has been some time blocks in their realization, nevertheless a sort of renaissance has been seen in recent years. This important collection of the works present in our territory still in only at the beginning: an archive of Italian artifacts does not exist and I consider this to be a really important issue to must be pursued in the future.
The long list of bridges gathered during my PhD years has allowed me to make considerations about many issues that are closely related to the design of bridges: the holistic view towards the bridge allows to highlight how it is going to unfold in history, what its relationship with the surrounding environment is like, which are the most important phases of construction and how people become an integral part of the finished structure by living it in their everyday lives. An attempt was done to show how architecture and engineering go parallel in the design of arch bridges, taking into account all factors, both formal and structural.

In final part all the issues considered in the various chapters are combined, considering the construction method as a unifying element as the arch shape is also its structure and in addition each structural decision is at the same time an architectural decision. Construction method ranking is defined by means of all the features taken into account in each single chapter. This investigation of the construction methods according to the architectural features allows us to understand what are the most widely used methods. Structural considerations are confronted with environmental issues, because the environment is a key element in the design phase: this suggests in advance the relationship between arch bridge typology and the method of assembly within a context. The proposed study is intended as a first step, a baseline, to be developed and deepen the topics of the arch bridge. Factors influencing the choice of the bridge are many and their number is so great that getting a straightforward solution for a finished work becomes a challenge. So the initial idea of the designer should therefore consider architecture, technology and the surrounding conditions.

The attention given today towards bridge projects and particular regard to the arch bridge, is revealed in the frequent meetings, lectures and conferences on the subject, in particular the Arch Bridges conference, that in 2010 has come at the 6th edition.

Today arch bridges acquire a new form of life, thanks to the development of construction methods and materials, but also to the people that are needed: the design of a bridge starts from the people who have a need and that will use it in their everyday lives. Bridges must be made with a correct analysis of the construction phases, in respect to the place where it will eventually be positioned. The architectural design, the materials used and the construction details are the elements that will dictate the formal characteristics of arch bridges and at that the same time making them a place to be lived.

CHAPTER 1: DESIGN
What beauty means?

Who does not see in a Roman bridge the strength of being?
Or in a Renaissance bridge a place to live?
Or in the nineteenth century metal bridges the strength of the scientist-artist?
Or in the eight-twentieth-century rail achievements
Of long and small bridges the apotheosis of the arch (that never sleeps …)?
Or in many reinforced and prestressed concrete works
Of the last century the depth of thought-action?
In all this, the skill of the craftsman-builder is combined
with a knowledge able to blending tradition and innovation, form and structure,
where everyone, from the great designer to the most humblest of workers
all, I tell all, concur to the uniqueness of the result, even ethical,
of pass to those who will come after us.
Enzo Siviero

1.1 Introduction
Relation between bridge shape and construction method through history

Bridges rise over natural obstacles, across wide rivers and deep valleys, overcoming obstructions and opening new paths of communication. Bridge construction has been a main feature of progress in the connecting of different places and passing over difficulties, but at the same time it represents the evolution within the technological field, through the improvement of materials, and we can see the evolution of the architectural bridge shape through history. Bridge typology demonstrates progress more than any other man-made structure and bridge engineers act as agents in this evolution. During history, from the first examples to modern ones, this evolution can be clearly seen from the past to the present. History is a combination of many conditions: economic, political and social, which together generate the situations that are favourable or not for transformation of places.

As written by Charles Smith Whitney in Bridges of the World: Their Design and Construction[1], "*Bridges are built to further human welfare and not to exploit and exalt scientific principles*", but it is also true that this evolution owes a debt to science, especially in the last century, where structural systems and construction methods evolved tremendously. The Roman intuition in the use of the arch has been handed down for use and is still used today. The arch is the same but the shape and the artistic expression has changed. The shapes of bridges, of any historical period mirror the society of that era and the technological evolution achieved up until then. Each arch bridge reflects and marks its political and historical settings.

The technique helps the progress, but beauty of a structure is a "*thing apart from the human progress*"[2] and could be a individual quality. In every case a "*bridge must possess two general elements: these are structural efficiency and unity of appearance: structural considerations require that the material of the bridge shall be so proportioned and placed as to provide convenience and durability. The width and arrangement of roadways or waterways should suit the needs of traffic. The construction should be strong enough to stand safely for as long as it is needed*."

On the other hand, "*beauty does not demand elaborate ornamentation, and is not in any way opposed to efficiency. Beauty is in fact so closely related to efficiency that it sometimes seems to result entirely from perfect fitness*."

We have seen over the years a gradual evolution in bridge design, from simple shapes and structures to more complex ones. Some periods were distinguished by invention and the appearance of new shapes, systems, and types of bridges; others

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[1] Whitney, C. S., 2003, *Bridges of the World: Their Design and Construction*. Dover Publications, New York, USA, p.24

[2] Ibid.

were characterized by mastering and perfecting existing systems along with the development in scientific research.

The fastest progress came about in the late 19th century with the use of new materials, which permitted the gradual abandonment of the use of stone, which had highlighted ancient times, like that of the glorious Roman Empire. The appearance of cast iron, due to the development of industry and transport, gave a great turning point in all respects. The first 40 or 50 years of the 19th century were spent creating the iron beam bridges, and the second part of the century was devoted to developing expedient systems and improving construction.

The first use of concrete, and later on reinforced concrete, brought knowledge regarding the possibilities this material possessed. However, with the general development of science and technology, the role of scientific research was increasingly racing alongside novelty, rationalization and invention. When you think of something new, it should not be regarded as something directly related to actual economic condition. In fact this concept can be easily found in the various uses of prestressed concrete in different periods: while at the beginning these new materials were expensive, now its use should be considered as an economic advantage thanks to its typical characteristic of being industrially produces and also because of mass production.

The industrial revolution introduced new materials, new building techniques, new working methods and new relationships between social classes and the problems brought about the urbanization.

Along with new materials the amount of designers were also distinguished: architects and engineers embody consequently a technical thought and a new formal value. A new method of design was to develop from the second half of the 19th century. As Edoardo Benvenuto says "*the construction might as well as be characterized by different criteria aim at meeting venustas, utilitas and firmitas requirements. The new realizations searched the evocative strength of forms; beauty was reached in one act in which science, technique, imagination, poetry, memory interpenetrated*."[3]

It is in this way that more technical designs met these principles related to architectural design in general: the characteristics of proportion, symmetry, rhythm, repetition, contrast become values to take into consideration during the drawing phase. The master schools in the past, such as Vitruvius and Palladio had rules and guidelines for these characteristics. Surely these guidelines are still valid today and they can be of valuable help in designing beautiful structures and avoiding formal mistakes and Torroja said that "*the enjoyment and conscious understanding of*

[3] Benvenuto E., *1850-1880: Bridge-building and modern structural mechanics*, in Sinopoli A., 1998, *Arch Bridges: History, Analysis, Assessment, Maintenance and Repair*, *proceedings of the Second International Arch Bridge Conference, Venice, Italy, 6-9 October 1998*, Balkema Editor, Rotterdam, Netherlands, p.4

aesthetic pleasure will without doubt be much greater if, through a knowledge of the rule of harmony, we can enjoy all the refinements and perfections of the building in question”.[4]

The primary element that characterizes any design is the desired function of the project: bridge design has to fulfil this purpose in an optimum way. A structure should reveal itself as a pure, clear form and impart a feeling of stability. The form of the basic structure must also correspond with the materials used. The second one is its integration with the environment: the need to integrate a structure into its environment, landscape or cityscape, particularly where its dimensional relationships and scale are concerned. Dimensions of structures must also be related to the human scale.

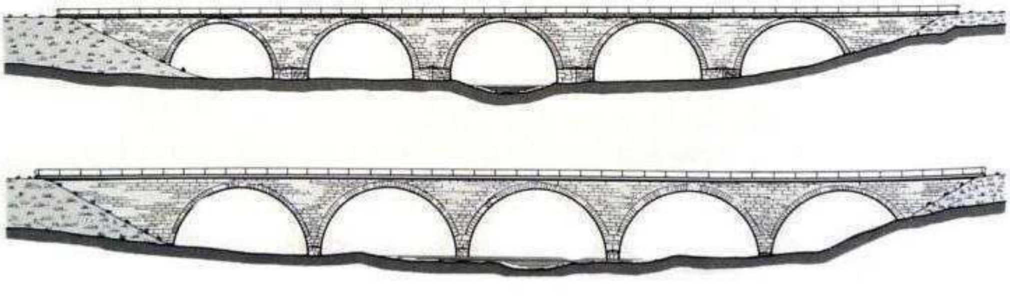
The others elements that must be considered are related to the architectural shape of the object:

- Proportion: an important characteristic, necessary to achieve beauty in building, are good, harmonious proportions in the three-dimensional space. Good proportions must exist among the relative size of the various parts of a structure; among its height, width and breadth; among its masses and voids, closed surfaces and openings, and between the light and dark caused by sunlight and shadow. Proportions of the geometric dimensions are important not only for individual parts of the building, but also for the entire structure. In a bridge these relationships may exist between suspended superstructure and supported columns; between depth and span of the beam, or among height, length and width of the openings. Harmony is also achieved by the repetition of the same proportions in the entire structure or in its various parts.
- Order: repetition of elements provides rhythm, which create satisfaction. But too many repetitions, on the other hand, lead to monotony. In the case where too many repetitions occur, they should be interrupted by some other design elements.
- Surface texture and colour: in the integration of a building with its surroundings, a major role is played by choice of materials, texture and surfaces, and particularly by colour that plays a significant role in the overall formal effect. Many researchers have studied the psychological effects of colour.
-Character: a bridge should have character and a certain deliberate effect on people. The nature of this desire depends on purpose, situation, type of society, and on sociological relationships and intentions.

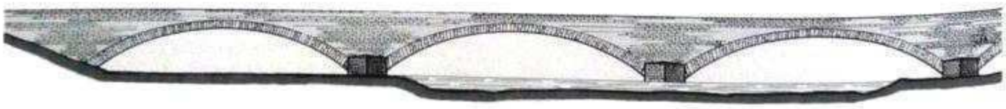
The choice of the arch shape become from the importance that an arch bridge acquires in the entire human culture, how it attends the progress and how it identifies an icon in the story of construction. Fritz Leonhardt says that “*the arch is the strongest embodiment of a bridge. Its shape directly expresses its ability to*

[4] Leonhardt F., *Developing Guidelines for Aesthetic Design*, *in Bridge aesthetics around the world*, 1991, Committee on General Structures, Subcommittee on Bridge Aesthetics, Transportation Research Board, National Research Council, Washington, p.32

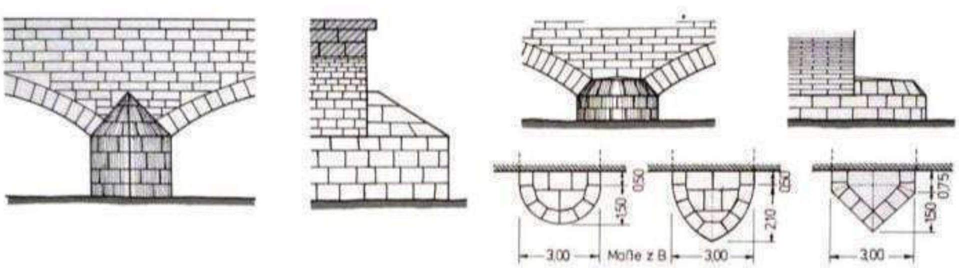
carry loads across river, valley and gorge. Arch bridges are therefore considered beautiful by their obviously suitable shape, this is valid for small and large arch bridges alike, and it has represented in all the historical period an important landmark, and has seen significant developments and formal architectural".[5]



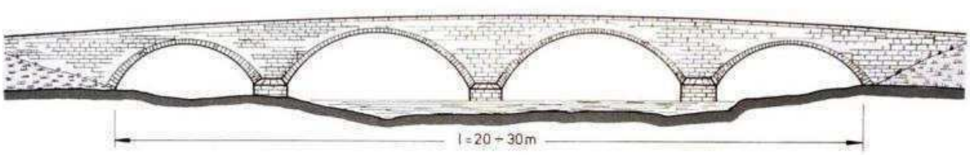
1. 1 Sequence of arches, wide piers look better that narrow ones



1. 2 Flat arches with parapet without ledge



1. 3 Shapes of piers

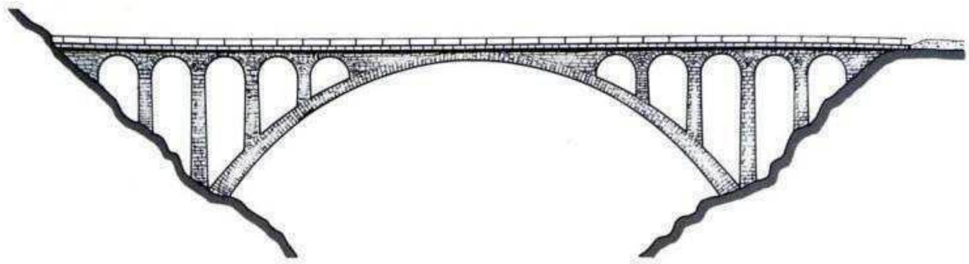


1. 4 Variation of spans corresponding to curved vertical alignment

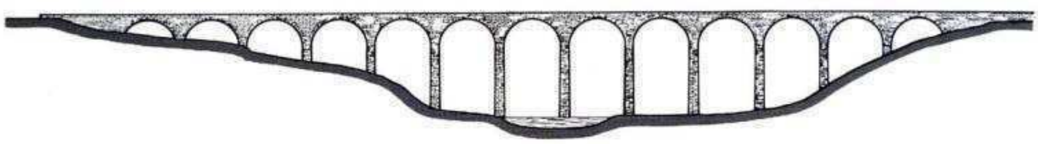
In regarding to masonry in arch bridges the beauty of natural stone is best expressed in small bridges when the arch and face walls form a unit. They are often

[5] Ibid., p.35

characterized by a multi-span shape and old bridges do show such variations. To obtain an impression of stability, it was necessary that the piers between arches were sufficiently thick and high in relation to width and depth of the span (fig. 1.1). This is especially valid for flat arches which should not be too thin at the crown, because this would cause an impression of insufficient stability and create a lack of balance in relation to the face wall (fig. 1.2). For the shape of the piers, there are also many possibilities. In new bridges, piers generally rise up only to the spring of the arches and are covered with stone plates in the form of a roof (fig. 1.3). Though very often old bridges, that do look so charming, have a different curvature of the road in elevation between the ramps (fig. 1.4).[6]
Another masonry arch bridge type is the barrel structure: the opening of the structure above the arch with transverse walls and small vaults decreases the weight of the bridge and the arch thrust. The good proportion between the wall thickness and the spacing should be at least 1:4 (Fig. 1.5). For viaducts on high piers, the Roman semi-circular shape is preferable shaping the arch by following the thrust line (Fig. 1.6).



1. 5 Masonry barrel arch.



1. 6 Series of arches on tall piers (viaduct).

From this first reference we will look at how the arch shape changed through history up until modern times. The historical periods were taken into consideration from the conventional periods: Ancient Roman, Middle Age, Renaissance, 18th century and 19th century. The aim of the following brief description of every period, with some important examples, is to characterize the arch bridge in different historical contexts along with the use of different materials and construction techniques. In this chapter

6 The images are taken by: Leonhardt, F., 1994, Brücken / Bridges, Deutsche Verlags-Anstalt GmbH DVA, Stuttgart, Germany

we will also see the arch design up until the 19th century. The modern period and the state of art of the latest realizations will be explained in Chapter 3 *State of art*.
Before discussing what occurred in the world closest to us, I would like to give a brief introduction on the first construction of arch bridges which were made in China. The development of this subchapter is not only due to the presence of interesting arch bridges in China but also to the period I spent abroad at the Tongji University in Shanghai, more precisely under the guidance of professor Airong Chen in the Department of Bridges. The research work carried out at this foreign university allowed me to come into contact with a reality that is different and charming as well as having access at their material, that consists mostly of recent realizations and planning projects. This brief introduction, however, is meant to give a historical background on some known examples with great architectural value.

1.2 Chinese ancient arch bridges[7]

Throughout history, the Chinese nation has erected thousands of bridges, which form an important part of its culture. Ancient Chinese bridges are universally acknowledged and have enjoyed high prestige in the bridge history of both in East and in West.[8]
China is a big country where nearly every region has a different language, culture and necessities. In the case of stone bridges, diverse land transport and the varying morphologic position between north and south, permitted the different styles in the construction of the arch bridges. To the north the flat-deck bridge with solid spandrel prevails, thick piers and arch rings, whereas to the south, with the presence of many rivers, the hump-shaped bridge with thin piers and arch structure prevails.
The most ancient Chinese bridge is the Anji Bridge, and maybe the oldest arched stone bridge in the world, also known as the Zhaozhou Bridge(Fig. 1.7), at Zhouxian, Hebei Province, built in 605 A. D. during the Sui Dynasty by an architect named Li Chun. It is constituted by a single arch span made by stone and composed of 28 individual arches connected transversely. The stone arch was built by vertically juxtaposing 28 arch rings, each 34 cm wide and capable of standing erect by itself, which facilitates the construction work and independent repairs. With

[7] A big part of the material available and directly consulted in China was written in the original language with the obvious problems of understanding. Therefore, the material provided has been obtained from books transcribed in English and from the website of the Tongji University that collect an interesting survey of the bridges built in their country (http://bridge.tongji.edu.cn/cb/ancient/ancient.htm).
[8] Gies J., 1966, *Bridges and Men*, Universal Library Edition, USA., p.19
Troyano L. F., 2006, *Terra sull'acqua, Atlante storico universale dei Ponti*, Dario Flaccovio Editore, Palermo, Italia, p.120

its solid foundation and a grand view, the structure features a completely reasonable design and ingenious construction techniques. The bridge is 37 m span with a rise of 7.23 m. Each of its spandrels is perforated by two small arches, 3.8 m and 2.8 m respectively in clear span, so that flood water can be drained and bridge weight is lightened as well. The bridge represents a unique structure for that period and we can only see similar such examples in Europe from the start of the Middle Ages.

1.7

1.8

1. 7 Zhaozhou Bridge, Hebei Province, China, 37 m span, 605 A.D., Li Chun
1. 8 Lugou Bridge, near Bejing, China, 1192 A. D., 212.2m long, 11 semicircular arches, ranging from 11.4m to 13.45 m in span

1.9

1.10

1. 9 Seventeen arch Bridge, Summer Palace, Beijing
1. 10 Jade Bridge, Summer Palace, Beijing

"Over this river there is a very fine stone bridge, so fine indeed, that it has very few equals in the world." These are the words Marco Polo described the Lugou Bridge (Fig. 1.9) that crosses the Youngding River near Beijing city. The project was completed in 1192 A. D. during the Jin Dynasty. It is 212.2 m long and it presents 11 semicircular arches, ranging from 11.4 m to 13.45 m span. Every column is decorated with lions sculptures, each one different from the other. As well as being famed for its formal features, the Lugou Bridge is also considered to be an architectural masterpiece.
In Beijing there are two of the most important ancient Chinese arch bridges, both located in the Summer Palace Garden: the Seventeen arch Bridge (Fig. 1.9) is a decreasing arch with a total length of 150 m and the famous Jade Bridge (Fig. 1.10) that is a single marble arch with humped-shape. The need of the bridge to overcome water at a sufficient height as to allow the navigation below meant that the shape of the bridge was determined by two sloping roads. It is really fascinating to cross the bridge where the deck in the middle part follows the trend of the arch perfectly.

In the southern part of China, in the Jiangsu and Zhejiang provinces, connected by navigable rivers, boats were the main means of transportation. As bridges were to be built over tidal waters and their foundations laid in soft soil, even stone arch bridges had to be built with thin piers and shell arches in order for its weight to be lightened as much as possible. The Fengsheng Bridge (Fig. 1.11) in Zhu jia jiao, in the Shanghai province, built during the Qing Dynasty, is characterized by its shell arch and with piers so thin that the arch stones meet on it.

1. 11 Fengsheng Bridge, Zhu jia jiao, Shanghai Province

The Gongchen Bridge (Fig. 1.12) in Hangzhou, Zhejiang province is a typical example. The bridge was built in the 4th year of Chongzhen's reign (1631 A. D.) during the Ming Dynasty. The middle arch is 15.8 m long in clear span, while the two side ones are 11.9 m each. The middle pier is around 1 m thick. Another example of this type of arch bridge shape is the Guangji Bridge (Fig. 1.13) in

Tangqi, Zhejian Province, with seven arches and both bridges present decreasing spans.

1.12 1.13

1. 12 Gongchen Bridge, Hangzhou, China, 15.8 m
1. 13 Guangji Bridge, Tangqi, Zhejian Province, China

The longest surviving multi-span bridge with shell arches and thin piers is the Baodai Bridge (Fig. 1.14) in Suzhou, Jiangsu Province. Built in the Tang Dynasty but having undergone a series of renovations in successive dynasties, the bridge is now 316.8 m long and has 53 spans in all. The three central arches are higher than the rest to allow the boats to pass through and both ends of the bridge are ornamented with lions, or pavilions and towers, all of stone.

1. 14 Baodai Bridge, Suzhou, Jiangsu Province, China

1.3 Roman Period (700 a. C. – 400 d. C.)[9]

The arch was applied later on respect to the beam, and after an initial period where the false arch was introduced, it can be said that the important use of this structure began with Romans. During Roman times, most bridges were constructed as stone arches, also known as masonry or Voussoir arches. These wedge-shaped elements were made by means of precise rules: the roman arch is characterized by geometrical perfection and the Voussoir arch have the same dimension from the imposts to the keystone.[10]

Romans were magnificent builders and many of their masonry bridges are still standing today. Stone arch bridges are very beautiful and much admired and a wide number have become the fundamental core of their cities. Stone is capable of supporting very large compressive forces: the arch is stable as long as the thrust line is contained within the cross-sectional area.[11] Masonry arch bridges are very durable: Voussoir arches were even more durable and robust than the stone beams.

Romans had the issue of crossing the rivers, so how could the placing of the piers on a mud river be solved? How could the construction problem be resolve? The typical Roman arch, and the only one that they knew, is represented by the semi-circular shape. In fact, Romans intuited that the thrust from the arch was going directly down onto the support piers. From this experience it was clear to note how the shape of piers acquired a key role in the design and construction of a bridge. Piers were usually made, especially earlier on, by a ratio scale of pier/arch span equal to unity: the pier had the same amplitude as the arch span. The choice of having a large sized pier was useful in the construction phase: if they were built wide enough at about one-third of the arch span, then any two piers could support an arch without shoring or propping from the sides. In this way it was possible to build a bridge from one shore to the other shore, one span at a time, without having to assembly the entire structure across the river before even starting the arches.[12]
The size of the piers was also influenced by the difficulty in the construction of the

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[9] As mentioned before, the arch and its use in bridge construction has a long history and there are countless bibliographies about it. Here there are cited: J.J. Arenas, 2002, *Caminos en el aire*, Colegio de Ingenieros de Caminos, Canales y Puertos, Marid, Spain; Withney C.S., 1983, *Bridges, their art, science & evolution*, Greenwich House Edition, USA.; Gies J., 1966, *Bridges and Men*, Universal Library Edition, USA.

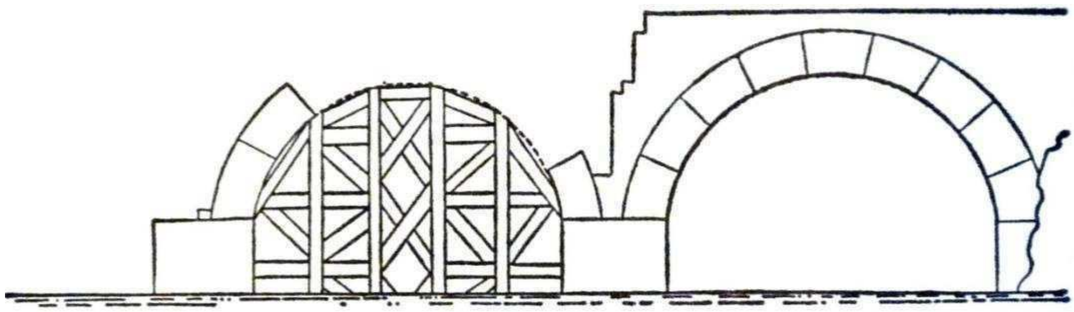
[10] Troyano L. F., 2006, *Terra sull'acqua, Atlante storico universale dei Ponti*, Dario Flaccovio Editore, Palermo, Italia, p.126

[11] Gerard F. Fox, *Arch Bridges*, in Chen W.F. and Duan L., 2000, *Bridge Engineering Handbook,* CRC Press LLC, USA

[12] David Bennett, *The history and aesthetic development of bridges*, in Ryall M.J., Parke G.A.R.& Harding J.E., 2000, *Manual of bridge engineering*, Thomas Telford Edition, London, UK, p.5

foundations. For all these reasons Roman bridges are generally composed of a series of stone arches that permits them to pass over the water.[13]

The stone arch was built by means of a wooden framework resumed with the exact profile of the final arch (Fig. 1.15). The semi-circular arch meant that all the stones were cut identically and that no mortar was needed to bind them together once the keystone was locked into position. The compression forces in the arch ensured complete stability of the span. What is still standing today, whether it be a bridge or an aqueduct, rank among the most inspiring and noble of bridge structures ever built, considering the limitations of their technology.[14]



1. 15 Construction procedure of Romans arch bridges

The strength of Romans was dependent on their transportation system. Along the roads, realized throughout the Empire, many bridges were built and we can find important examples of them in France and Spain. Romans understood that the establishment and the maintenance of their empire depended on efficient and permanent communication routes. Building roads and bridges was therefore of high priority. Their influence on bridge building technology and architecture has been profound. Roman bridges, which remain standing today, are admired as much for their artistry as for the monumental form built with limited technology.[15] Arch bridges respected order in the design shape and this sensitivity in construction became culture and tradition.

An example of this is the Sant'Angelo Bridge (Fig. 1.16) over the Tiber River in Rome: it was built in 136 B. C. and in 1668 by suggestion of Bernini was embellished with the angel statues. The bridge is faced with travertine marble and spans the Tiber with five arches. The piers are thick and taper upstream to divide

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[13] To a greater knowledge about the scenario of Roman bridges, see: Galliazzo V., 1995, *I ponti romani*, vol. I: *Esperienze preromane, storia, analisi architettonica e tipologica, ornamenti, rapporti con l'urbanistica, significato*, and vol. II: *Catalogo generale*, Treviso, Italia; S. Delli, 1977, *I ponti di Roma*, Newton Compton Editori, Roma, Italia

[14] Ibid.

[15] Bennett D., 1997,*The architecture of bridge design*, Thomas Telford Publishing, London, UK., p.6

the floodwaters. The face walls are terminated at the top by a slightly projecting ledge.[16]

1. 16 Sant'Angelo Bridge, five spans of 18 m, 135 m total length, completed in 134 B.D., Rome

The most famous Roman bridges are the great aqueducts used for the transportation of water to the cities. The aqueducts consisted of open channels, without pressure, with a considerable height in order to overcome the valleys. Romans resolved the problem of the height by superimposing one deck to another until reaching the altitude required.

1.17

1.18

1. 17 Pont Du Gard, Gardon RiverNimes, France, I sec B.D., 24 m span
1. 18 Segovia Viaduct, Spain

Probably the most famous aqueduct is the Pont Du Gard at Nimes in France. It stands as a monument (Fig. 1.17). This is the largest well-preserved Roman bridge of all, and it is simultaneously a road bridge and an aqueduct, built in 63-13 B. C. Above the lower six arches the long aqueduct rises into two storeys to a height of 46.4 m above the river. Built on three levels, the Pont Du Gard is 49 m high, the longest level is 275 m long, the lower level is 142 m long with 6 arches, the middle

16 D'Amelio M. G., *Il ponte degli angeli a Roma*, in Calabi D. and Conforti C., 2002, *I ponti delle capitali d'Europa, dal corno d'oro alla senna*, Electa, Milano, Italia

level is 242 m, and it has 11 arches, the upper level has 35 arches with a total span of 275 m. On the first level there is a road and at the top of the third level, a water conduit. It was entirely constructed without the use of mortar. Another important famous aqueduct is the Segovia Viaduct (Fig. 1.18).

Bridges built by Romans had a significant development from the start up until the end of the Empire, because of their accumulated experience. From these descriptions it is easy to understand that the intention of those who created the bridge was to try to alleviate the pressure as much as possible on the piers. The continuous research to lighten the structure led to the use of small arches at the springing site.

As mentioned above, there are many bridges that have survived over the centuries, some famous examples are described here just to give an idea of the arch shape used at the time. When the Roman Empire collapsed, it seemed as though the progress around the world had stopped for a long period of time. It was left to the spread of Christianity and the strength of the church to start the next boom in road building and bridge building around 1000 A.D.

1.4 Middle Ages period (500-1400)

In the 12th century important bridges were built by Fratres Pontifices, a monastic order, who were the first to start building with flat segmental arches. The shape of the arch bridges in the Middle Ages improved respect the Romans by using narrower piers, thinner arches and lower span-rise ratio. The slenderness of the arch increased significantly decreasing the ratio between the thickness of the stones and the span of the arch. As said by Bennett[17], the aim of this church order, "*the brothers of bridges*", obviously apart from its spiritual duties, was to aid travellers and pilgrims by building bridges along pilgrimage routes, offering boats for their use and welcoming them to stay in hospices built for them on the riverbanks.

In this period the mechanism of the resistance of arches became clearer: the shape of the arch structure is amended in favour of a lowered form, however there are examples of semi-arch bridges. The medieval bridges also have bigger cutwaters than Romans, sometimes with the presence of rear cutwater that demonstrates a greater knowledge of the effect of water on foundations.

A famous example of this during this period is the bridge over the Rhone River in Avignon (Fig. 1.19). It had an original length of some 900 m but it suffered frequent collapses during floods and had to be reconstructed several times. In the end the bridge was put out of use by a catastrophic flood in 1668, which swept away much

[17] Ryall M.J., Parke G.A.R.& Harding J.E., 2000, *Manual of bridge engineering*, Thomas Telford Edition, London, UK, p 6

of the structure. The consequent abandonment meant that the bridge had subsequent collapses and only 4 of the initial 22 arches remain intact to this day.
Medieval bridges have the characteristic of having fortified lookout towers built in the middle or at the ends of the bridge. In the Middle Ages, bridges constituted strategic routes and for this reason they had to be defended. Many bridges had a part that could be raised as to block the passage over it. For this reason, some examples of medieval bridges have an arch with a shorter span.

1. 19 Avignon Bridge, over the Rhone River, France, XVI century, 34 m span

The Scaliger Bridge (Fig. 1.20) over the Adige River in Verona is of the same period (1354-1356). Built in red brick at the top, like all the medieval monuments of Verona, and white marble on the bottom, the bridge consists of three arches of decreasing span. The major span was daring for the time, and every length is respectively 48.70 m, 29.15 and 24.11 m. The bridge is then longer than 120 m. The face walls of red brick are crowned by pinnacles, which are typical for the Scaliger period.
Bridges of the Middle Ages were equipped with fortification towers and gates like the Valentre Bridge (Fig. 1.21) over the River Lot in Cahors, France (1308-1355) that was built with six Gothic arches and three square towers. The face walls are joined to the massive parapet without any interruption by a ledge.

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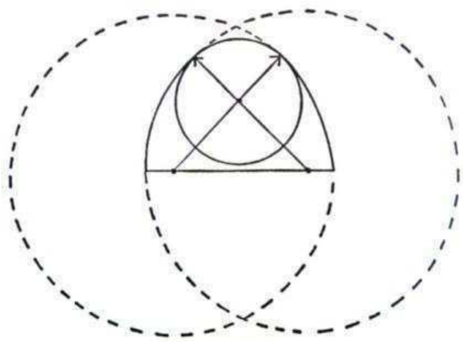
1. 20 The Scaliger Bridge over the Adige River, Verona, Italy, 24 m-27 m-48.70 m, 1356
1. 21 Valentre Bridge, Lot Riverin Cahors, France, six spans of 16.50 m length, 1350

The Gothic elliptical arch presents a shape with the long axis in a vertical position, this is an effect achieved by constructing the arch from three separate circles, with the smallest at the top (Fig.1.22). This typology required a pier of only one fourth of the arch span rather than the Roman semi-circular arch that required from one third to one half of the arch span.[18]



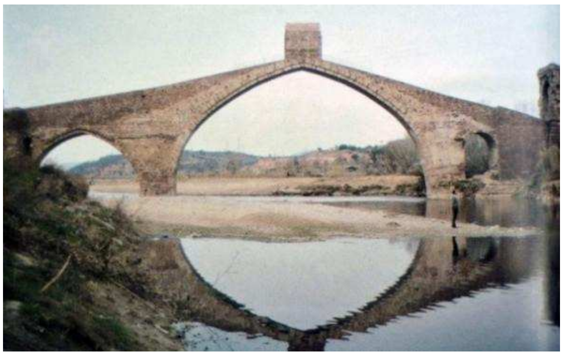
1. 22 Gothic arch

A peculiarity of the Middle Ages is represented by the so-called hump-back bridges[19], which consist of two ramps that meet at the summit, at the centre of the arch: the two road ramps reach the middle at the height of the key stone leading to the point of change of inclination. Hump-back bridge permits to have a major height of the deck from the water level, allowing a greater flow in case of flooding. In this way it can cover large spans with a single arch, without intermediate piers that become necessary in a bridge with a horizontal plane.
This particular form, named “moon bridge” in Asiatic countries, comes from the size of the rise: it was necessary to raise the height above the river banks in order to develop the arch. The hump-back bridge was a structural necessity, which could be more or less accentuated according to the formal intentions of those who had designed and built the bridge and also to the historical period. This architectural solution is used at different epochs of history because it assured the parts of the bridge would be less prone to the violence of the water. The slenderness of the arches increased significantly, decreasing the ratio between the thickness of the stones and the span of the arch.
Many medieval bridges in France, Spain and Italy, were designed by local people called "magister muri" who were the architects of their time, and were built because of the work of the monks which was also provided to the maintenance of roads.
A good example of a hump-back bridge with inclined planes is the Maddalena Bridge (Fig 1.23), over the Serchio River, near Lucca in Italy, dating from the 12th

[18] Gies J., 1966, *Bridges and Men*, Universal Library Edition, USA., p.30
[19] Donà D. and Laconi L., 2010, *I ponti a schiena d'asino della Romagna Toscana e i "magister muri" costruttori di ponti*, tesi di laurea, relatore Siviero E.; correlatore Palaoro S., Università IUAV di Venezia

century. The bridge is called, just like many others, the Devil's Bridge: this name derives from a legend that recounts that the construction of it seemed so impossible the builders were forced to ask the devil for help, who in exchange for the completing the bridge in one night, demanded the first soul that would ever cross the bridge. The story relates that the devil get cheated in his prize, seeing an animal cross the bridge for first. The shape of the river mainly affects the morphology of the artefact: the Maddalena Bridge, is asymmetrical as is the river bed. Another one of the problems, that has always been attempted to be reduced or avoided, and that led to the ruin of many stone bridges, is the reversal of tympanums which is caused by the thrust due to the filling of the walls.
In some examples of this period there is the presence of a votive construction on the key, necessary to concentrate load in this part and to have a correct structural regime, balancing the presence of massive loads at the abutments, and to prevent rupture of the arch (Fig. 1.24).

1.23



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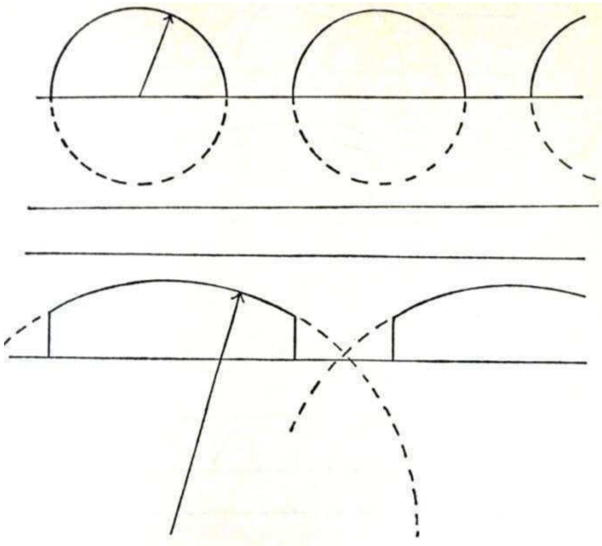
1. 23 Maddalena Bridge, Serchio River, Lucca, Italy, 1100
1. 24 Martorell Devil Bridge, Llobregat River, XIII century, 37 m span

1.5 Renaissance (1300-1500)

After the Dark Ages and Feudalism came the age of Enlightenment and Renaissance. During the Renaissance, also known as the age of the arts, there was a notable change of style in the arch bridge construction. The size of the piers was similar to the medieval period while arch shape resumed the Roman slenderness.
It is in this period, however, the greatest change of the arch shape was seen: from the semi-circular arch it passed to the segmental arch. The shape of the “segmental” arch (Fig. 1.25) consists basically of a part of a circle. This typology has deep structural differences: with this type there is horizontal forces that are burdened on the piers. The new shape of the arch bridge acquires significant advantages, especially for the needs dictated by the environment.



1. 25 Semi-arch and Segmental arch shapes

Also in this period there are many examples of hump-back bridges, even though the arch tends to have a more horizontal profile. The arch shape looks descending from the centre towards the ends (as seen for the ancient Chinese bridges). Renaissance is synonymous for the use of decorative orders and architectural proportions. Construction techniques was improving continuously paying attention to the stability of the bridge and the lesser use of material.

At the end of Middle Ages and at the beginning of Renaissance many bridges had constructions on them, many of which intended for housing. The Ponte Vecchio in Florence (Fig. 1.26), erected in 1345, is a famous example an inhabited-bridge with buildings along its full length. The architecture of this bridge is truly unique, not only for buildings, but for its most innovative feature the extremely shallow arches compared with any previously built arches: very low 30 m span and it is for this reason that was considered a turning point for Dark Ages.

One of the most famous bridges of the Renaissance is the Rialto Bridge on the Grand Canal in Venice (fig. 1.27). It consists of a single segmental stone arch with 27.5 m span and 7.3 m rise. It was constructed between 1588 and 1591under the supervision of Antonio Da Ponte (1515-1597 circa). The construction was made difficult by the conditions of instability and by the height of the sea bottom. The structure, very similar in style to the previous wooden bridge, is formed by two inclined ramps, with shops on each side, covered by a portico. John Ruskin once said of it: "*The best building raised in the time of the Grotesque Renaissance, very noble in its simplicity, in its proportions and its masonry*".[20] This shape type is

[20] Ryall M.J., Parke G.A.R.& Harding J.E., 2000, *Manual of bridge engineering*, Thomas Telford Edition, London, UK, p.8

commonly used in Venetian bridges because the banks are all at water level and the arch needs to be high enough to allow for navigation.

1.26

1.27

1. 26 Ponte Vecchio, Florence, Italy, three span of 30 m, 1345, (Vasari attributed to Taddeo Gaddi)
1. 27 Rialto Bridge, Venice, Italy, 27.5 m span, 1591, Antonio Da Ponte

Equally innovative bridge construction was developing across Europe. In the state of Bohemia over the Moldau River in Prague the famous Charles Bridge[21] (Fig. 1.28) was built in 1503. It took a century and half to completely finish it. The bridge is 516 m long and nearly 10 m wide, and consists of 16 arches.

1. 28 Charles Bridge, Prague, Czech Republic, 16 spans (length: 16.62 - 23.38 m), total length 515.76 m, 1380, Peter Parler

The finest examples of late French Renaissance Bridge built during the XVII century are the Pont Royale (Fig. 1.29) and Pont Marie Bridge, both of which are still standing today. The Pont Royale was the first bridge in Paris to have arches with elliptical features and the first to use an open caisson to provide a dry working area in the river bed.

[21] De Meyer D., *Il ponte Carlo e la controriforma a Praga*, in Calabi D. and Conforti C., 2002, *I ponti delle capitali d'Europa, dal Corno d'oro alla Senna*, Electa, Milano, Italia, pp. 131-141

1. 29 Pont Royale, Paris, France, 20.58 m - 22.70 m - 23.52 m - 22.44 m - 20.64 m span, 1687, Jules Hardouin Mansart

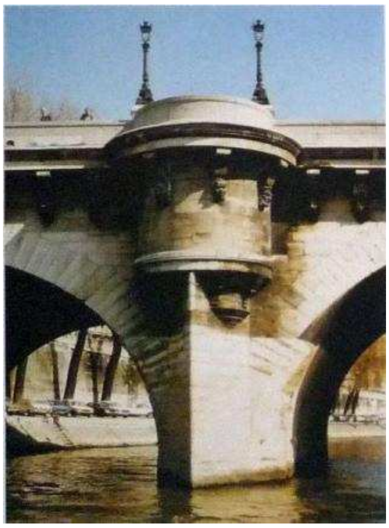
It is in this period that the major European cities evolved. Thanks to their tactical locations, were often positioned in transit zones and with the presence of water that divides the city into separate parts, they therefore become important nodes along the lines of communication and economic routes. Venice, Florence, Paris, London, Nuremberg, Seville, and many more, are concrete examples of how a place, characterized by a considerable problem of division could become a centre of commerce. The economic fortune of some cities is mainly due to the position of the market, compared to other city destinations that constitute a focal point around which the lives of citizens revolve: the presence of public spaces, ranging intersections with the mesh of the residences, and the possibility of paths meant that the "passage" became a fundamental requirement and at the same time an opportunity. The bridge is not only a constrained route, but becomes "inhabited", a place where multiple interests can exist together, a point of connection between two residential areas growing on two opposite sides.
The examples cited above, Rialto, Ponte Vecchio and the bridges in France, then came to acquire an economic significance, beyond the purely strategic transition. Bridges on the River Seine are defined by the archbishop Andrea Minucci during his travels "*so wide and with buildings above them so big* [that those who walked on it in seemed to be] *in a square rather than on a bridge*." The symbol that these bridges possessed inside the city was certainly greater than any other value: they are a sign of entrepreneurship for the people who live in these cities that went beyond the national pride, because for a long time the construction of bridges, which are among the world’s most popular, were funded by private donations from citizens who saw through their implementation the progress of the city as a whole.[22]

At the start of Renaissance the role of the architect integrated the theoretical structurer and the manufacturer into one person. Filippo Brunelleschi (1377-1446),

[22] Calabi D., *Il ponte e la città europea in età moderna*, in *De pontibus, Un manuale per la costruzione di ponti*, 2008, a.c.d. Dobricic S. e Siviero E., Il sole 24 ore, Milano, pp.71-87

Leon Battista Alberti (1404-1472), Leonardo Da Vinci (1452-1519), Michelangelo Buonarroti (1475-1564), Andrea Palladio (1508-1580) and Antonio Da Ponte (about 1515-1597) all experimented new architectural forms of bridges.


1.30


1.31

1. 30 Bridges in Paris
1. 31 Pont Neuf, Paris, France, 1607, spans of 19,5 m and 17,7 m length, Baptiste Androuet Du Cerceau

1. 32 Mostar Bridge, Bosnia, XVI century, 30 m span, Hajrudin

In the 17th century and especially during the 18th century there was a notable development of communication links between many European countries. These new roads demanded the construction of many bridges. During this period, France remained the country of ingenious bridge builders, which contributed to the further development of stone bridge, and French techniques were then considered as a model to be followed in most European countries. Primarily there is Paris with its numerous bridges crossing the Seine River (Fig. 1.30). The most known of these old stone bridges is the Pont Neuf (Fig. 1.31), at the end of the Seine Island, which was built in 1607 and designed by Baptiste Androuet Du Cerceau (1544/47–1590).

The bridge consists of two independent sections, one with seven arches and second with five. The arches have a semi-arch shape with decreasing spans, as the classic typology of hump-backed bridge required, which was modified over the century due to subsequent necessity of reparation. The bridge represents one of the more typical masonry bridges in the city.
The arch shape changed from the semi-arch to a lower form, until the arrival of the engineer Jean Rodolphe Perronet (1708-1794) in the mid 18th century.
The examples of bridges with an significant history are very numerous all over France, but not only, like in Spain, England or in Turkey and in the Balkan countries where there were bridges built after Roman age. The Bridge over the Neretva River in Mostar (Fig. 1.32), in Bosnia, was built in 16th century. The bridge narrowed between the rock and fortress has a span of 30 m and a rise of 19 m above the river. It was destroyed in 1993 during the Bosnian War. Subsequently, it was rebuilt in 2004.

1.6 18th century

In the 16th century, Palladio described the bridge in the following way: "*The convenience of bridges was first thought upon because many rivers are not fordable by reason. Of their largeness, depth, and rapidity: upon which account it may be well said, that bridges are a principal part of the way; and are nothing else but a street or way continued over water. Bridges therefore ought to have the self-same qualifications that are judged requisite in all other fabrics: which are, that they shall be convenient, beautiful and durable*".[23]
The 18th century was the era when civil engineering was finally born as a profession, when the first school of engineering was established in Paris at the Ecole de Paris. With the presence of a vast knowledge it was inevitable that building architecture and civil engineering should be separated into the two fields of expertise.[24]
In the second half of the century, the engineer Jean Rodolphe Perronet (1708-1794) introduced important innovations in the construction of stone bridges. The arch shape that he chose was the curve of a segment of a circle of larger radius, instead of the familiar three-centred arch. In his works he greatly reduced the size of the piers through offsetting of the arches thrust with the adjacent forces: when the arches have equal length the resultant of the two forces is vertical.

[23] Whitney, C. S., 2003, *Bridges of the World: Their Design and Construction*. Dover Publications, New York, USA, p. 27
[24] Ryall M.J., Parke G.A.R.& Harding J.E., 2000, *Manual of bridge engineering*, Thomas Telford Edition, London, UK, p.11

The main issue of new projects was the construction method: to avoid failure of thrust it was in fact necessary to erect the arches with the simultaneous use of a falsework under all the spans. Unlike Roman bridges if one of the arches were to fall there would be the subsequent and inevitable destruction of the entire bridge. Perronet tried to overcome these problems by designing two distinct types of piers: after a number of slender arch spans one larger pier was made that would have prevented the complete destruction of the entire bridge in case of a collapse of one arch, but that would have allowed for the destruction of a single part.[25]

1. 33 Pont De La Concorde, Paris, France, 1791, 25 m - 28 m - 31 m - 28 m - 25 m span, J. R. Perronet

Of Perronet's greatest enterprises only his last bridge remains, the Pont de la Concorde in Paris (Fig. 1.33): it is one of the most slender and daring stone arch bridges ever built. It was realized between 1787 and 1791 and has a total length of 153 m span (25 m - 28 m - 31 m - 28 m - 25 m). The spans and rises are different for the five arches: the roadway is not the same level along the entire length of the bridge but it rises towards the centre part to give additional clearance for boats.

1.7 19th century

Even if at the beginning of this century can be found many examples of stone arch bridges, the development of the techniques and materials permitted to have a significant structural improvement in the construction of bridges. Industrial Revolution allowed the realization of new transport routes, including railway development, to keep up with the increasing coal exploitation and the manufactory of textile and pottery. A rapid assembly of manufactures was necessary for the construction of new road routes.
Heavy steam engines and longer freight train subjected the bridge structures to new larger stresses than before. Bridge had to be stronger and more rigid and had to be

[25] Troyano L. F., 2006, *Terra sull'acqua, Atlante storico universale dei Ponti*, Dario Flaccovio Editore, Palermo, Italia, p.159

faster to assemble to keep pace with progress. When car arrived, it was necessary to create an infrastructure network that crossed the entire countryside from town to city, over mountains, valleys, streams, rivers, estuaries and seas. This is the period of iron and arch trusses.

A significant iron bridge is the famous Coalbrookdale Bridge, constructed in England to span the Severn River. It is the first realization with the use of this new material. The potential of iron was much greater than the materials known up until that time and with much higher resistance characteristics. The Coalbrookdale (Fig. 1.34), completed in 1779, is a semicircular arch spanning 30 m designed by Pritchard for the owner and builder Abraham Darby III. The size of the cast iron elements in the early arches is astonishing: the ring of some of them is made in two pieces with lengths of over 15 m. The lightening of the tympanums was made by overlapping the main arch of other segments of circles, ending at the deck with support function. These elements are interconnected by bars positioned according to a radial design, as well as the circles under the deck.

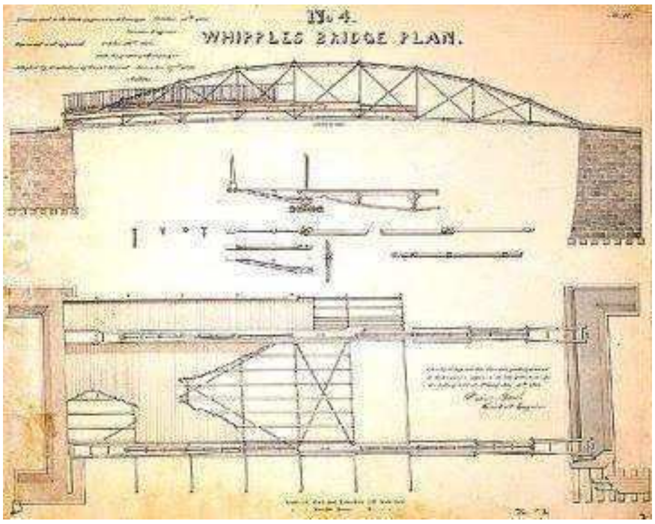
1. 34 Coalbrookdale Bridge, Severn River, England, 1779, T. Pritchard, A. Darby III and J. Wilkinson

The architecture principles of the preindustrial period appear to have been carried forward very successfully into this design. These along with subsequent developments heralded the birth of what can be considered the modern bridge, in which there was a profound marriage between the conceptual understanding of structures and the practice of bridge construction. Steel became competitive with iron, and this material had vastly superior qualities, both in compression and tension. The age of steel opened the door to tremendous advantages in long-span bridge building technology.

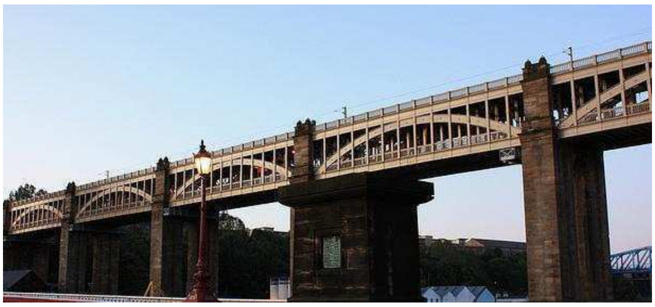
The first metal bridge in France was built in 1803, the Les Arts over the Seine in Paris (Fig. 1.35) with 18.5 m span. The Pont des Arts, or Passerelle des Arts, is a pedestrian bridge in Paris which crosses the Seine River. It links the *Institut de France* and the central square of the *Louvre Palace*. The elegance of its architecture and the great delicacy of the steel sections make it a structure of rare lightness, elevated in relation to the piers. Although it was rebuilt during the Second Empire, the original structure of the footbridge was far too light and the new footbridge(completed in 1985) is not made of cast iron but of steel and has only seven arches instead of nine.

1. 35 The Pont des Arts, Paris, France, 1803, 18.5 m span

The purpose of the introductory part on the bridges of the 18th century was not meant to be a thorough overview of all the works performed, but merely to give an idea as to define how the arch shape has evolved through the use of a new material: Steel. There were many designers in this period have experimented with steel bridges, many of which have not lasted to this day. A new arch shape was born in this period: the bowstring arch was introduced for the first time in 1841 with the patent Iron Squire Whipple Bowstring Bridge, even if according to the project these examples are very close to the design of a beam (Fig. 1.36). The use of steel allows to create new forms of structure, and the arch shape joins the truss shape achieving both a rigid structure, consisting of two superimposed ribs interconnected by vertical elements or St. Andrea Crosses, and a light architecture with the presence of solids and voids.
One of the first examples of this type is the Newcastle Bridge (Fig. 1.37) designed and built by Stephenson in 1849. The bridge consists of six bowstring arches, with a span of 38 m, positioned above very high piers. The bridge has a double deck, the upper one used for the railway line and the lower one for the road.



1. 36 Bowstring patent



1. 37 Newcastle Bridge, 1849, six spans of 38 m, R. Stephenson

This bridge, that is remembered mostly in this period for its massive use of steel in the main structure of the arch and for the innovative construction techniques used, is the St. Louis bridge, called Eads Bridge, after the name of the designer James Buchanan Eads (1820-1887). When completed in 1874, the Eads Bridge (Fig.1.38) was the longest arch bridge in the world, with three longest central spans of 157 m.[26] The construction phase had some difficulties due to the considerable depth of the water: for this reason, the positioning of the falsework for the construction of the arches seemed improbable. Eads used a new construction system, of his own invention, which allowed for this bridge to be built: which was the cantilever construction process.[27]

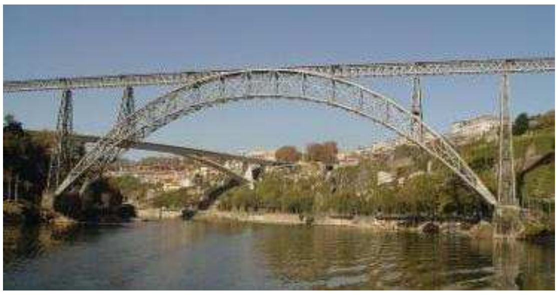
[26] Billington D. P., *The Tower and the Bridge*, Princeton University Press, 1983, Chapter 8: *Big steel bridges: from Eads to Ammann*, p.112

[27] To provide better understanding of this topic, see the next chapter, Chap.2 *Construction methods*, in which the cantilever construction technique is explained with more details.


1. 38 St. Luis (Eads) Bridge, Mississippi River, USA, 1874, 152 m – 157 m – 152 m span, J. Eads

The St. Louis bridge was built starting from piers and advancing symmetrically on both sides. The weight of the cantilever arms was supported by provisional cable stays. The construction of the triple spans, tubular metallic arches, was supported by two shore abutments and by two mid-river piers. It has four pairs of arches per span (upper and lower) that are set eight feet apart, supporting an upper deck for vehicular traffic and a lower deck for rail traffic.
The construction method was later used for the realizations of many other metal bridges, among which there are the notable bridges of Gustav Eiffel (1832-1923). He believed that: "*the first principle of architectural beauty is that the essential lines of a construction be determined by a perfect appropriateness to its use*". Eiffel clearly saw that the new materials and the new structural forms defined a new art form for large scale building.[28] The Maria Pia Bridge (Fig. 1.39) is a railway bridge built in 1877 in Porto, Portugal. Built of wrought iron and its two-hinged crescent arch was used to carry the railway line and with this project Eiffel demonstrated that the more beautiful forms coincides with the most useful structures.
The Douro is a River that has seen the construction of many bridges over the centuries, including the Arrabida Bridge, built in 1963 and designed by Edgar Cardoso (1913-2000)[29].
The Garabit Viaduct (Fig. 1.40), the second crescent arch bridge designed by Eiffel, is a railway bridge spanning the Truyère River, in France. The bridge was constructed between 1880 and 1884 and was opened in 1885. It is 565 m long and has a principal arch of 165 m.

[28] *Bridge aesthetics around the world*, 1991, Committee on General Structures, Subcommittee on Bridge, Aesthetics, Transportation Research Board, National Research Council, Washington, USA, p. 67 and Billington D. P., *The Tower and the Bridge*, Princeton University Press, 1983, p.61.
[29] Please refer to the next chapter for a more detailed explanation of the bridge along with some images.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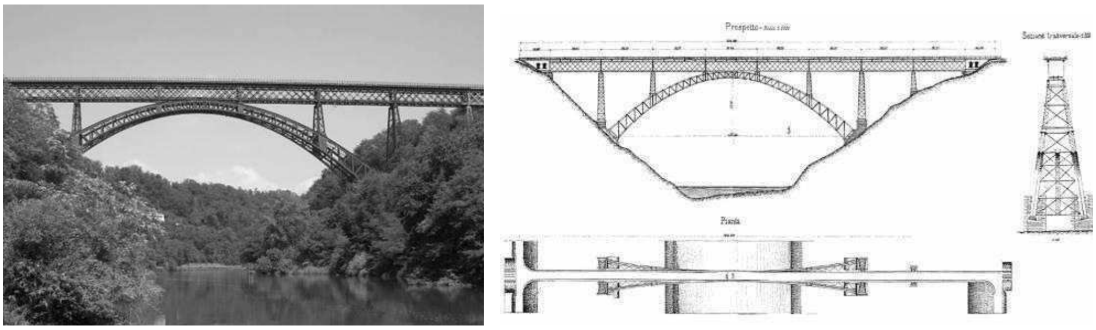
1.40

1. 39 Maria Pia Bridge, Duero River, Oporto, Portugal, 1877,160 m span, G. Eiffel, T. Seyrig
1. 40 Garabit Viaduct, Truyere River, France, 1884, 166 m span, G. Eiffel, L. Boyer

This structural system and the use of steel had also developed in Italy, although it was not very frequently used. Here the Paderno Bridge over the Adda River will be discussed (Fig. 1.41).[30]



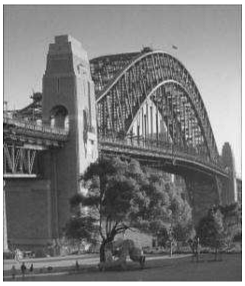
1. 41 Paderno Bridge, Paderno D'Adda, 1889, 150 m span, J. Röthlisberger

The use of steel and of the cantilever construction system saw great develop in America in building bridges of remarkable spans. The Hell Gate Bridge (Fig. 1.42), built in 1917 and designed by Gustav Lindenthal (1850-1935), has a 298 m span and for many years remained the longest span in the world. The bridge is a half-through truss structure with resistant stone abutments and it was built using the cantilever construction process: cables were not required for the central part thanks the important weight of the lateral sites.
The shape of half-through truss bridge could be found in another two projects of this period: the Sydney Harbour Bridge and the Bayonna Bridge in New York.

[30] For historical references, please refer to chapter 3 *State of art in the Italian Steel bridges.* For more information about the project and the evolution of the Italian bridges see:
Nascè V., Zorgno A. M., Bertolini C., Carbone V.I., Pistone G. and Roccati R. 1984, *Il ponte di Paderno: storia e struttura*, Conservazione dell'architettura in ferro, Restauro
Gentile C. and Saisi A., 2010, *Dynamic monitoring of the Paderno iron arch bridge (1889),* proceedings of ARCH'10 – 6th International Conference on Arch Bridges, Fuzhou, China, 2010, p. 22-37

The Sydney Harbour Bridge (Fig. 1.43), in New South Wales, Australia, designed by Ralph Freeman (1880-1950) and completed in 1932, is not very different to the Hell Gate Bridge: as the shape and construction processes used were identical. The only difference is the length of the span: the Hell Gate Bridge is 298 m span and the Sydney Bridge is 503 m span.
The Bayonne Bridge (Fig. 1.44), over the Kill van Kull River, New Jersey, USA, was built between 1928 and 1931 and has a span of 504 m. The designer Othmar Ammann (1879-1965) focused on efficiency, economy and elegance saying "*the arch, flanked by massive masonry towers, was almost favourably adapted to the purpose" and "an elaborate stress sheet, worked out on a purely economic and scientific basis, does not make a great bridge. It is only with a broad sense of beauty and harmony, coupled with wide experience in the scientific and technical field, that a monumental bridge can be created*." Ammann was an assistant during the construction of the Hell Gate Bridge and he took example from Lindenthal in the design of the Bayonne Bridge, but without adopting the lateral towers that gave it a monumentality perception.[31] In this new bridge the arch does not have a notable variation in the thickness of the lateral site. The abutments that are not covered by stone are surely lighter.


1.42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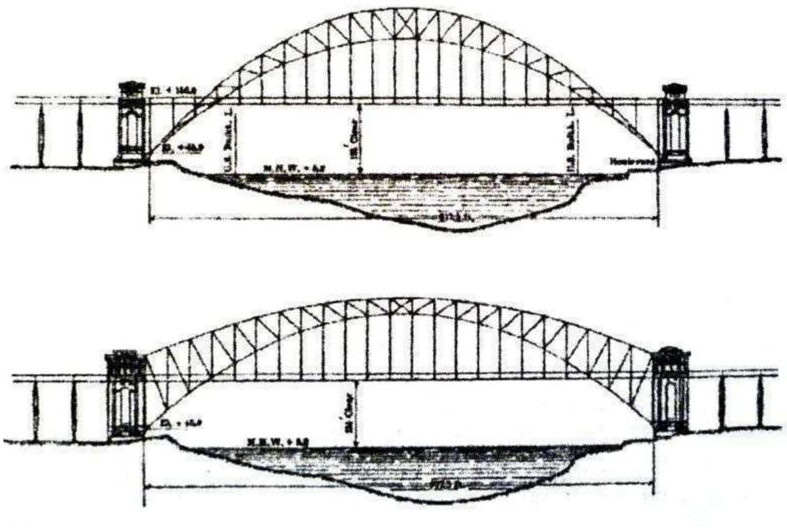
1.44

1. 42 Hell Gate Bridge, East River, New York, USA, 1917, 298 m span, G. Lindenthal
1. 43 Sydney Harbour Bridge, New South Wales, Australia, 1932, 503 m, R. Freeman
1. 44 Bayonne Bridge, Kill van Kull River, New Jersey, USA, 1931, 504 m span, O. Ammann

The most noticeable thing of this period is that the arch span had a remarkable increase in length, reaching unthinkable spans until a few years ago, and as the arch shape changed assuming new forms: from the last examples presented it can be seen that the truss shape had structurally important features in the construction process, besides giving new possibilities to the architectural form of the arch.
Therefore, spandrel braced arch and crescent arch (Fig. 1.45) represent the historical period, with important differences though: spandrel design offers advantages in terms of the cantilever construction method when dealing with constraints presented on the site; the crescent arch, that features an arch form that

[31] Billington D. P. and Thrall A. P., *Bayonne Bridge: the work of Othmar Ammann, master builder*, Journal of bridge engineering, ASCE, November/December 2008, pp.635-643

is deep at the crown and narrows to points at the ends, needs to have cables that support the entire structure until it is completed at the key.
With the use of steel in construction there was a continuous increase of the span length right up until the latest achievements of 1900, discussed in Chapter 3 *State of Art*.



1. 45 Crescent arch and spandrel braced arch

Concrete bridges began to be constructed at the end of the 19th century and in 20th century arch bridges were becoming increasingly sophisticated structures, combining modern materials to create exciting functional urban sculptures. Francois Hennebique (1842-1921) was the first to understand the theory and practical use of steel reinforcement in concrete, but Robert Maillart (1872-1940) was the first pioneer and builder of bridges in reinforcement concrete. Eugene Freyssinet (1879-1962) was also keen to experiment with concrete structures and went on to discover the art of prestressing. All these men were great engineers and champions, as it were, of concrete bridges construction. What they achieved set the trend for future development in concrete bridges, precast beams, concrete arch, box girder and segmental cantilever construction.
Concrete, that will be discussed again later on, is to be considered the material of the last century and for this reason it will be better taken into account in the analysis of the construction methods and in the data raising for the state of art building. Therefore, see the following chapters: Chapter 3 S*tate of art*, it will see some examples of Italian arch bridges and Chapter 4 titled *Construction*, there will show some examples of concrete arch bridges realized in different historical periods, analyzing the different construction methods used in the assembling phase.

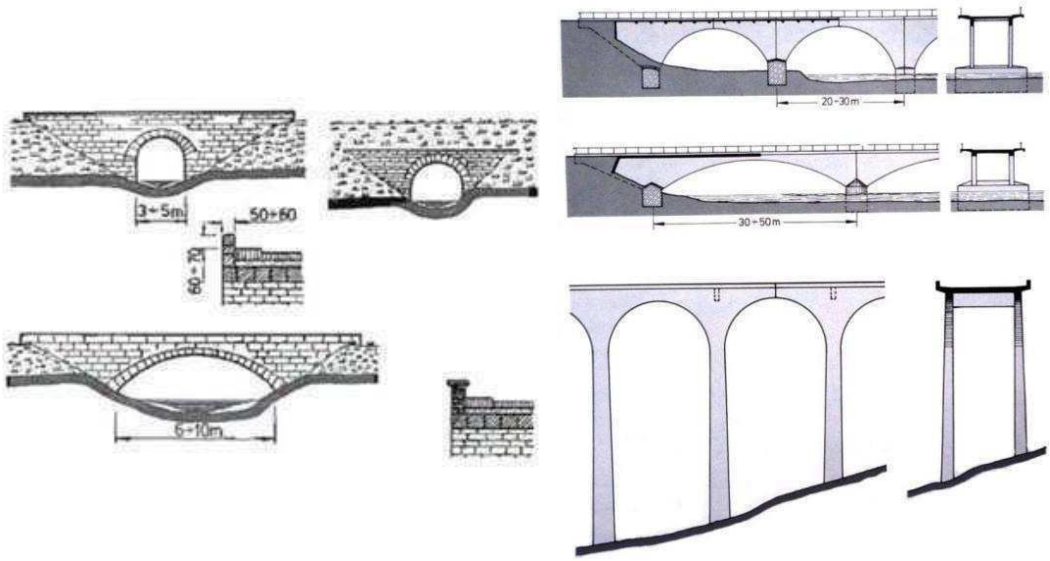
1.8 What beauty means?

From the brief historical excursus above, it can be easily deduced how the discovery of new materials and the creation of new construction techniques, as well as the development of knowledge of the structural strength of the arch, have greatly influenced the architectural form of the arched bridge. Every historical period is characterized by a certain shape and each century has taught us how arch bridges are not only a useful means of transit, but are objects in themselves that become an integral part of their surroundings. From here questions derive like: at what point can a bridge be considered beautiful? What design process must be followed as to allow the viewers appreciate the work that they are looking at or passing through?
The definition of beauty is: "*the quality present in a thing that gives intense pleasure or deep satisfaction to the mind and to senses and is associated with such properties as harmony of form or colour, excellence of artistry, truthfulness, and originality*". In the project phase it is important take into consideration many aspects that can influence the entire life of the structure starting from the design. "Originality" of a work, if done well, will make the object become the symbol of the place where it is built. The "Harmony of the form" is strictly connected to the "truthfulness" of the structure.

"Form follows function"
Architect Louis Sullivan (1856-1924)

According to this famous citation, that is especially suitable when you consider the very structure of the arch that works only once completed, if the shape does follow the function of the structure, it is true to say that for each project carried out there would be a different example of arch bridge throughout the world. This means that in accordance to the finality of the bridge, which is to pass over an obstacle and to allow for a quicker crossing, the design not only pursues the structurally efficiency but also a pleasing appearance. The project of a new bridge is influenced primarily by the location and by the length to be attained.

An arch bridge project must appropriately assume the context of all the elements that characterized it. For example for spans between 20 and 40 m (Fig. 1.46) we have seen as the development of architecture and structure of the arch made it possible to have smaller thickness using less material. From Roman arches with full sections it then passed to sections consisting of only the load-bearing walls with the use of other materials, which are very simple to construct and much cheaper than they would be in stone or brick.



1. 46 Roman arch bridge with full section and modern bridge with lateral walls

Depending on the construction site, which could be for example a flat plain or a valley with a deep gorge to overcome, the bridge has to be modelled according to the requirements This implies that if the terrain is flat, the arch of the bridge will be very close to the ground following its trend, but if the road, that the bridge will be forming, is for any number of reasons at a height greater than the level of the land, the bridge will be built on high piles, as we have learnt from the ancient Roman aqueducts.

If the span, that is to be used in the design phase depending on the requirements of the site and on the construction process, is more than 30 m or so (Fig. 1.47), it is better to employ an open structure in order to use less materials as possible and to make the complete image of the bridge lighter. On the contrary, a filled structure would be synonymous of heaviness. The supports of the deck can be made by either walls or structural columns, depending on the type of the deck installed.

1. 47 High arch: pleasing appearance is created by open spandrel above arch crown
Shallow arch: deck and arch are joined at crown.

The formal feature, that reflects the architecture, is the relationship that exists between deck and arch, where they are joined at the crown or remain separate and distinct from intermediate supports.[32]
The shapes and dimensions of the arch are characterized by the choice of building site and by the entire structure considered for the implementation of the new project. The typological choice of the arch influences firstly the architectural aspect and secondly the structure and the construction phase.
The deck arch bridge, in which the deck is positioned over the arch, is the most commonly used type for arch bridge construction and for all stone arches.
For deck arch bridges and for low rise arches (Fig. 1.48) the two hinged type can be advantageous both technically and formally. On flat terrain it is preferable to build arches above the roadway level such as two-hinged arches. Though sometimes the soil is not able to resist the high thrust force, so the "tied arch type" could be used in which the thrust being carried by the tie and the structure works like a beam.

1. 48 Multi-span deck arch bridge

The second typology of arch bridge in relation to of the deck position is the half-through arch bridge: the deck is at an intermediate level between the arch abutments and the crown. To avoid invading the road, the arch divides into two lateral ribs or there is a single arch positioned in the middle of the road. The deck is supported by rods in the central part area and it is backed at the arch in lateral sites by columns. A special case is the fly-bird-arch (Fig. 1.49), that consists of three spans: the central part is a half-through arch and the lateral parts are half-deck arches. The arch ribs are fixed at the arch springings to form a rigid frame structure, tie bars of high strength wires are anchored at the ends of two site spans to balance thrust forces of the arches under deal loads. In this way, it can be built on a flat area with weak foundations. It is also called a self-balanced or self-anchored arch bridge.[33]

1. 49 Half-through arch bridge and fly-bird-arch bridge

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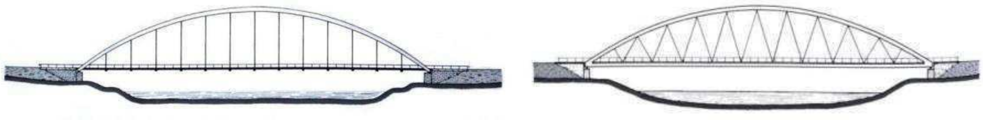
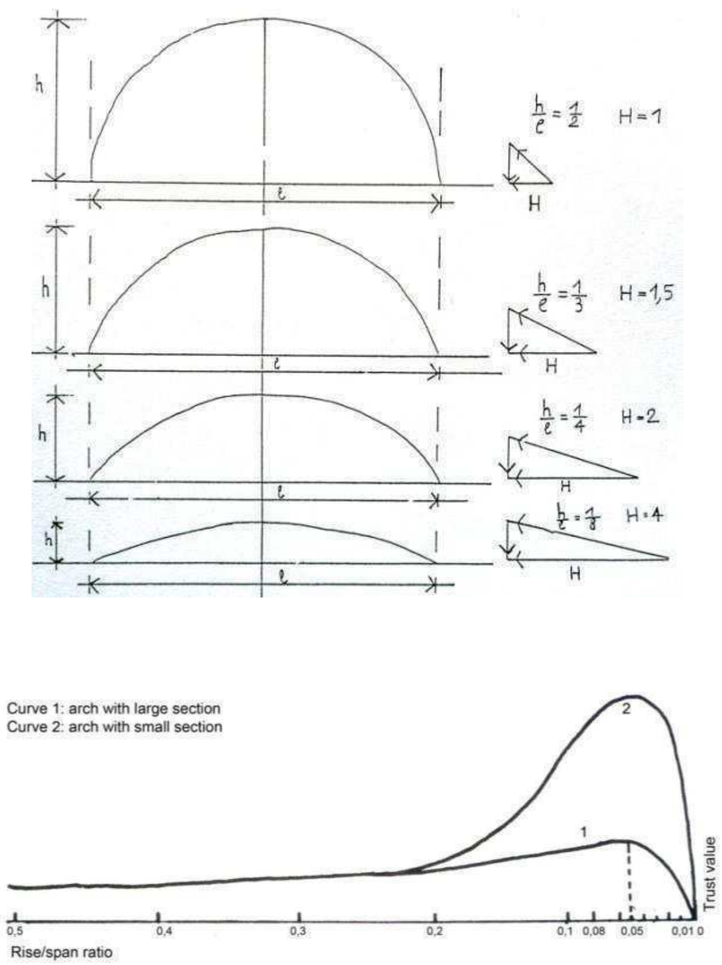
[32] See chapter number 3 for an analysis of the state of art about this architectural feature.
[33] Chen B.C., Gao J., Zheng H.Y., *Studies on behavior of fly-bird type cfst arch bridge*, Proceeding of Bridges International Conference, Dubrovnik, Croatia, May 21-24, 2006, p. 205



a b

1. 50 a) Through arch bridge and b) Whipple arch bridge

If the deck is located below the arch it is a through arch bridge (Fig. 1.50, a) and the deck is located at the supports of the arch. This typology does not permit to transmit horizontal forces to the ground, the deck works as a chain absorbing horizontal forces. The deck is suspended by means the arch hangers, which are subjected to pulling. It is also possible to combine the arch and deck using truss structure (Whipple, 1841): Nielsen invented a system that adopts hangers inclined symmetrically in two directions (Fig.1.50, b). These two solutions have a structural effect similar to a simply supported beam.



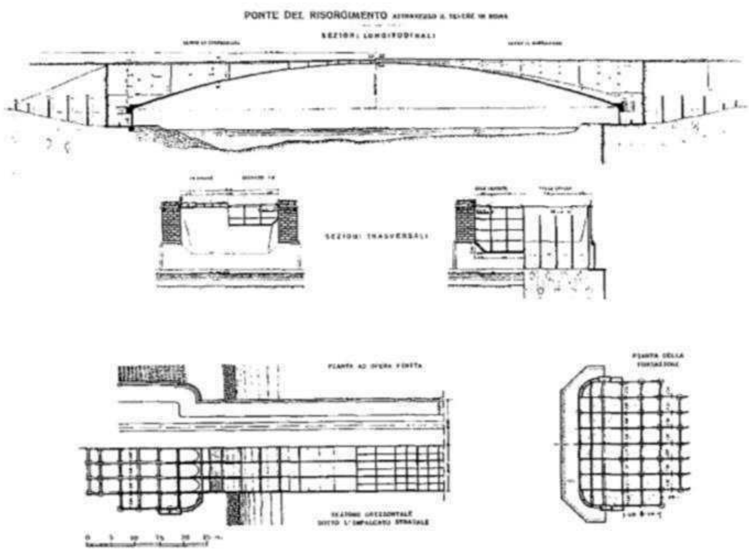
1. 51 Rise/span ratio and scheme of the thrust variation

One problem closely related to the arch is its thrust[34], which if initially resolved using a semi-arch shape, with the use of modern materials like steel and concrete causes the trend to have an ever more shallow shape. Intuitively, thrust grows with the decrease of the rise, and more the lower arch the higher the thrust (fig.1.51).
The relationship between length and height of the arch, defined as rise-span ratio, is a fundamental characteristic in a bridge project from both the architectural point of view, because the general shape of the arch is closely linked to the proportion that exists between length and height, and the technical standpoint, because the thrust value influences the size of the individual parts of the structure.
The continuous research of understanding this structure has allowed the designers to recognize that there is a measure of static continuity between the arch and beam, leading on to propose a new type of bridge, hybrid: the arch-beam.

A famous example of this arch bridge typology is the Risorgimento Bridge (Fig. 1.52,a/b) in Rome, realized in 1911 by F. Hennebique[35]. With its 100 m span and 10 m rise, it represented a brave construction of the period, but is also an example in modern times too.
It is made by a low arch with a cellular section and with a thickness at the key of 85 cm and a deck of 20 m wide. The bridge presents a rigid structure that is at the same time really light. For the construction of the vault a wood formwork was used supported by a concrete falsework. Aldo Raithel said: "*The Risorgimento Bridge, and the derived types, are well-defined transition point between the arch and the beam as they are characterized by a low ratio of f/L and are similar at highly variable section beams*".

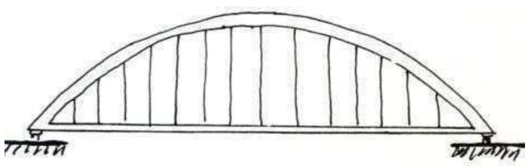
1. 52/a Risorgimento Bridge (picture and project), Rome, Italy, 1911, 100 m span, F. Hennebique

[34] Casucci S., *Il sistema arco*, in *Studio e recupero del ponte*, a.c.d. Siviero E. con Casucci S. e Gori R., Architettura e strutture – Collana diretta da Siviero E., n°8, Ed. Biblioteca di Galileo, 1995, p.25
[35] There are many references to this bridge. Cited below:
Gori R., Simoncelli B., *I ponti di Hennebique in Italia*, in *Il progetto del ponte*, 1994, a.c.d. Siviero E. con Casucci S. e Cecchi A., Architettura e strutture – Collana diretta da Siviero E., n°6, Ed. Biblioteca di Galileo, p.87
Nelva R. and Signorelli B., 1990, *Avvento ed evoluzione del calcestruzzo armato in Italia. Il sistema Hennebique*, AITEC



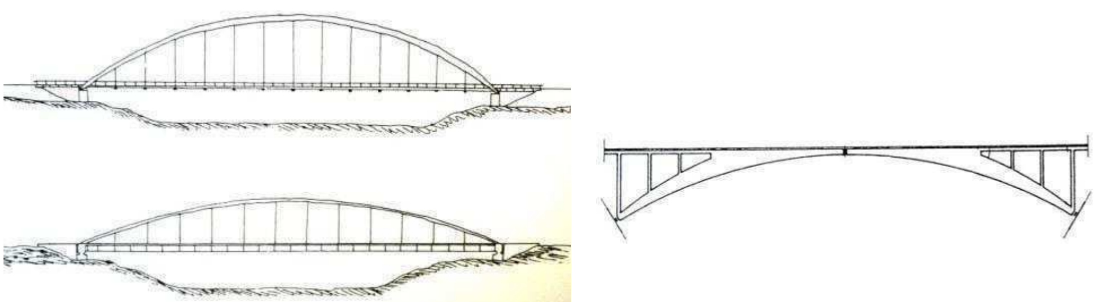
1. 53/b Risorgimento Bridge (picture and project), Rome, Italy, 1911, 100 m span, F. Hennebique

After this bridge was built there were a number of structures that used a mixed arch-beam behaviour. These examples consist essentially of an arch and a beam connected by elements working in traction or in compression: bowstring arches, langer beams, deck stiffened arches. (Fig. 1.53)



1. 54 Example of structures with an arch-beam behaviour.

There are even other architectural shapes, such as the “sickle” bridge with the deck that works as a tie, the arch stiffened deck and the Maillart bridge with thin arch and stiffened deck. (Fig. 1.54)



1. 55 The “sickle” bridge, arch stiffened deck and Maillart bridge

In particular, the relationship between arch and deck is represented by their relative stiffness: when the deck beam prevails and the arch can be extremely slender, this bridge type is called deck stiffened arch. The shape of the arch follows the antifunicular of the loads that is reduced at the minimum expression. It is the deck that has all the structural stiffness. This technical consideration makes for a particular shape of the entire arch bridge and here below are some examples (Fig. 1.55).

Nanin Bridge
Mesocco, Grisons, Switzerland
1967, 112 m span

Veitshöchheim Viaduct
Veitshöchheim, Germany
1986, 162 m span

Passaro Bridge
Costa river, Italy
1961, 100 m span

Infante D. Henrique Bridge
Porto, Portugal
2002, 280 m span

Alagon River Aqueduct
1966,4 x 60 m span

Reichenau Bridge
Grisons, Switzerland
1962, 158 m total length

1. 56 Examples of deck stiffened arch bridges

Where architectural expression is reduced to the essence of structural form, it relies only on shape and scale to achieve elegance and beauty. Materials and construction methods are now so different from those of a hundred years ago that modern bridge engineers have paid little attention to the works of previous centuries, which have made modern bridge building possible. Today, engineers find themselves heirs of a great wealth of experiences, accumulated gradually by their predecessors. Having this important background, designers have the possibility to pay more attention in all the project processes as to reach a good arch bridge design: the quality of the space that the bridge occupies and its linkage and connection with the environment has become an essential characteristic to take into consideration, that will be explained in Chapter 2 *Perception*, that looks at understanding the connection between object and landscape.

When you are designing or building a pedestrian bridge you have to know and to use the experience gained from designing road bridges and rail bridges. You should then detach yourself from them, or that you are not restricted to the few forms that have become generally accepted in the field. Restrictions that are imposed by fast traffic and the economic constraints imposed by a materialistic society, which do tend to kill the creativity.
Jorg Schlaich[36]

Another important factor in the design phase is the total cost of the new construction. It is not true that an elegant bridge is more expensive to build than a standardized design. Robert Maillart[37] and Eugene Freyssinet, as seen before, both pioneers of modern concrete bridge building technology, won bridge design awards because their bridges were more economical to built than those of their rivals. They created some of the bridges in the early 1900s – the Salginatobel near Schiers in Switzerland and the Plougastel Bridge over the Elorn Estuary (Fig. 1.56), that became the icons of the century, having understood the project site, the ability of concrete to be moulded into the most economical structural shape, and the control of the dynamic forces that act on a bridge.

a

b

1. 57 a) Plougastel Bridge, Elorn River, France, three span of 188 m, 1930, E. Freyssinet
b) Salginatobel Bridge, Switzerland, 90 m span, 1930, R. Maillart

In this study the contribution due to the cost will not be considered, not because it is not important, on the contrary, but because we want to further analyze the relationships that exist between the characteristics that influence architecture and construction methods, that are mostly used in a certain environment.

[36] Bennett D., 1997, *The architecture of bridge design*, Thomas Telford Publishing, London, UK, p.10
[37] Gauvreau P., *Innovation and aesthetics in bridge engineering*, Canadian Civil Engineer, Issue 23.5, Winter 2006-2007

And according to the text by Antoine Picon[38], the bridge must be economical both in terms of form and material effects, as Freyssinet insistently reminds us in his writings, when engaging in particular to the legacy of his ancestors, "*a civilization characterized by an extreme worry of the form simplification and means economy*".
The importance that the environment influences on bridge design. The sensitivity of the sites, both urban and rural, demands the use of the appropriate materials. As with all forms of bridges, appearance should derive from its location, structure, construction, function and materials. On the other hand landscape, as underlined by the philosopher Alain Roger[39], does not exist in itself but always derives from a glance, from an interpretation of the scene. Landscape represents a dynamic process of interpretation rather than a static image (see chapter 2 *Perception*).

1.9 Final considerations

What is a good design today? It may be the celebrated bridges of the past like the works of Thomas Telford (1757-1834), Isambard Kingdom Brunel (1806-1859), Gustav Eiffel (1832-1923) and Othmar Amman (1879-1965) or the Pont Du Gard built by the Romans. Or modern designers: for these who have travelled extensively in France and Switzerland and are aware of modern bridge design, good design might be suggested by the work of Eugene Freyssinet (1879-1962), Robert Maillart (1872-1940), Jean Muller(1925-2005),and Christian Menn (1927). In Germany it could be Fritz Leonhardt (1909-1999) and Jorg Schlaich (1934). In Spain it might be the work of José Eugenio Ribera (1864-1936), Carlos Fernandez Casado (1905-1988) and the son Leonardo Fernandez Troyano (1938), Francisco Javier Manterola Armisen (1936), Juan Josè Arenas de Pablo (1940) and Santiago Calatrava (1651). In France Marc Mimram (1955), in Czech Republic Jiri Strasky (1946) and in Austria Dietmar Feichtinger (1961)[40].
Regarding Italian arch bridges see Chapter 3 in the section dedicated exclusively to the evolution of Italian steel and concrete arch bridges, starting from the works of the 1900. The ones mentioned here are Attilio Muggia (1860-1936), Arturo Danusso (1880-1968), Armando Landini (1881-1956), Eugenio Miozzi (1889-1979), Giulio Krall (1901-1971), Riccardo Morandi (1902-1989), Carlo Cestelli Guidi (1906-1995), Silvano Zorzi (1921-1994) until reaching the contemporary designers as Giorgio Romaro (1931), Mario De Miranda (1954), Massimo Viviani (1959), Luca Romano

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[38] Picon A., *Le opere di ingegneria l'architettura e il paesaggio. Note sull'estetica dei ponti*, in *De pontibus, Un manuale per la costruzione di ponti*, 2008, a.c.d. Dobricic S. e Siviero E., Il sole 24 ore, Milano, pp.89-100
[39] Ibid., p.98
[40] *Il mondo dei ponti. The World of Bridges*, 2003, Edited by Siviero E. e Ceriolo L., Editrice Compositori, Bologna, Italia

(1964) and the realizations of Enzo Siviero and his school of "Architecture of Bridges" at the Università IUAV di Venezia.

A good design can seem to be an arbitrary decision and one of personal preference, a rationalization of one’s inner thoughts and impressions, based on past experiences. Like music: music is always written with the usual seven notes that have always the same sound, but with a different interpretation of the harmony, notes can be heard in different ways and with different emotions. Beauty is an indefinite, elusive quality: it does not depend on what a thing is but what it appears to be. Each person may decide at their own satisfaction when one design pleases the eye and while another does not.[41]

The historical examples shown in this section *Design* are good examples of bridge engineering, so that succeeding generations can learn what a good bridge design is like. During the last decade or two, engineers have shown a renewed interest in formal design, coupled with an awareness of the need to relate their structures to the environment. The proportion of the elements of a structure has always been considered to be important. The history of bridges clearly demonstrates that concepts of good proportion can change with time and are greatly influenced by improved materials and methods of construction. Therefore, material is an important element to take in consideration in the construction: because of the variety of materials, it has often happened in modern building that one has been substituted by another without properly modifying the form. Whenever a new material is introduced, instead of taking advantage of its peculiar properties, there is tendency to build into the familiar shape determined by the nature of the material formerly used. This is the story of the arch.

Bridges are usually dominated by the landscape or buildings, and its proper architectural treatment is determined by its relations with its surroundings. The points of contact between the bridge to land and water should be studied and therefore designed so the bridge will be properly related to the river and to its banks.

The best design for a bridge is one that takes into account not only the economy but also how the function of the entire structure must interact with the environment. Arch bridge design must acquire two properties: the first one to be taken into account is its functional aspect and structural composition, and the second one is that it also reaches a certain degree of architectural beauty.

The point of architecture is in fact to understand the meaning of the construction: how various forms come together to create one. “Science” cannot be neglected, however, as simple intuition is not enough. Therefore reason must also be applied to architecture. This means researching into Vitruvian triad “firmitas, utilitas,

[41] Whitney, C. S., 2003, *Bridges of the World: Their Design and Construction*. Dover Publications, New York, USA, p.27

venustas", which can be adapted to Architecture with the "three rule": structure, form and spirit.[42] The knowledge of the "utilitas" and "firmitas" is easier, since it is tied to the rationality of knowledge and to everyday practice. While the knowledge of "venustas", is tied to the personal and cultural aspects of each operator and is therefore not always very easy to understand. Therefore, the three Vitruvian components can not equate, as they are on different levels, though the last one prevails over the other two, being the master key for the assembly of the other two.

As we have seen, the shape of the arch has characterized the history of arch bridges, as it undoubtedly represents one of the most important and significant static data in architecture and engineering. The project of an arch bridge is a concrete example of the design philosophy, in which architectural type and structural flexibility find opportunities for various applications.

Building a bridge has to be considered from three points of view: scientific (with an emphasis on their efficiency and performance), social (stressing their construction and maintenance costs), and symbolic (with a focus on their appearance and their meaning for the community). If the site, form and construction are in true harmony, then beauty may well be an outcome.[43]

From every essay regarding the various issues of arch bridges, some important elements are found that will be discuss all together at the end. From this first Chapter *Design* some architectural characteristics stand out which influence the project of the arch bridge: span, rise, rise/span ration, arch typology (position of the deck).

[42] Siviero E., Casucci S., *The evolution of Maillart's arch bridges: a prototype for the coming years*, Arch bridges: proceedings of the First International Conference on Arch Bridges, p.99

[43] Ibid.

CHAPTER 2: PERCEPTION

Landscape perception

It is indeed thought that a bridge is above all,
and in itself, just a bridge.
Then it can sometimes also express other things.
As such an expression it becomes a symbol,
an example of all the aforementioned.
However, if a bridge is really a bridge,
it is never first just a bridge, and then a symbol.
Martin Heidegger

2.1 Architecture, place and perception

Architecture constitutes a fundamental part of human life, becoming a living part of the entire world. Our daily coexistence with it suggests that the carrying out of works (in this case arch bridges that allow the passage over an obstacle, thereby facilitating the transit from one place to another) are functional in their static nature, but are also pleasing from an architectural point of view. As seen in Chapter 1 *Design*, the beauty of a bridge depends not only on how it is designed, but also on what it looks like and how it is perceived by the people that live it.

The word architecture could mean a place with a continuous flow of people and all the interrelationships between them, a place made by things, material systems and landscapes. For this reason the parameters that interact with the context in the project of an any architecture has to be taken into consideration. The people are an important part of this reality and the design of a space must make them feel integrated with their surroundings through sensorial experiences: this is the task of architecture.[1]

As Manuel Castells writes in his book *La città delle reti* (Venezia, 2004), within the city there is a continuous interlace of physic and static spaces, and human and dynamic flow. Architecture becomes an important part of the landscape and the territory turns into a complex system that is subject to continual change. So from this point of view architecture has a considerable interrelation between people and landscape.[2]

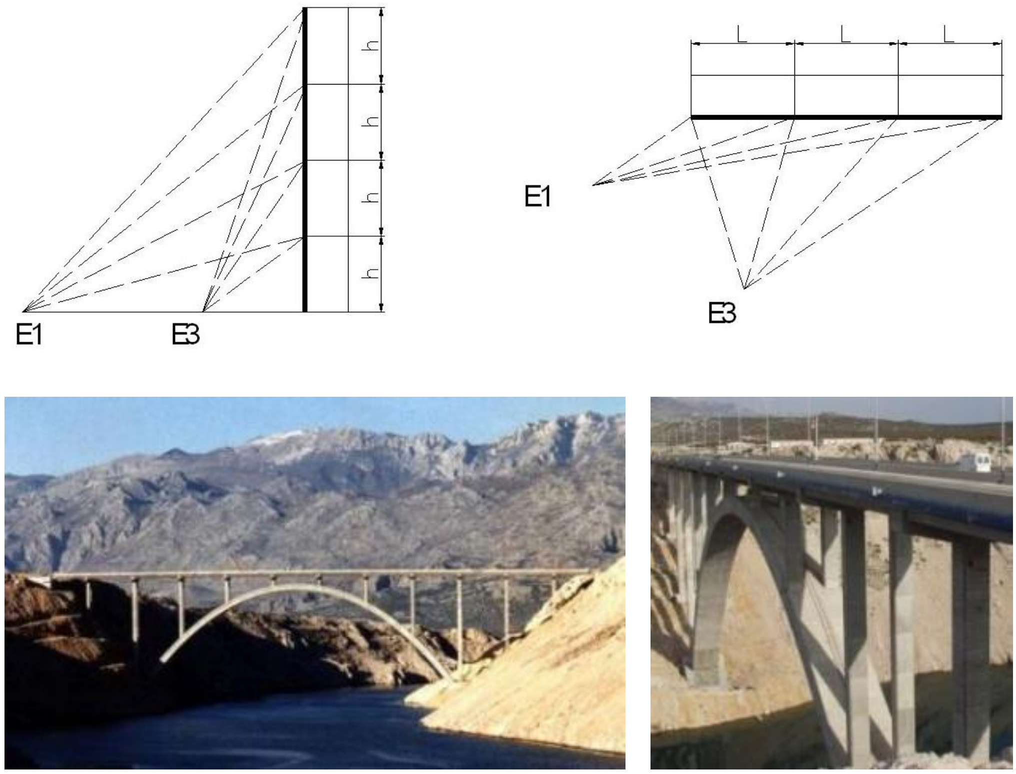
Nowadays anybody can enter urban conglomerations thanks to the new multimedia tools such as internet. It is essential to know that what we see is not reality because a real place is made up of sounds, thermal and tactile sensations. There are a multitude of stimuli that cannot be perceived in a conscious way but that are fundamental for the complete perception and knowledge of a place. In the same way it could be said that reality is not only an easy addition to all the different things that influence the formal aspect, but it is very difficult to understand all of the entire information.[3]

A dynamic balance of the system between man and environment is reached by making a perceptive balance, where all the senses follow an important rule: in the psychology perception the shape follows function when the last one means integration with the real place. The shape takes up a meaning of a completed sensorial system. The interpretation and the transformation of the place depends on the human perception.

As Bruno Zevi writes in his book *Sterzate architettoniche* (Bari, 1992), "*it is important not forget the substantial difference between the "use" of the architecture*

[1] Catalano C., 2010, *Architettura, Scienza e Percezione,* Aracne editrice, Roma
[2] Castells M., 2004, La città delle reti, Marsilio Editore, Venezia
[3] Catalano C., 2010

and the "contemplation" of a work of art. Buildings are designed for the living and their visual perception is only one of many components. While a work of art, is painted only to be looked at. The users of the architecture are the protagonists, the user of the work of art are the spectators. Not one picture can replace the living experience of the building, as you can to go inside, up, through, catch the color, the heat, the odors, the empty space and the crowding".[4]
Another point to take in consideration is that what we see is not exactly the truth but are sometimes familiar view illusions in form design. For example when a high building is divided into different parts with the same dimensions, the higher part is seen shorter than the lower part (when people look up at the piers of the bridge, this phenomenon occurs). And in the same way if the viewpoint is nearer to the architecture, view illusion appears even more clear. The effect of prospective permits to live an object in different times and spaces: firstly having a distant and total perception, then going closer to it and live it in each stage while changing point of view (Fig. 2.1).



2. 1 Maslenica Bridge, 200 m span, 65 m rise, 1997, Zadar, Croatia

When considering bridges it is clear that this structural type has the advantage to be lived in its every part: over, under, in the later site, in front of it, etc.

[4] Zevi B., 1992, Sterzate architettoniche, Dedalo Editore, Bari

The Arrábida Bridge (Fig. 2.2), by Edgar Cardoso, is an arch bridge over the Douro River that connects Porto to Vila Nova de Gaia, in Portugal. At the time of its construction in 1963, the bridge had the largest concrete span of any bridge in the world. The total length of the bridge is of 615 m, 270 m arch span and 52 m rise. The structure of the bridge is interesting, built by two arches combined with X connections as well as having an important structural function and a very particular and recognizable architectural arch shape.
The bridge is an element that frames neighboring towns. Only the observer near, as the bridge can be enjoyed from many points of view, the richness of the design can be seen, where structure and architecture go hand in hand. Driving quickly over it does not permit a perception of its impact within the urban context.

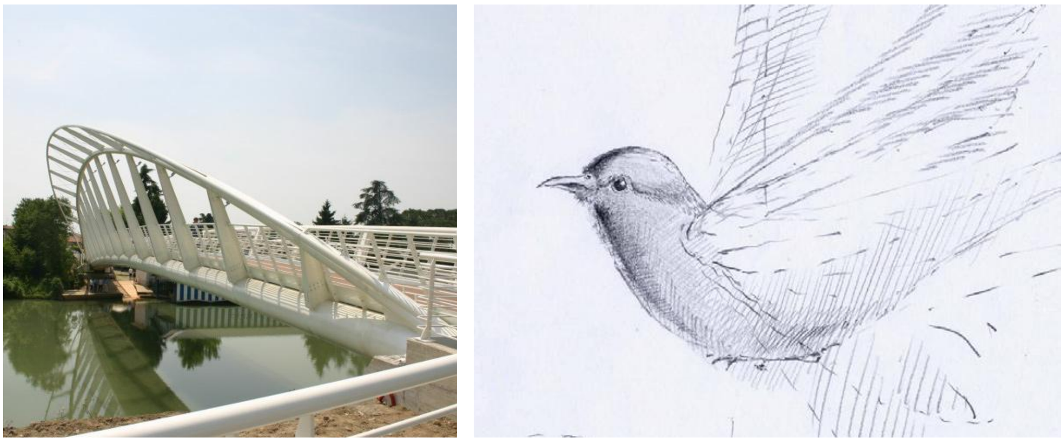
2. 2 Arrabida Bridge, Porto, Portugal, 1963, 270 m span, 52 m rise, E. Cardoso

Hence one wonders what the perception is: from the beginning the perception was the process of attaining awareness or understanding of sensory information. The definition of the word perception is "*receiving, collecting, and action of taking possession, apprehension with the mind or senses*." One person perceives elements as result of cultural past experiences and interpretation of what is perceived.
Two types of consciousness are significant when regarding perception: the first one to considered until now is the phenomenal way (any physical occurrence that is observable) but just as important is the second one, the psychological view.
The processes of perception are modified according to what is observed. When you look at something of which you have a preconception, it tends to evaluate these initial thoughts as true. Man is not able to immediately understand new information without giving rise to any prior knowledge. A person's knowledge creates his reality as much as the truth, because the human mind can only contemplate on what it has already been exposed to. Human thought contemplates what it sees and transforms reality into truth. When objects are observed without being understood the mind associates them with something it has already seen in order to process the whole vision. What we see is closely related to past experiences. The experience of a

person must be taken into account in the comprehensive way, both physically and mentally, because each component is part of a dynamic system of relations.
When you see a landscape, it consists of several elements that characterize its unity and in the recognition process; structures depend not only on the objective situation but also on the sensitivity of the observer.
During the project phase the designer tries to reproduce something that he remembers. The Changfeng Bridge (Fig. 2.3) opened in 2008, has a total length of 226 m and consists of three arch ribs that resemble the shape of a bird in flight. In some cases, the architectural design of an arch bridge is inspired by examples that are found in nature. At night, when it is illuminated, the bridge look more like a crescent moon rising from the river to link the two commercial district that are located respectively on the two opposite sides.

2. 3 Changfeng Bridge, 132 m span, 2008, Ningbo, China

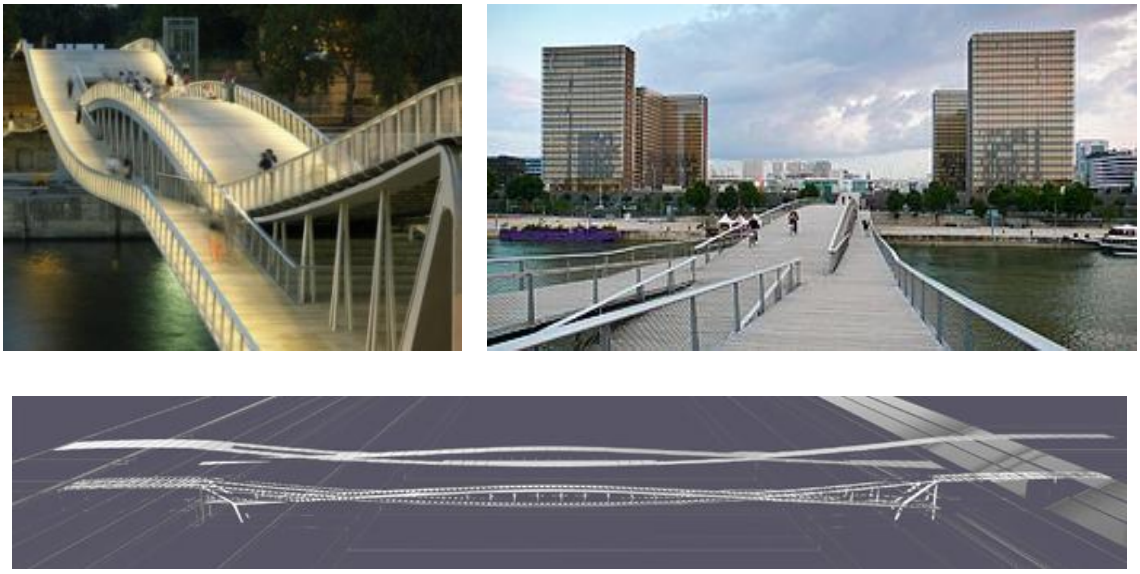
A similar example of a bridge that attempts to resemble something from nature is represented by the footbridge Rari Nantes (Fig. 2.4), built in 2009 and consists of an inclined arch with a span of 75 m. The design inspiration comes from the on-site presence of waterfowl, the *Gallinula Chloropus*. The curved band that crowns the arch is also inclined to appear like the bird’s beak that from the structural point of view it acts as a counter-balance. One can see the tension that underlies the idea of the structure taking flight.



2. 4 Rari Nantes Footbridge, 75 m span, 2009, Padova, Italy, Progeest

In order to understand the nature and the surroundings of the artificial world built by man, it is important to analyze the connections among all elements: infrastructures, streets and bridges that consent to move fast or even to stay still. There are two different ways to exist: dynamic or static, and as it follows the perception of objects is completely different too.
Moving fast allows reaching others places in a short time, like travelling by car or train through infrastructures that connect cities and country. Bridges are architectures that modify nature for man’s necessity. Very often a good project, a usefully bridge, is not noticed by the travellers that use it when moving from a place to another one: the motorway viaducts or the railway bridges have the first important function to permit a fast route and for this reason they are not enjoyed as architecture but as helpful infrastructure indispensable to overpass certain obstacles. This type of architecture, although not seen and completely understood by its users, are put into the environment and become part of it. A new project changes the original place into a new one.
The Simone de Beauvoir Footbridge (Fig. 2.5) links the Bercy Park with the riverside and the French National Library in Paris. The total length is 304 m without intermediate supports and with a main span of 190 m. It is made up of three elements which work closely together: the intermediate part, with the lateral sites forms an arch over the Seine, and two footbridges over the arch. The central part is made by a concave arch and a convex catenary. The pedestrian bridge is made by two curves. The lightness of the profile and the absence of intermediate piers reduce the impact of structure on the river whose breadth continues to be perceived in its entirety. The combination of arch and chain forms two viewpoints positioned at different heights, which can also become places for events or temporary installation. Pedestrians crossing the bridge suspended over the water, not only have the opportunity to study closely the system on which the structure was built, but also have the sensation of being transported by the wave of the footbridge. The extreme

linearity of the structure, which follows the waterline below, gives a feeling of horizontality, making the basic shape of the arch bridge structure almost disappear: the bridge becomes more like a square, a place where the people can stop and stay, living the place and therefore the city.



2. 5 Simone de Beauvoir Footbridge, 2006, total length 304 m, Paris, France, D. Feichtinger

The Langwieser Viaduct, built between 1912 and 1914, is an example of Railway Bridge. The Langwieser Viaduct (Fig. 2.6) was the world's first railway bridge to be constructed in reinforced concrete, and at that time represented a significant breakthrough and until then was the longest railway bridge in the world.

2. 6 Langwies Viaduct, Langwies, Switzerland, 1914, 100 m span, 42 m rise, K. Arnstein, E. Züblin

It was built with an important falsework. The bridge is 284 m long and the main span consists of a 100 m long arch, with a rise of 42 m. The bridge represents an important sign for the valley, a symbol of unity that’s recognizable from far away. Even though from the passengers’ point of view on its high velocity train route do

not appreciate what they are crossing, they can appreciate the beautiful panorama they get of the natural valley.
Moving slowly allows one to percept a place with a lot more attention, stopping over, under, on the lateral sides and living the area with calmly and gradually. Staying still permits the human eye to see things like objects and details that are not perceived while moving, and observing these things allows for the understanding and appreciation of the architecture. This case of time-perception is more common obviously for footbridges as they are crossed slowly.
Stopping, moving and perceiving depend a lot on the position of the bridge for where it is situated and on the type of external environment: in fact it is very different (see Chapter 3 *State of art*) to design and build a bridge within an urban setting rather than in a natural one.
The Natchez Trace Parkway Bridge (Fig. 2.7) is a concrete double arch bridge. It is 479,1 m long and carries the two-lane Natchez Trace Parkway 44,2 m over State Route 96 in a heavily wooded valley. The 177,4 m long main span is symmetrical, while the 140,8 m long second arch is not, due to the slope of the valley at the southern end of the bridge. It is an open-spandrel bridge and the weight of the bridge is concentrated at the crown of the arch. The lack of columns permits it to be light in appearance. The arches and deck were constructed using a balanced cantilever method: each arch was supported by temporary cable stays anchored from the top of the piers and the valley sides until it was fully built. This method allows to minimize any environmental damage to the valley.
The natural landscape, where the bridge is built, brings out the white color that characterizes the architecture. The two arches take the form of two hills, with the aim of continuing the present design of the scenery by stylizing the pure and simple shapes. The deck becomes a connecting ribbon between reality and artifice.

2. 7 Natchez Trace Parkway Bridge, Tennessee, USA, 1994, 177,4 m span, 44,2 m height, Florida-based Figg Engineering Group

One exclusive tendency present in manmade creations, is the relationship between the different objects that can become an important design motive, where man is the unquestionable protagonist and our necessities become shapes in our daily life.
The Japan Footbridge (Fig. 2.8) is a connection between two tower buildings. The arch bridge is suspended by two arches with a triangle section. The pedestrian route is protected by a transparent roof held by arches set perpendicular to the deck. In this example even color is an important choice during the project phase, as it clearly underlines the presence of this architecture that now, is not only a passage way, but also emphasizes its existence within the urban space.

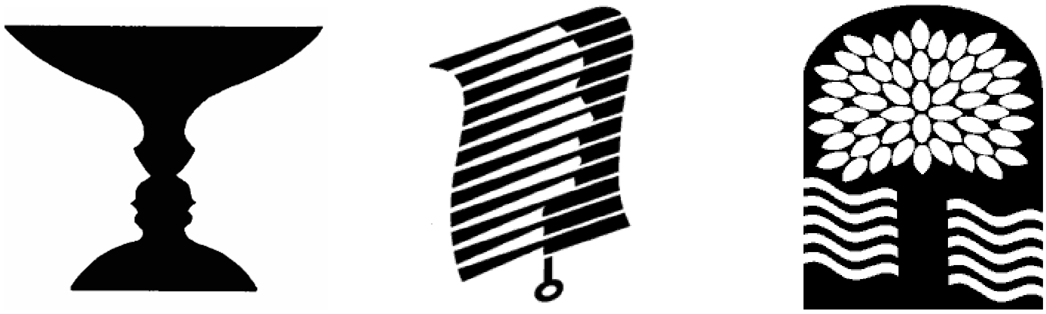
2. 8 Japan Footbridge, Paris, France, 1993, 100 m span, K. Kurokawa, H. Dutton

It is through the perceptive experience that man lives the landscape therefore through the senses. The relationships between the observer and the architectures depend on the initial project and on the interaction with the context. The sense of sight is one that above others allows to acquire an immediate perception of the objects, of the space and time, caught by paying attention to shapes, colors and movements.

2.2 Gestalt theory and bridges

One part of the perception psychology, called Gestalt, follows the fundamental principle of "pithiness" which says that we tend to order our experience in a manner that is regular, orderly, symmetric and simple. Between the objects that integrate themselves inside the environment creating some relationships. These relationships between the visible architectures produce a particular kind of spatial sensation. The interrelations among the bridge and other natural elements and architectures spring up from the perceptive Gestalt phenomenon.
When you open your eyes to see the world you can see the same objects that you can find everywhere: cars, trees, buildings, etc. These objects exist because you can see them. This phase represents the first level of the vision, where the perception helps to understand what is around us thanks to the elementary

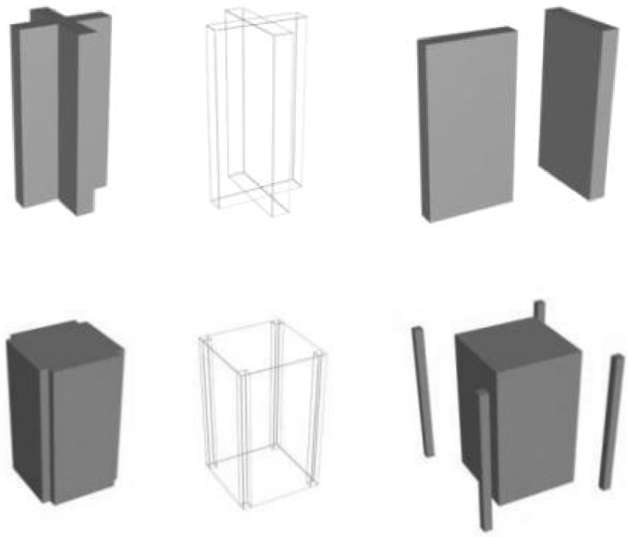
sensations. With the second level we can see interactions of this perceptive process in all the human faculties such as memory, judgment and reasoning.
The objects (architectures – bridges) are single unities that are different from the rest of the things seen: they are percepted as single item with borders that delimit them. The psychologist Edgar Rubin studied how we able to distinguish items and objects from the rest of what we see. In general a small area emerges more than the others: a slim figure could seem lighter (for example the parapet of a bridge) and on the contrary as the architecture relates with the landscape, where they either dissolve together or where it becomes the protagonist like an actor on the stage.



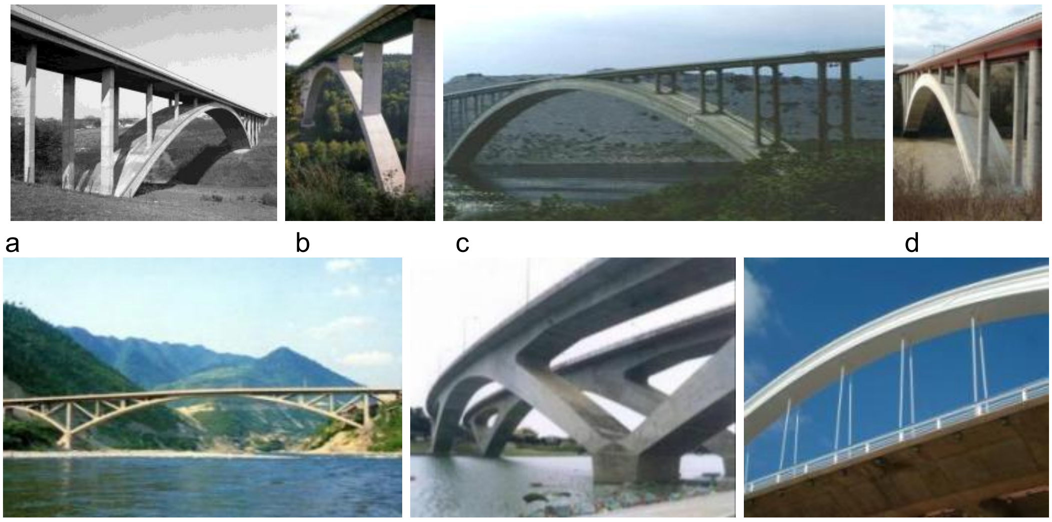
2. 9 Rubin vase and other two perceptive figures.

The eye tends to differentiate the object from its surroundings. The object is perceived as a form, a shape, while the landscape represents the background. The entire image is captured by balancing objects with its background. In the second image, the relationship between the figure and background changes as the eye perceives the form of a shade or the silhouette of a face. The third image uses complex figure/background relationships which change upon perceiving leaves, water and tree trunk.

The border can be subdivided into points – surfaces – volumes, and as the whole is made by the sum of the parts, the single parts are determined themselves by composition and breaking up. This point is clear if we speak for examples for bridge columns (Fig. 2.10 and 2.11). With concise and explicit surface is easy to be distinguished, comprehended and remembered.
The choice of the piers shape determines a different architecture in the bridge design. This means that every single part of the arch bridge becomes a fundamental element when drawing up a project.



2. 10 Addition and subtraction

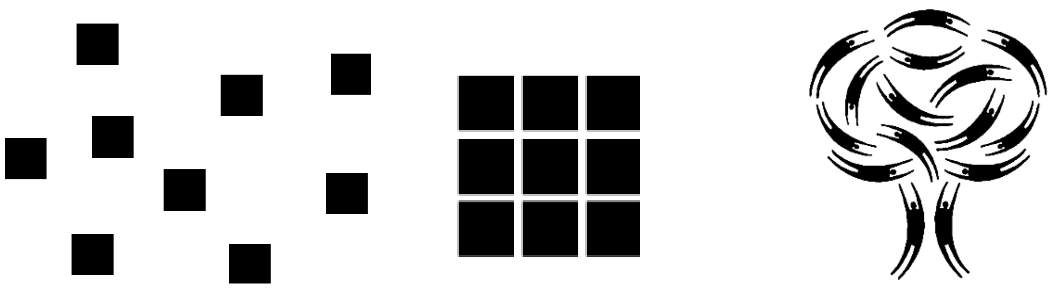


2. 11 a) Bombachtal Bridge, Wuppertal, USA, 1959, 150 m span
b) Wild Gera Bridge, Ilmenau, Germany, 2000, 252 m span
c) Krk Bridge, Krk Island, Croatia, 1980, 390 m span, I. Stojadinovic
d) Chateaubriand Bridge, Plouer sur Rance, France, 1990, 261 m span, J. Mathivat, A. Arsac, C. Lavigne
e) Jianhe Bridge, Jianhe, China, 1985, 150 m span
f) Bitan Bridge, Taiwan, 160 m span
g) Saint-Pierre-du-Vauvray Bridge, Saint-Pierre-du-Vauvray, France, 1923, 131 m span, E. Freyssinet

The factors to take into consideration in the project phase come from three different fields: the architectural point of view, the technical elements and the characteristics of the environment where the bridge will be inserted. A good design is reached when all of these three components have an important weight in the final project.

Regarding the architectural shape, the object must present unity in appearance which means that every single element should become a part of the whole, because as Gestalt theory suggests: the whole is greater than the sum of the parts. The shape starts from the choice of the architectural typology of the arch bridge that depends strictly on the deck position respect the arch structure. The relationship between arch and deck is fundamental: if the bridge is a spandrel or open-spandrel arch bridge, or if the connection is made by columns and as seen the different form that they can have. The dimension of the elements can characterize the entire structure: so the deck section type and its dimension, the arch section type and the dimension, the numbers of ribs and connection between them, and the number of spans are all important elements that all together create the arch bridge architecture. Technical factors must guarantee the structural efficient: material, structural typology (fixed, two-hinged, three- hinged), rise-span ratio and the construction method.
All these elements, clustered into three fields, jointly work towards the final common aim of accomplishing good architecture.
The scientific and phenomenological psychology approach to perception, canonize a series of perceptual laws independent of the external experience (not related to learning about culture) and are present from birth. These laws analyze figures and objects taking into account the separation from the background (by color, density, texture and contour). The most important elements to take into consideration for the union and the organization of the perception views are: proximity, similarity, continuity, closure, past experience and prägnanz (German for pithiness).

Proximity
Spatial or temporal proximity of elements may induce the mind to perceive a collectiveness or totality. This concept occurs when elements that are placed close together tend to be perceived as a group.



2. 12 Proximity examples

The nine squares above are placed far apart. They are perceived as separate shapes. A perception of unity occurs when the squares are given close proximity, they are now perceived as one group. The fifteen little figures above form a unified whole (the shape of a tree) because of their proximity. This factor could be considered in relation to the objects-architectures present in a certain natural context or in a detail scale with the single elements that make up the objects.

2. 13 Poggettone and Pecora Vecchia Viaducts, Sole Motorway, Italy, 1960, total length 455 m, 8 poligonal arches, A. Carè, G. Giannelli

Here the concept of symmetry can be introduced: in fact, symmetrical images are perceived collectively, even in spite of their distance.

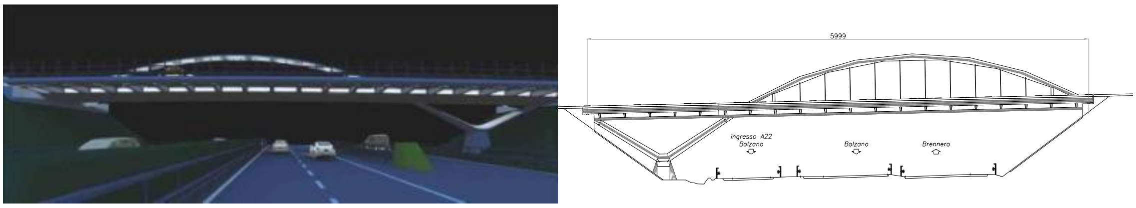
2. 14 Symmetry example

An example where the symmetry law can be seen in an architectural design is the Svinesund Bridge[5], a through arch bridge joining Sweden and Norway. The bridge is 704 m total length and has a main span of 247 m. The arch is made with reinforced concrete and the superstructure with steel box-girder. The arch was built using cantilever construction supported by temporary cable stays. The construction system had a hydraulic self climbing casting mould which was anchored to the most recently completed arch segment, and segments were then added at a rate of about one per week. Once the arch was in place, the stays, temporary concrete stay towers and cable conveyors were removed, and the roadway segments added. Some were added on site, but the center roadway section under the arch was floated in on barges, as a complete section, and raised into place.
The bridge is not only a structure that allows for passage, but becomes a symbol of connection between countries and peoples. This half-through arch bridge underlines that the structural strength of the arch allows to support the union-way and together become a whole. The semi-circle created by the bridge finds its missing half in its reflection in the water.

[5] Santacesaria M., Un arco tra i fiordi, 2006, Journal iiC Industria Italiana del Cemento, n°826, dicembre 2006, pp.980-991
Jordet E. A., Jakobsen S.E., 2007, The Svinesund Bridge, Norway/Sweden, Journal Structural Engineering International 4/2007, pp.309-313

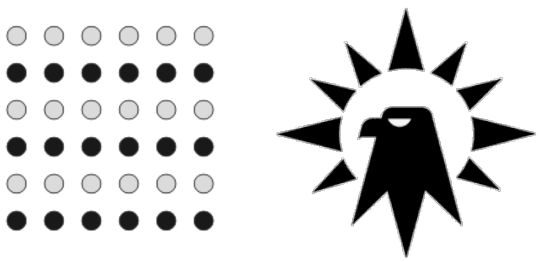
2. 15 Svinesund Bridge, connection between Sweden and Norway, 2005, 247 m span, 30 m rise, R. Schubart, B. Berger

In another way the bridge over the motorway in Egna designed by Antonio Capsoni could be considered an example of asymmetrical architecture. The structure consists of a bowstring arch bridge that has a support on the external abutment, and a second one that is a V-shaped element that gives the structure a dynamic effect but also a feeling of insecurity.



2. 16 Bridge over the motorway, Egna, Bolzano, Italy, 2004, 42 m span, A. Capsoni

Similarity
The mind groups similar elements into collective entities or totalities. This similarity might depend on relationships of form, color, size, or brightness. People often perceive objects as a group because the elements are similar.



2. 17 Similarity examples

The example above appears to be a single unit because all of the shapes are similar. Unity occurs because the triangular shapes at the bottom of the eagle symbol look similar to the shapes that form the sunburst. When similarity occurs, an object can be emphasized even more if it is unlike to the others. This is called anomaly. The figure on the far right becomes a focal point because it is dissimilar to the other shapes.

Continuity

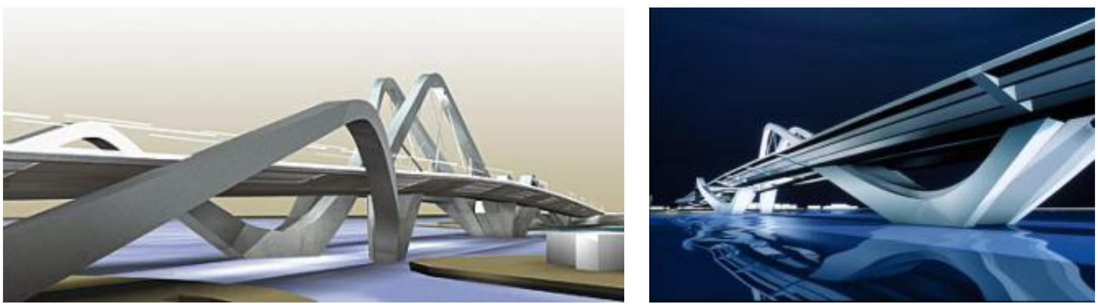
The mind continues visual, auditory, and kinetic patterns. The eye can see the dynamicity of the object.

2. 18 Continuity examples

The figures above show examples of continuity. In fact the viewer’s eye follows the line or the curve: the smooth flowing crossbar of the "H" leads the eye directly to the maple leaf.

The Sheikh Zayed Bridge in Abu Dhabi[6] (Fig. 2.19), in the United Arab Emirates, will link Abu Dhabi Island with the mainland, including Dubai and the international airport. The architectural shape seems more like a sculpture snaking it way between the lanes of traffic and the sinusoidal waves create the structural silhouette shape.

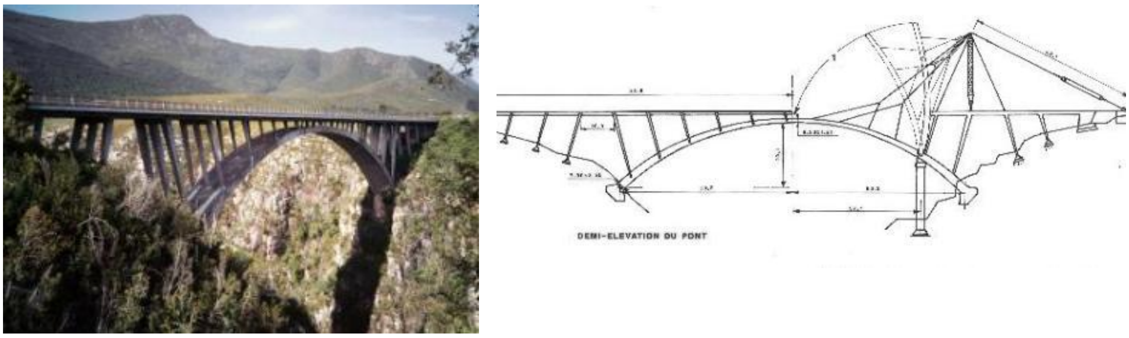
The bridge will have a total length of 842 m and will include three arches with the longest being 234 m long. The total width of the bridge will be up to 67.4 m. The mainland is the launch pad for the bridge structure emerging from the ground and approach road. The decks are cantilevered on each side of the spine structure. Steel arches rise and spring from mass concrete piers asymmetrically, in length, between the road decks to mark the mainland and the navigation channels.



2. 19 Sheikh Zayed Bridge, Abu Dhabi, 2011 (under construction), 234 m span, Z. Hadid

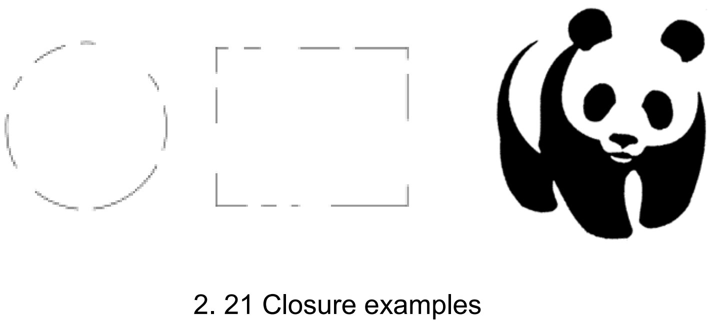
[6] http://www.zaha-hadid.com/transport/sheik-zayed-bridge

Another method to visualize the continuity of the elements is “the orientation in the space” for example the radial arrangement of the hangers in an arch bridge: the elements with the same moving direction are perceived as a collective or unit. This mechanism is important not only in the space but in time too.
The Paul Sauer Bridge (Fig. 2.20) is a reinforced concrete arch-bridge over the Storms River with an arch span of 100 m. The design of an arch bridge, allows it to transfer the weight of the bridge downwards along the arch to the abutments where, in the case of the Paul Sauer Bridge, the arch meets the walls of the gorge. Storms River is unusual for having inclined spandrel supports that radiate out from the main arch rib. The approach supports are also inclined in the opposite direction balancing out the profile of the entire bridge. The use of inclined supports is a Riccardo Morandi trait, visible on nearly all of his bridges.



2. 20 Paul Sauer Bridge, Estern Cape, South Africa, 1956, 100 m span, R. Morandi

Closure
The mind may experience elements it does not perceive through sensation, in order to complete a regular figure (that is, to increase regularity). The elements that take up less space are perceived as the object, while the large ones are perceived as background. The identification of the objects is possible even though the figures are not completed.



2. 21 Closure examples

This principle occurs when the object is not completely closed, but at the same time if enough of the shape could be perceived it would be see the whole shape by filling in the missing information. As the examples above are not completed but there is enough information for the eye to complete the shape.
While the emphasize of the contour gives a sensation of completeness, this means that if we watch the object we can recognized all its shape from the beginning to the end as the designer wished to restrain the attention of the observer on the closure shape.
The span layout of the Chongqing Chaotianmen Yangtze River Bridge (Fig. 2.22) has a main span of 552 m. It is a half-through arch bridge with tie girders in double-level traffic. The upper deck carries 6 lanes in two directions and a pedestrian lane on either side, and the lower deck carries dual tracks for municipal light rail in the middle and 2 lanes on either side. The red color seems to underline the contour of the structure and pulls all the attention to its shape.[7]

2. 22 Chaotianmen Bridge, 552 m span, 2008, Chongqing, China

The past experience:
During the project phase the tendency is to design objects that are familiar, things that we saw before, rather than something that we do not know that is new, strange and uncertain.
The Infinity Bridge (Fig. 2.23) is a pedestrian and cycle footbridge across the River Tees in the north east of England. The bridge is a dual bowstring bridge: the main arch is 120 m span and the short one is 60 m span. It has a pair of continuous, differently-sized structural steel arches with suspended precast concrete decking and one asymmetrically placed river pier. The arches both bifurcate within the spans to form a double rib over the river pier. A reflex piece between the two arches holds them together making the two arches into one continuous curve.

[7] Feng M., 2010, *Recent development of arch bridges in China,* Proceedings of the 6th International Conference on Arch Bridges, Arch’10, 2010, Fuzhou, China
Chen B., 2009, *Construction methods of arch bridges in China*, Proceedings of the Second Chinese-Croatian Joint Colloquium, Construction of arch bridges, Oct. 5-9 2009, Fuzhou, China pp. 1-192

The name derives from the infinity symbol formed by the bridge and its reflection. At night from certain viewing angles when the river surface is flat and calm, the twin arches together with their reflection in the river look like an infinity symbol ∞, and it is this optical effect that inspired its name.


2. 23 Infinity Bridge, Stockton (UK), 2009, 120 m span, 32 m height, Expedition Engineering, Spence Associates.

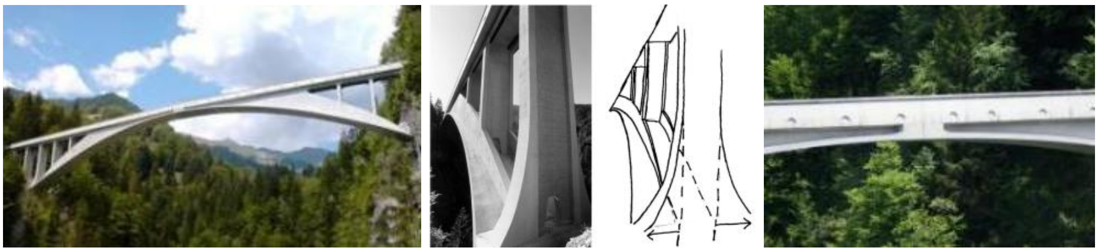
Prägnanz (German for pithiness)

This law is called “good Gestalt” or “good shape”. The concept of pithiness corresponds, in fact, to the sum of all the principles: something has a good shape when all the factors are taken in consideration for the construction of a stable piece of architecture. Alternatively, when these principles are conflicting, the figures become unstable and ambiguous. With this law we have the unit between senses psychology and personality psychology and could be described better with the concepts of simplicity, order, symmetry regularity but overall structural coherence and unit character of the whole.

The Salginatobel Bridge (Fig. 2.24) is a reinforced concrete arch bridge designed by Robert Maillart between 1929 and 1930. In 1991, it was declared the thirteenth International Historic Civil Engineering Landmark and was the first concrete bridge to be named so. It is a three-hinged arch bridge and for this reason it is thinnest at its crown and springing points, thickening in between to reflect the shape of its bending moment diagram. The Salginatobel Bridge arch is 133 m long in total, and its main element is a hollow concrete box girder over the central part of the arch.

Regarding this bridge David P. Billington said : “*Its visual elegance ... goes together with its technical brilliance*.” However, the engineer Fritz Leonhardt has suggested that: “*These Maillart-type arch bridges only look good in special situations as here over a gorge and against a mountainous background*.”

Since its creation it is considered a masterpiece in the architectural and engineering world. As mentioned before, these structures have to be structural bold but have to also blend into their surroundings: a white blade through the green valley, like a lightning bolt that fades out quickly, but that at the same time leaves us with an unforgettable image.



2. 24 Salginatobel Bridge, Schiers, Switzerland, 1930, 90 m span, R. Maillart

To achieve a good example of architecture we must take into account shape, structure and environment. When these three factors work together towards a common aim to build bridges that are useful and where the people can live by, also being pleasing to the eye, comfortable and resistant, you can consider it a good structural piece of architecture. Like music, that is always different even though it is made by the same seven main notes, but with their combination different melodies can be created. Like wine, there are countless varieties from many different types of grapes, but when can we say that a vine is a good one? A sommelier once told me that a good taste in wine is an objective analysis of all the elements and ingredients that are used in its production. Furthermore, if it is only pleasing-tasting the vine is not very good because all the elements have to be perfect: color, density, presentation.
The perceptive field appears as a group of objects that are as balanced as possible, harmonic, built with a good principle in each individual part in a way that each element belongs to the others in forming a good unit.

2.3 Gestalt and the design: the arch bridge becomes architecture

Discussing perception in terms of psychology and the Gestalt theory, gives some concrete insight to understand how people see reality. The main formula of this theory is to understand the whole item determined by its individual elements. Gestalt suggests some elements of sensational images, feelings, are useful for live experiences.
For example when we hear a melody for the second time it is memory that enables us to recognize it. If the same melody is played in a different key, with a transportation, a person can recognize it. Some maintain that in addition to the seven musical tones there are intervals – relations – and that these are what remain constant. In other words, they are asked to assume not only elements but the

“relations-between-elements” as additional components of the total complex. So, what I hear in each individual note is apart, which in turn determines the character of the whole tune. What we get from the melody does not arise as a secondary result from the sum of the pieces as such, but rather, each single tone already depends upon melody as a whole. [8]
The theory of Gestalt therapy has two main ideas. The first is that the proper focus of psychology is the experiential present moment, our perspective is the here and now of living. The second point is that there is a web of relationships between all things.
We can see that the Gestalt theory is closely related to the “present centered”. There are many areas that work in this way: physics, chemistry, biology, architecture, and nursing. This means that for these sciences what is here and now is important and not what is potentially here or what is in the past. We are considering the present and in terms of location too. From this point of view a present-centered approach is distinguished from a historical one, in which the present is seen as a consequence of past causes. The historical point of view stands inevitably in the present, looking backward to the past. A present-centered approach stands in the present and looks at it, here and now.[9] Landscape is considered as a set of past experiences, human, historical, architectural, relational.
Environment enters into a transition with humans. It is therefore impossible to conduct valid studies of human behaviour without making reference to the context of the environment. A building, a bridge, is single thing, something which has integrity and can be singled out from the rest of the physical setting. In a sense we treat buildings as individual objects – good, bad, indifferent, expensive, rare, cheap, well or poorly constructed, beautiful, ugly, cherished or despised. We assign them all the qualities of objects and seldom think of them as “statements” – active agents in the human situation.[10]

As already mentioned, there are three separated but interrelated factors that have to be taken into consideration regarding bridge projects:
1_the structure itself, its program, design, workmanship, materials, detailing, etc.
2_the people, as physiological and psychological organisms that perform the functions of the structure and that will live alongside the object
3_the landscape and the relations with objects and people.

Following the perspective psychology laws it is clear that accomplishing a good project the arch bridge should be well integrated into its environment and have a good relationship between the object itself and its background: this means the

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[8] Wertheimer M., 1944, *Gestalt theory*, New York
[9] Nevis E. C., 1996, *Gestalt Therapy: Perspectives and Applications*
[10] Hall M. R., Hall E. T., 1975, *The fourth dimension in architecture: the impact of building on behavior*, Sunstone Press, USA

choice of a good proportional dimension with the surrounding area (nature and building). The use of the materials and its color determines the depth of the visual field and during the night the choice of a studied illumination makes the object a landmark. The architecture of a bridge imposes a visual effect on its surroundings that highlights its linearity, both vertically and horizontally, and it becomes an important place for people to enjoy and look at.
The overpass arch that crosses the A1 motorway and high-speed rail line (Fig. 2.25) reaches a height of 50 m and with its 221 m span is the longest Italian arch bridge and represents an example of verticality. The arch reaches a maximum height of 57 m. The construction and installation of the bridge has been designed in such a way as to cause the minimal possible disruption to highway traffic and local roads. The structure that makes up the arch was divided into four parts, positioning the scaffolding and thrust with it.
After the completion of the overpass operations, the parts of the arch were raised in three stages, ever higher by strand jacks attached to the tops of temporary towers and, once in the final position, welded in one piece.

2. 25 Reggio Emilia Bridge, Reggio Emilia, Italia, 2007, 221 m span, S. Calatrava

The Gateshead Millennium (Fig. 2.26) is a clear example of a landmark where the site becomes a living place as the bridge is not only a structure that permits the passage way, but also a square and a technological attraction.
The request of the initial competition was to create a structure that would allow the passage of pedestrians and cyclists as well as ships beneath. The winning design was by Wilkinson & Eyre Architects and Gifford & Partners that met the criteria perfectly. The bridge not only serves a functional purpose as the River Tyne's only foot and cycle bridge, but its grace and engineering attract people from all over the world. The structure was made by two parabolic arches in white steel: the pedestrian and cycle deck is an almost-horizontal curve, suspended above the river from a series of suspension cables. These suspension cables going to and from the arch and deck help to give stability in the crossing phase. The bridge tilts as a single, rigid structure. As the arch lowers, the pathway raises, each

counterbalancing the other. The bridge is sometimes referred to as the Blinking Eye Bridge or the Winking Eye Bridge due to its shape and its tilting method.
The bridge has become the symbol of the city.

2. 26 Gateshead Millennium Bridge, Gateshead, UK, 2001, 105 m span, Wilkinson Eyre

Another example of the horizontality arch is the Ripshorst Footbridge (Fig. 2.27). The bridge is a part of the larger requalification project of the natural park, besides being an important step of the cycle path. The Ripshorst Bridge has a structural configuration that is particularly innovative: a tubular metallic arch acts as support struts of steel, of varying angles, which in turn support a reinforced concrete deck. The final result is a light, transparent and dynamic structure, which blends into the landscape without touching it. The perception is clear: the arch starts from a point on the bank and over it a curved deck that crosses the river. In many ways, it is as if the bridge is not simply crossed the river, but preferred to wander around to observe it and contemplate on different points of view. This dynamicity of the bridge gives its real importance to the river.

2. 27 Ripshorst Footbridge, Oberhausen**,** Germany, 1997, 78 m span, J. Schlaich, Bergermann and Partner

When we speak of an architectural object that is inserted into the landscape, in addition to its size there are other elements that characterize the place of construction: material, color and transparency.

The Rainbow Bridge (Fig. 2.28) with a 167 m span connects Neihu and Songshan districts in Taipei. The bridge facilitates local foot traffic and serves as an attraction as well: the bridge brings more convenience for local residents while improving the city's landscape. In addition to shortening the divide, the bridge itself is an attraction, as it looks stunning at night when it's all lit up. The color is the most important chose in this project making it become a landmark, a connective point and a special area where the people can go or stay.

2. 28 Taipei Rainbow Footbridge, 167 m span, Taipei, Taiwan

2. 29 Pedro and Inês Bridge, Coimbra, Portugal, 2006, 110 m span, A. Adão-da-Fonseca

The Pedro and Inês Bridge is named after an age-old love story. Opened in 2006 it represents the union of two different sites. The bridge is made up of two parallel elements that join and balance in the middle. The central island section has no

deep beam supports, giving the visual effect of a bridge that seemingly doesn't reach the other side. This special place becomes a square where people can stop and talk or look at the river and city.
The architecture in this case is characterized by a dynamic shape: the two semi-arches are transferred, one in front, one in the back side producing a motion effect and a game of light and shadows. The particular yet interesting parapet made in a zig-zag shape of the handrail and colored and inclined glasses that with the light create a variable feeling of the architecture while walking on it. The dynamic of the structure is just one concept of the design, in fact material, color, light and landscaping to either side of the bridge demonstrate how pure structural techniques can introduce a new form into architecture.

The bridge is lively at any time of the day, it’s timeless, but with the passing hours it transforms itself, thanks to its handling of shadows, and at night it shines in a new light. The lighting system takes up a fundamental role during the design phase.
Even the construction phase can become an important moment for the entire life of the bridge. One significant example is the construction of the forth bridge over the Grand Canal in Venice. The Costituzione Bridge (Fig. 2.30 and see Chapter 3 *State of art* Fig. 3.64), designed by Santiago Calatrava, has become object to discussion since the first design phase, but also object to concern of the media and to the local population during the construction phase. In the scenographic part of the central part of the bridge, it became the protagonist of the city during its transfer to the final situ.

2. 30 Costituzione Bridge, Venice, Italy, 2008, 80 m span, S. Calatrava

The similarity that the structural shape can have with nearly thing gives the observer the sensation of welfare and comfort staying in a place that has common characteristics.
Speaking about the architectural details of a bridge, the elements arranged on a line or curve are perceived to be more related than elements not on the line or curve. And the symmetry used for the different elements thanks the curved line of the arch allows it to have a unified image of the entire bridge.

The structural element, as the choice of the rise/span ratio, determines not only the arch thrust, but also includes the overall architectural form. In fact it is this relationship between height and length of the bridge that leads the perceptual characteristic of dynamic or fixity, of the object that becomes a place, a square, a space for socializing and dialogue, but even simply for relaxing in the sun, reading a book or contemplating the beauty of the city.
These initial considerations of the arch bridge shape, connected with the human thinking and feeling, are only the initial point when defining a better relationship between arch bridge project and external environment. On the base of the chief design experiences during the last twenty years some indications will be looked at, laws for good design methodology. These objective principles will take into consideration not only structural and functional view but also architecture and perception.
The response to the competition for the third bridge over the lake in Brasilia (Fig. 2.31) saw the winning concept in the Juscelino Kubitschek Bridge: a daring, dancing variation on an ancient structural form. Crossing the water the bridge jumps from side to side The idea was to create a landmark for the enjoyment of the community. This is surely an example of dynamic architecture.

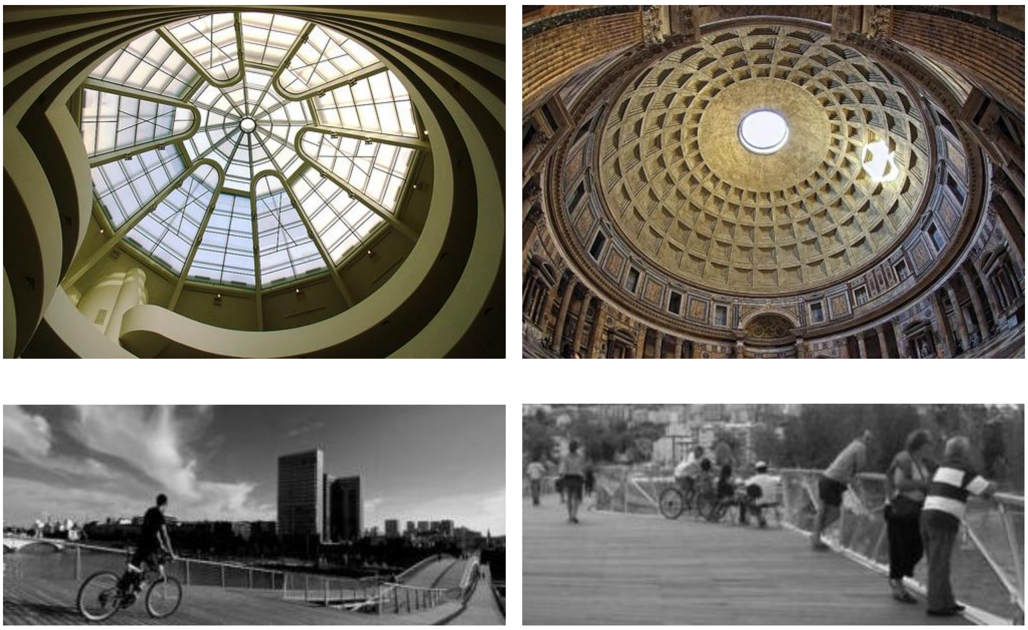
2. 31 Juscelino Kubitschek Bridge, Brasilia, Brasil, 2002, 240 m span, 60 m rise, A. Chan

2. 32 Third Millennium Bridge, Zaragoza, Spain, 2008, 216 m span, 36 m rise, J. J. Arenas de Pablo

An example of a fixed bridge is the Third Millennium Bridge in Zaragoza (Fig. 2.32). It was built as a showpiece of the city's Expo 2008 and is a concrete bowstring arch with 216 m span, a world record in his typology built on the ground and placed in its current position using hydraulic jacks. The building has three lanes in each direction of traffic, bike lanes and walkways covered with glass and steel that pedestrians are not subjected to inclement weather. This is an architectural example of static bridge, fixed into the place where it was built.

Dynamism and immobility are two perceptive ways to consider not only the architectural shape of a bridge design but also the movement of people that live the object. That is a sphere that takes into consideration the different living ways and the means of transport used for crossing the bridge.

The perceptions and feelings of each person is different for sure because it is something that come from our culture, past and character, so it is subjective and personal, but at the same time the study of human thinking, the design and the architectural shape allows us to follow some guidelines create a good project. Many projects each have some particular characteristics that demonstrate how it is possible to attain a good project: the position and the environment and how the person can live it in different ways, let it be a place where can they stop and enjoy, or a route to be rushed through quickly.



2. 33 Dynamic and static perception

2.4 Landscape and its perception

The perception of a place, although we have seen it is the psychological parameters that define the objective characteristics of quality, can be understood in a qualitative examination of the environment. It is not possible in fact to imagine the planning of a site without considering the physicality of the infrastructural phenomenon, seen as an integral part of the territory and an element that varying affects on the environment. Therefore we will try, using an evaluation system, to take into account not only the bridge as an object but to identify it on a larger scale: the infrastructure in fact is not only a connection between two parties, but it becomes an important reality that communicates with the territory and with its users in harmony or by contrast between the parties. In the design phase it is important to think about the work, in such a way that satisfies the appropriate specifications to the cultural, monumental, formal and symbolic factors.
Previously we saw how the bridge may possess, in addition to the primary purpose of functionality, certain features like the ability to communicate with its historical context, or the ability to provide the context and to become a symbol, such as its visibility from other parts of the city (landmark and meeting point), how the perspective and colour variations can change its visual perception, or like it can give a visual impact to the environment by means of lightness or heaviness of its figure; now consider the subject arch bridge, not as a single architectural element but as a construction which is positioned in an existing site changing its appearance. Consequently, no single object will be evaluated as an architectural reality but in how it changes the quality of the place despite the good structural and formal characteristics.

Thanks to the invaluable support of Michele Culatti, who has been dealing for many years with landscape evaluation[11], a mathematical judgmental approach was research with particular attention paid to the qualitative aspects of regaining the infrastructure, in order to find a design for the optimal solution for the place in question through an analysis of the factors taken into account.
The goal of this analysis is to be able to identify the concept of “design quality” and as a code this Italian law is used, the DPCM 12th December 2005, which stipulates that the public and private management of the territory is authorized through an obligatory landscape report whose contents and purposes are determined by the decree.[12]

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[11] Culatti M., 2000, *Proposta metodologica per la valutazione delle opere infrastrutturali*, Tesi di laurea, relatore Siviero E., correlatore Rizzato P.
[12] The Council Minister’s Decree of 12th December 2005 completes and integrates the Legislative Decree 22nd January 2004 n° 42 (Urbani Codex). According to the article 15 of

The drafting of this landscape report must consider a number of elements that help to identify what may be the landscape qualities to be protected, the parameters appropriate to contain evident damage at the expense of the territory and to verify the compatibility of the architectural design in the environment: this analysis therefore allows to ascertain how the object may affect the environment and to avoid the possible landscape risks by determining the adequacy of the project. This law is used to solve the problem of valuating the changes in the landscape in the absence of the appropriate cognitive tools.

The Decree of the Council Minister gives some indications of the ways in which to read the landscape and consequently how the architect or engineer can design the changes: the landscape report does not only intend a methodological approach for the protection and evaluation of the new projects, but intends to constitute methods to help landscape design to be compatible with any building in both public and private sector.[13]

The landscape is identified through the analysis of its characteristics, of its morphology, of the natural and artificial materials present, of the visual and perceptual relations that exist between the elements, from an historical point of view and from the present realizations accumulated over time in a place and from the understanding of possible future changes.

To literally understand what the concept of LANDSCAPE PERCEPTION means see what has been written previously on this issue regarding the perception, instead here we are looking into the single meaning of the word landscape: position of the territory considered in terms of prospective and descriptive point of view, mostly with an emotional influence, to which can be also added an artistic and formal evaluation. The landscape is the set of characteristics of a given area. Landscape perception is valuated in two different periods defined here as BEFORE and AFTER the construction. Before, is identified with everything that is present in the landscape (natural and anthropic) prior construction. After, refers instead to how the landscape quality is going to change with the presence of a new the arch bridge.

Modification means partial transformation/change of something specific if introduced to obtain an improvement, then a partial transformation suffered over time mainly in order to achieve greater efficiency or functionality. From the definition of modification it can be seen that the primary goal that moves the design and construction of a new project in a certain context is to increase its functionality: with the construction of a new arch bridge the intention is to improve the traffic flow with new traffic routes and facilitate the passage over an obstacle with a structure while having the goal of producing an object that fits into the context trying to make positive changes. If this does not happened it would mean that the bridge makes

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the Landscape European Convention ratified on 9th January 2006, the landscape is defined as a "good" as an essential component of the people's lives context.

[13] Costa A., 2010, *Aspetti valutativi dell'impatto paesaggistico di ponti e viadotti : il caso della Progeest srl, Tesi di laurea*, relatore Siviero E., correlatore Culatti M.

alterations to the environment which by definition are appearance changes due to forgery, counterfeiting, often worsening the appearance. Every new architecture should be aimed at improving the landscape quality or at least make sure that there is not a decrease in the qualities despite the changes.
The use of the criteria listed in the DPCM (described below) does not constitute a scientific method but a discussion method for some concepts: this evaluation method of the landscape perception does not represents a technical manual, does not indicate mathematical models to follow but provides some evaluation elements that could be used as a base for a critical judgement to the context. These elements have the aim of sensitizing the designers to the themes of landscape, emphasizing the importance of the quality in the design and the land management.
After this introduction we list these evaluation parameters with their own indicators that the DPCM provides and which are used to check the prior condition before the construction, both in the design features and overall to represent the condition at the end of the realization. In this case the evaluation will analyze the place with the presence of the object already realized indicating the changes that it may cause to the place and delineating it if the new bridge were to led to an increase in the quality of the landscape or if it were to change the characteristics negatively.
In this regard, the annex of the DPCM indicates to administrators, technical evaluators and designers, a number of parameters of LANDSCAPE CHARACTER of the places and a set of PARAMETERS for testing the impact of new constructions on the landscape (MODIFICATIONS) and possible negative effects (ALTERATIONS). In particular for the character of the scenic places, the technical annex of the DPCM lists some READING PARAMETERS OF QUALITY AND LANDSCAPE CRITICISM (diversity – integrity – visual quality – rarity – degradation) and some READING PARAMETERS OF ENVIRONMENTAL AND ANTHROPIC RISK (sensitivity – vulnerability/fragility – visual absorption capacity – stability – instability).
There is also a list of the main types of MODIFICATIONS that could affect the existing character of the landscape: morphology, natural or anthropic skyline, environmental-historical situation, natural situation, environmental perception, scenic/panoramic, ecological function and its effect to the landscape, margins built, material character, colour, construction, agricultural characteristic.
Below is part of the original text of the DPCM, in particular paragraphs 2 and 8 of the annex:

Point 2: it lists as examples some parameters for the reading of the landscape features, useful for the verification of the compatibility of the project:

READING PARAMETERS OF QUALITY AND LANDSCAPE CRITICISM:
-***Diversity****: recognition of the peculiar and distinctive characters/elements, natural and anthropic, historical, cultural, symbolic, etc.* (if there is recognition of the general character of the landscape and the objects that constitute it);

-***Integrity****: permanence of the distinguishing characteristics of natural systems and historical anthropic systems* (functional, visual, spatial, symbolic, relations etc., among the constituent elements and if there is homogeneity between the quality and quantity of the present objects);
-**Visual quality**: presence of particular scenery and panoramic scenery;
-***Rarity****: presence of characteristic elements, existing in small number and/or concentred in particular areas or site;*
-***Degradation****: loss, defacement of natural resources and cultural, historical, visual, morphological, witnesses characteristics.*

READING PARAMETERS OF ENVIRONMENTAL AND ANTHROPIC RISK
-***Sensitivity****: ability of site to receive changes, within certain limits, without alterating effects or decrease of the connotative characters or degradation of the quality;*
-***Vulnerability/Fragility****: condition of easy alteration or destruction of the connotative characters;*
-***Visual absorption capacity****: ability to absorb visual changes, without substantial decrease of the quality;*
-***Stability****: ability to maintain functional efficiency of ecological systems or situations of anthropic structures established.*
-***Instability****: instability of the physical and biological or anthropic components.*

Point 8: main types of modifications and alterations:

To facilitate the verification of the potential impact of the proposed actions on the landscape some types of ***MODIFICATIONS*** *are given as examples .*
-***Morphology modifications****: significant earth moving, removal of the recognizable routes (network of canalization, parcel division, secondary roads…) or used for alignment of buildings, of for margins, etc.;*
- ***Modifications of the vegetation****: felling tree;*
-***Natural and anthropic skyline modifications****: different profiles;*
-***Modification of the ecological functionality****: hydraulic and hydrological balance, highlighting landscape changes;*
- ***Perception, scenic, panoramic modifications****;*
- **Settling-historical modifications**;
-***Typological, material, colour, constructive modification*** *of the historical settlement (urban, widespread, agricultural);*
-**Agriculture and culture modifications**;
-**Modification of the agricultural characteristics** (main features, distribution methods of the settlements, networks, etc.).

Also shown as examples are some of the most important types of ***ALTERATIONS*** *of the landscape system where it is still recognizable integrity and coherence of functional, historical, visual, cultural, symbolic, ecological relations; they can have totally or partially destructive, reversible or not reversible effects.*
-***Intrusion****: insertion in a landscape system of extraneous and incongruous elements to its peculiar features of composition, perception or symbolic, for example industrial building in an agricultural area or in a historic settlement;*

*-**Subdivision**: new road through an agricultural system or a urban settlement;*
*-**Fragmentation**: gradual insertion of foreign elements in an agricultural area, dividing it into smaller parts that do not communicate anymore;*
*-**Reduction**: progressive reduction, elimination, alteration, replacement of parts or elements structuring a system, for example a network of canals, historical buildings.*
*-**Visual relationships elimination**: historical, symbolic, cultural elements with the surroundings;*
*-**Concentration**: excessive density of new construction in a limited geographical area that has an impact on the landscape;*
*-**Ecological and environmental process disruption** (large or local scale)*
*-**Deconstruction**: altering the structure of the landscape system with fragmentation, reduction of elements, removal of structural, perceptual, symbolic relations;*
*-**Not-connotation**: altering the constituent elements of the landscape.*

The design of every single piece of infrastructure must take into account the need of development, of landscape protection and of its risks. We will try to evaluate the landscape risks and the development potential of a single piece architecture, choosing the arch bridge as a type of infrastructure for its completeness as a structural unit that can give benefits and disadvantages of all scales of interest. Speaking about materials, with the investigation of concrete arch bridges will continue, which will be taken into account in Chapter 3 *State of art*.
The territory changes its expression with the addition of a new infrastructure. In some landscapes all types of infrastructure can be harmful, while in other areas it may be necessary to enrich and improve the landscape and the way in which it is expressed: it is possible to use a bridge not only for its actual functional purposes, but also for other reasons such as visual reference.
The examples examined have already been completed, so we wanted to look at the parameters of landscape quality, landscape risk, modifications and alterations of the environment introduced by the Italian law and used in some concrete cases for the individuation of elements of coherence or conflict for the insertion of particular infrastructures into the landscape. Through the parameters used, are the relations with the territory will be verified and if the bridge is integrated with the area in the difficult mediation to absolve the needs of the new infrastructure. There is difficulty in the formulation of an opinion with a range of values by means of qualitative and non quantitative methods: in fact there is no specific literature that establishes a consolidated guideline for the identification of criteria. We tried to use the cultural matrix (by law) to develop a evaluative reasoning that motivates the formulation of value judgment expressed in numerical form.
The methodological process used to construct the evaluation matrix takes into account the parameters of landscape quality, landscape risk and the consequent changes in the environment after the construction of an arch bridge.
In the formulation of a judgement over a range of values, the first four indicators were considered appropriate (DIVERSITY – INTEGRITY – VISUAL QUALITY – RARITY) and the numerical parameter of DEGRADATION was not considered

being a negative character that lowered the other values. It is conventionally assumed principle that the landscape quality can be identified as the addition of the positive parameters adequately measured. From the numerical point of view is taken for the landscape quality a scale of number from 1 to 5 for each indicator placing the number 3 as medium value (almost to be considered intuitively equal to 0) and following the judging criteria decided in advance.

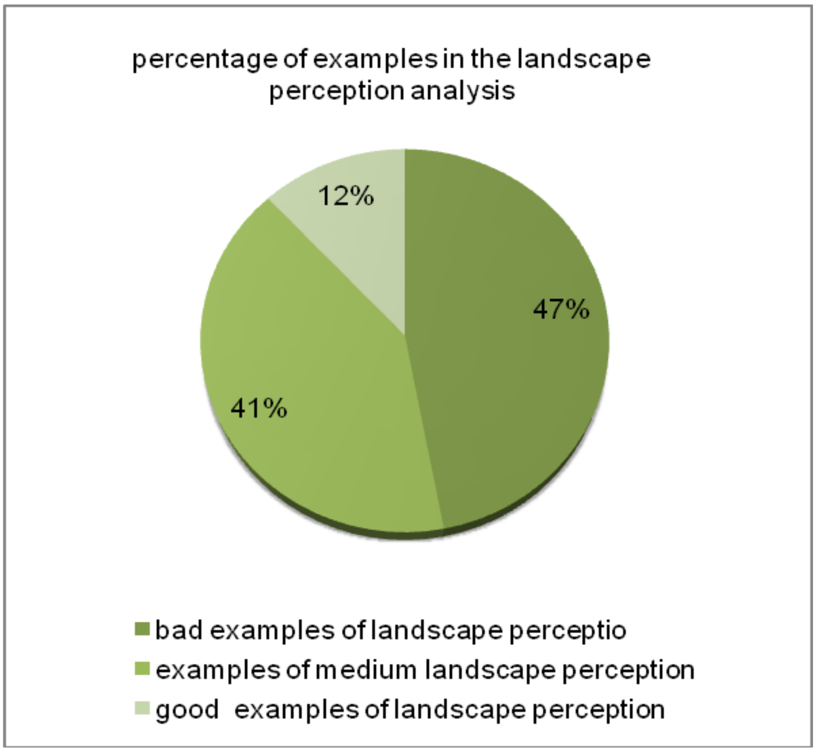
1	2	3	4	5
Low	Medium-low	Medium	Medium-high	Very high

In this way there will be a total value ranging for the four characters from 4 (4x1, minimum value) to 20 (4x5, maximum value).
Likewise at the reasoning conducted for determining the landscape quality, for evaluation purpose, even in the detection of a risk landscape it will be carried out defining a numerical scale for each parameter.

1	0.75	0.5	0.25	0
Low	Medium-low	Medium	Medium-high	Very high

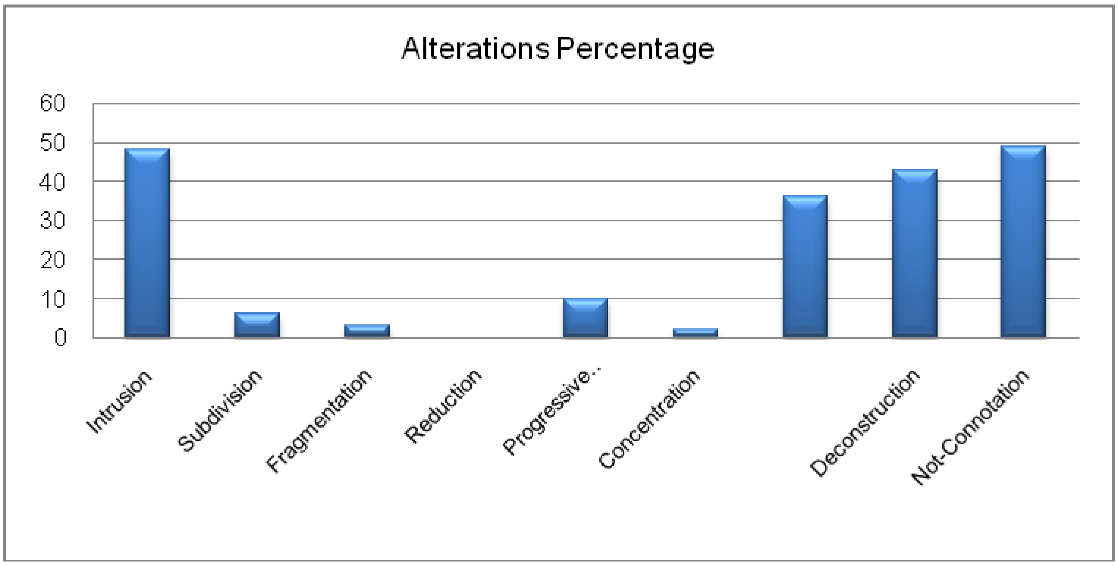
The total capacity ranging from 0 (5x0, minimum value) to 5 (5x1, maximum value).
The landscape quality of the environment before the construction of the arch bridge is at last found by the product between the quality and the risk of the site.
Bridges, for their dimensions and methods of use, have the potential to greatly change the landscape and these transformations may change – interfere – alter or improve the environment.
In addition with regards the MODIFICATION the numerical values ranging between 1 and 5 are considered (3 medium value) thus having a total value of 9 (9x1 minimum value) to 45 (9x5 maximum value).
The value of variation that occurs may be compared with the initial value of landscape quality. Subtracting the initial situation with the subsequent one of the construction, a series of numbers can derived ranging between 15 to -15. The range can be divided equally into three distinct subsets that would represent a good placement of the architecture in question in any given landscape increasing its initial quality (example with values ranging from 5 to 15), architectures with an average quality that become part of the context but without giving any specific variation in positive or negative (examples ranging from 5 to -5), and cases where instead the architectural design has a significant impact on the character of the place altering it in a negative way(examples ranging from -5 to -15).
In this phase, the indicators of the DPCM annex n° 8 could be adopted, which define the types of ALTERATIONS, and try to use them to help understand which are the cases where a project (even though having good architectural and technical qualities) causes a negative landscape perception.

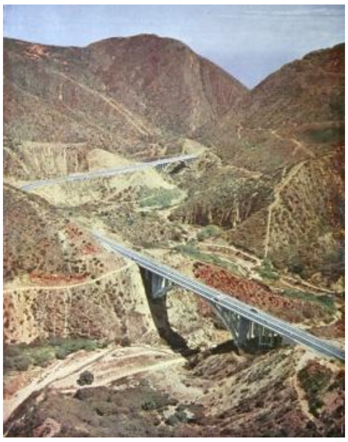
To further explain these theoretical concepts a group of about 120 concrete arch bridges with a span of over 100 m was studied.



The analysis shows that there are many examples of arch bridges that for various reasons alter the environment where they are installed.
How can a bridge be beneficial to the landscape and at the same time maintain the functional standards projected satisfying the viability demand in a single solution?
The study of existing bridges (arch and in concrete) and the perception that they have had in their host society may help us to understand by what processes they are "metabolized" by man. In the history of bridge evolution, in particular, the approach by which it was stabilized in the territory has changed: the bridges were originally built independently from the organization of roads and streets and were then readjusted to reach the bridges. Today the streets have the priority, so the bridge is placed in the area taking into account the routes that it is required to connect, thus obtaining directions and alignments. There are many examples identified in this category of infrastructure where the role of passage takes the dominance over the surroundings adding significant changes to the context.

Speaking about ALTERATIONS that occur in the landscape, in the negative examples the is a higher quantity of arch bridges that are infrastructures immersed in an unspoiled nature, needed to overcome deep green valleys or connect islands that are separated by sea.




a


b


c


d

2. 34 a) Caracas-La Guaira III, Venezuela 1953, 138 m span, E. Freyssinet, J. Muller
b) Pag Bridge, Croatia, 1999, 193 m span
c) Caracau Bridge, Caracau, Romania 1946, 100 m span
d) Van Stadens Bridge, South Africa, 1971, 200 m span, Liebenberg & Stander Western Cape (Pty) Ltd

The indicator that most impact on a place is the INTRUSION with the introduction of foreign and incongruous elements into a landscape with its peculiar characteristics of composition, perception or symbol. Please remember however that this analysis does not take into account the structure and the architecture of the arch bridge, but the relationship that exists between the object (good or bad) and the environment. The following images (Fig. 2.34) show examples of arch bridges made of concrete, a material not common in the natural place.

Regarding the criteria of PROGRESSIVE ELIMINATION OF THE VISUAL RELATIONSHIP, historical, cultural, symbolic of the elements with the landscape and with other parts of the system, the example the Bridge Los Tilos' (Fig. 2.35) is given that has got little villages on the both sides of the gorge separated before the construction by nature but that at the same time shows the main features of the site. The construction of the arch bridge has definitely altered the viability of the area, on one hand facilitating movement and simultaneously becoming the undisputed protagonist of the scenery, stealing the attention from the historical settlements and of the visual relations they had had within the context.

2. 35 Los Tilos' Arch Bridge, La Palma, Canary Islands, Spain, 2004, 255 m span

2. 36 Hoover Dam Bridge, Nevada, USA, 2004, 255 m span

The concept of CONCENTRATION (excessive density of architecture with landscape impact in a limited geographical area) is easy to understand and the example of the Hoover Dam Bridge (Fig. 2.36) emphasizes the comprehension of it. Very often the construction of new architecture and the need to pass over to reach the other side subdivides the place, uniform before the construction, dividing for example the farmland. The criteria of INTERRUPTION OF THE ECOLOGICAL PROCESS and of DECONSTRUCTION (when the landscape is altered with fragmentation, reduction of elements, removal of structural, perceptual or symbolic relations) strongly alter the existing state (Fig. 2.37).
The NOT-CONNOTATION (when the constitutive characteristics of landscape are altered) is another criteria that is seen in a significant percentage of all the cases analyzed (Fig. 2.38).

a b c

2. 37 a) Huayudong Bridge, Qingzhen, China, 1991, 150 m span
b) Sibenik Bridge, Croatia, 1966, 246 m span, I. Stojadinovic, L. Gojkovic
c) Jiangjiehe, Weng'an, Guizhou, China, 1993, 330 m span

a b c

2. 38 a) Podolì Bridge, Czech Republic, 1942, 150 m span
b) Zaporote Bridge, Ukraine, 1952, 228 m span
c) Fred Redmond Bridge, Yakima, USA, 1971, 167 m span

From another point of view with the evaluation of the criteria, that have been taken into account, results indicating that the arch bridges present in an urban area have positive values of landscape perception. This data is given by the presence on site of man and his construction materials, so even if the bridge has no particular value in its architectural and technical characteristics it is inserted into an environment suited to construction and the human development. In fact it is important to highlight that the values of DIVERSITY, INTEGRITY and RARITY generally do have a higher figure than in natural and uncontaminated nature.

However, the values of these examples are good indications in terms of landscape perception, it is considered that even if the design in a natural landscape is extremely difficult both from practical point of view (achieving the position of the construction site) and from the design point of view, an arch bridge in an urban site must respond to the dominance of buildings within that place and therefore the issue of mixing the existing architecture with the new. The bridge changes the skyline of where it is built and breaks into the everyday life of the urban site.

a b c d

2. 39 a) Rive-de-Gier Bridge, France, 1964, 100 m span
b) Seonyu, Seoul, South Korea, 2002, 120 m span
c) Royal Tweed, Berwick-upon-Tweed, UK, 1928, 108 m span
d) Saint-Claude Bridge, France, 1939, 130 m span

Landscapers have to therefore understand this living organism in constant evolution, which represents the meeting point between natural elements and expressions of human activities: town planning, architecture, art, economy, rural and handicraft are deposited into a complex and dynamic relationship. The arch bridge, as said it have already been said, represents a symbol of architectural beauty. For many years, due to time and economic reasons, there has been a minor use in the construction of new infrastructures and the territory is dotted with incongruous elements at the site.

While in the past with the circular and elliptical shape the bridge was synonymous of courage and incredible numbers of examples of these are today enshrined as a symbol of human culture, now the situation is completely different. An infinite number of new roads, highways, fast railways are subdividing the country, with the continuous need to built bridge of small, medium and long spans. The architectural quality of these bridges will remain unnoticed by drivers who are concerned with issues of safety and speed limits. The landscape perception varies if you are experiencing it from within or from afar. Travelling over any architecture gives the user a totally different perspective of the architecture, allowing to forget about the artificial element that changed the landscape and instead appreciate the fact to be observing it.

Observing from afar as the architecture fits into the landscape allows one to notice its characteristics, shapes, materials and as Salvatore Settis says: "*Beauty is not a postcard. The nice thing of beauty is that it is never alone but in company, together with the memory of what we are*".[14]
The landscape protection, as a common good, permits a better life quality and the awareness of the beauty grows by understanding what is ugly. For this reason in a new arch bridge design, more than any other architecture, should be very careful at all the relations that it will have with the existing surroundings and the eventual changes that it will cause: the bridge must be a good neighbour that fits in.

From this issue in the second chapter *Perception* a human characteristic stands out that influences the creating of the arch bridge: landscape perception.

[14] Settis S., 2010, *Paesaggio Costituzione cemento. La battaglia per l'ambiente contro il degrado civile*, Torino, Einaudi, 2010

CHAPTER 3: STATE OF ART
Arch bridges in the world and in Italy

I was tense and cold, I was a bridge;
I stretched across the abyss;
I lay and waited.

Except when it collapses,
a bridge that is built can never cease to be a bridge.
Franz Kafka

3.1 Introduction

Over the centuries, the arch has found multiple applications in buildings and bridges, but often the cost of the construction phases would become almost the same as the cost of the building itself. Nowadays however, arch bridge construction has again become economically competitive, thanks to the development of new erection methods (see Chapter 4 *Construction*), of materials and technologies used on the construction sites and to an ever increasing demand for aesthetically valuable structures.[1]

The designer searches for aesthetic elegance and structural quality and has the duty to give a correct form to a structure. The architectural designers give the form to an object that has a complex human use and see forms as a means of controlling the space used by people.[2] When architecture and engineering find a relationship between use and beauty, there is a very strict connection between structure and shape. As seen in Chapter 1 *Design*, the shape of the arch is the highest expression of the architectural form and it holds an aesthetically given pleasure and is easily integrated into the environment. The shape of the arch is itself the structure and the structure resists due to its shape. To function the arch must be completed, so all partial structures that may arise during the construction of the arch have little to do with the final structure: this difficulty and the cost of construction stem from this one fact.[3]

3.2 State of art in the world

Data and materials, relating mainly to examples of concrete arch bridges, were provided which define the basis for a graphic analysis. This study will show the architectural types of arch bridges and the architectural features most used and the construction methods employed in the various cases considered. The use of concrete in the construction of arch bridges has lead to the achievement of ever greater lengths. The world records in fact represent the evolution of construction techniques, which underlines the progress of the equipment used on the work site and the quality of the materials.

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[1] Palaoro S., Siviero E., Briseghella B. and Zordan T., 2009, *Evolution of the arch bridge type in Italy, In proceeding 2nd Chinese-Croatian Joint Colloquium on Long Arch* Bridges, Fuzhou and Shanghai.
Favre R., De Castro San Roman J., 2001, *The arch: enduring and endearing*. In Proceedings of the 3rd International Conference on Arch Bridges, Paris – France, pp.3-16

[2] Billington D. P., 1985*, The Tower and the Bridge. The new art of structural engineering*, Princeton University Press, New Jersey.

[3] Troyano L.F., 2004, *Procedure for the construction of large concrete arches*. In Proceedings of the 4th International Conference on Arch Bridges – Advances in Assessment, Structural Design and Construction, Barcelona – Spain, pp.53-63

Some 600 examples of arch bridges in the world were taken into account, with the two common characteristics of having been built after the year 1900 and with a span of more than 100 m. The analysis of the data (span, material, static scheme, construction method, year of construction, etc.) of the existing arch bridges is very important as to understand the evolution of arch bridge types in the world and also which kinds of materials and construction methods are now the most convenient. It can be clearly noticed that the longest arch bridge was built in recent years while the previous ones were erected many years before.[4]

N°	Bridge Name	Year	Span (m)	Country	Location
1	Wanxian	1997	420	China	Wanxian
2	Krk I	1980	390	Croatia	Krk Island
3	Jiangjiehe	1995	330	China	Weng'an
4	Mike O'Callagham	2010	329	USA	Hoover Dam
5	Hoover Dam Bypass	2010	323	USA	Boulder City
6	Yongjiang	1996	312	China	Yongning
7	Gladesville	1964	305	Australia	Sydney
8	New Indian River	2010	305	USA	Bethany Beach
9	Amizade	1965	290	Brazil	Foz do Iguaçu
10	Friendship	1965	290	Brazil	
11	Infante D. Henrique	2002	280	Portugal	Porto
12	Chishi Datong	1997	280	China	Gu-izhou
13	Infante D. Henrique	2002	280	Portugal	Porto
14	Bloukrans	1984	272	USA	Nature's Valley
15	Arrábida	1963	270	Portugal	Porto
16	Grümpen	2009	270	Germany	Schalkau
17	Sandö	1943	266	Sweden	Lunde
18	Fujikawa	2003	265	Japan	Shizuoka
19	Chateaubriand	1990	261	France	Plouër-sur-Rance
20	Takamatu Bridge	2000	260	Japan	Miyazaki

3. 1 concrete arch bridges: the darker grey lines represent the arch bridges built in China, then the European arch bridges and with the lighter grey lines the ones built in America.

The longest concrete arch bridges are listed in Table 3.1.Almost half of them are in Europe, but many are built in China where they represent about 70% of all highway

[4] Troyano L.F, 2004, *Procedure for the construction of large concrete arches*. In Proceedings of the 4th International Conference on Arch Bridges – Advances in Assessment, Structural Design and Construction, Barcelona – Spain, pp.53-63

bridges and three of the six longest arches in the world were built in an Asiatic country. It is very interesting to note that four arch bridges were built 50 years ago or more: the Gladesville in 1964 (Australia, 305 m long), the Amizade Bridge in 1965 (Brazil, 290 m long), the Friendship Bridge in 1965 (Brazil, 290 m long) and the Arrabida Bridge in 1963 (Portugal, 270 m long). The reason is probably due to the rapid development of the construction methods in recent years and of the latest researches carried put on the quality of materials, on the construction methods, on the life cycle and on the analysis methods.

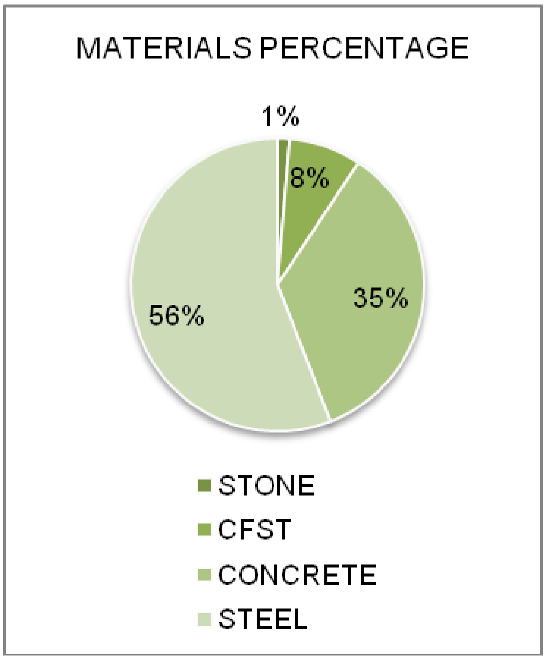
N°	Bridge Name	Year	Span (m)	Country	Location
1	Chaotianmen	2008	552	China	Chongqing
2	Lupu	2003	550	China	Shanghai
3	Banghwa	2000	540	Korea (S)	Seoul
4	New River Gorge	1978	518	USA	Fayetteville
5	Bayonne	1931	504	USA	New York
6	Sydney Harbour	1932	503	Australia	Sydney
7	Chenab River	2009	480	India	Kauri in Reasi
8	Xinguang	2008	428	China	Guangzhou
9	Caiyuanba	2008	420	China	Chongqing
10	Piscataqua River I-95	1971	410	USA	Kittery
11	Fremont	1973	382	USA	Portland
12	Numata River Gorge	2007	380	Japan	Hiroshima
13	Francis Scott Key	1977	366	USA	Baltimore Maryland
14	Port Mann	1964	366	Canada	Port Mann
15	Gateway	2005	360	USA	Detroit
16	Wan Zhou	2006	360	China	
17	Cold Spring Canyon	1963	350	USA	Santa Barbara
18	Americas	1962	344	Panama	Balboa
19	Dashengguan	2009	336	China	Nanjing
20	Laviolette	1967	335	Canada	Trois-Riviere

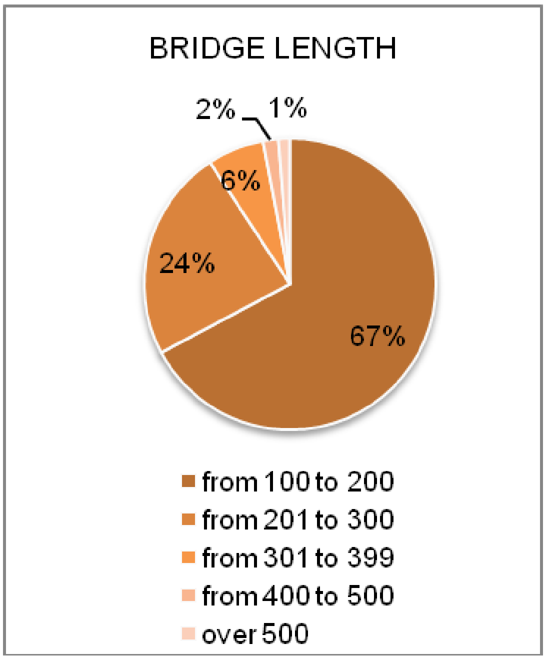
3. 2 steel arch bridges: the darker grey lines represent the arch bridges built in China and with the lighter grey lines the ones built in America.

Regarding the steel arch bridges (Table 3.2) we can add some further considerations: firstly, it is clear from the above list of the fifteen longest steel arch bridges there are not any European ones, and secondly that regarding concrete bridges, the world record belongs to China with the Chaotianmen Bridge built in 2008 with a span of 552 m (see Chapter 4 *Construction*, Fig. 4.41).

While America has predominantly uses steel in arch bridge construction. The reasons for this conclusion are found in the origin of this material: the USA has a long tradition in metal construction and steel began to be used in bridges at the end of the 19th century. In fact, the first large arch bridge which had a main structure in steel was the St. Luis Bridge (see Fig. 1.38, Chapter 1 *Design*) over the Mississippi River in the USA. It was designed by James Eads (1820-1887) and built in 1874 with the cantilever construction method. While it was in the first half of the 20th century that the great steel arch bridges were built in USA[5], where as in Europe, thanks to the experiences of some famous engineers, such as Eugene Freyssinet (1879-1962) and Robert Maillart (1872-1940), concrete and prestressed concrete structures were more commonly used.

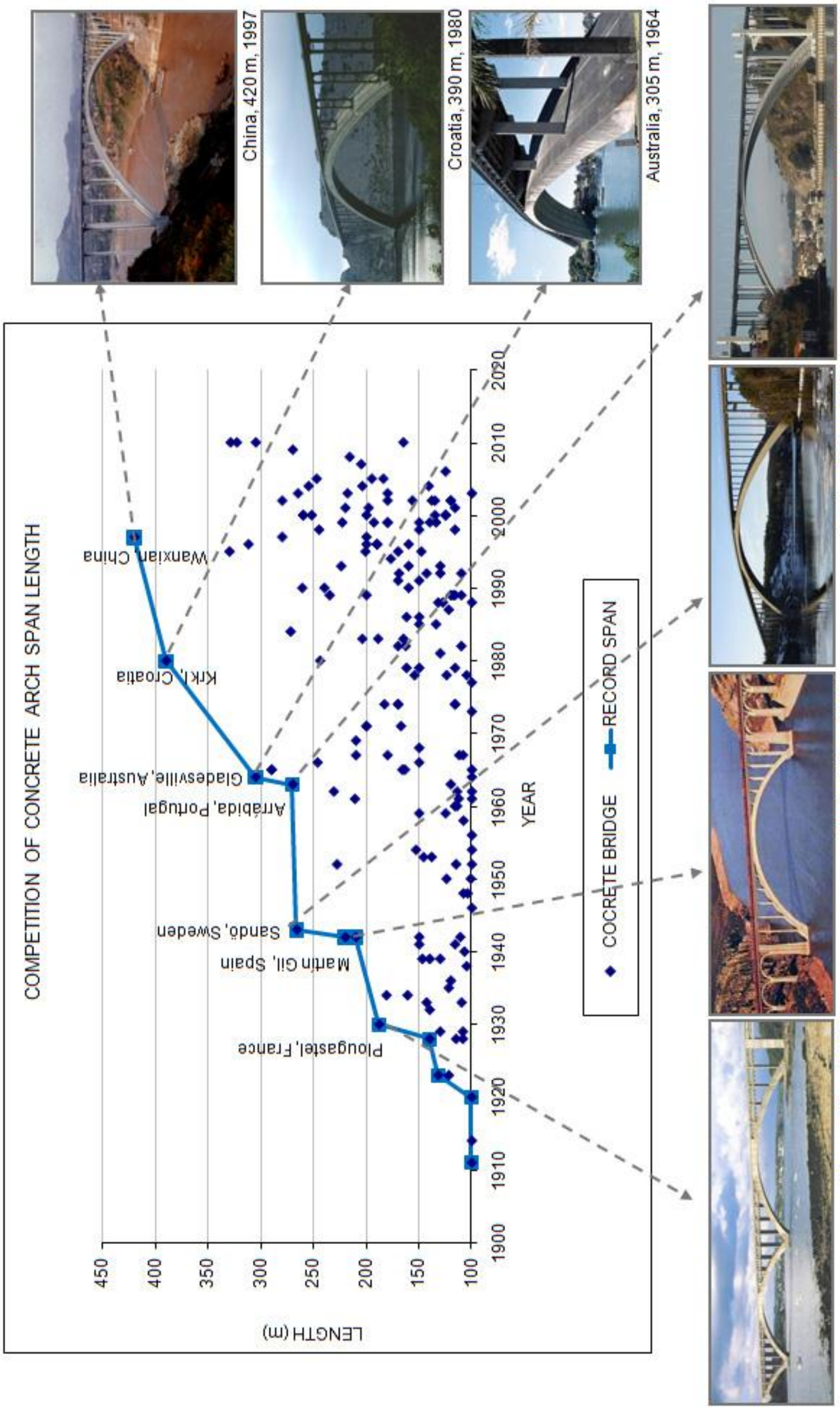
The statistics of the longest arch bridges built after 1900 and with a span of more than 100 m, allow us to understand what materials were used and how bridges are subdivided by their span. The pie charts 3.3 and 3.4, obtained from the approximately 600 bridges analyzed, show that steel bridges make up 56% of the total bridges and that the major quantity of arch bridges, 67%, has a span between 100 m and 200 m. The 1% slice represents the rare cases of bridges with a span of more than 500 m.



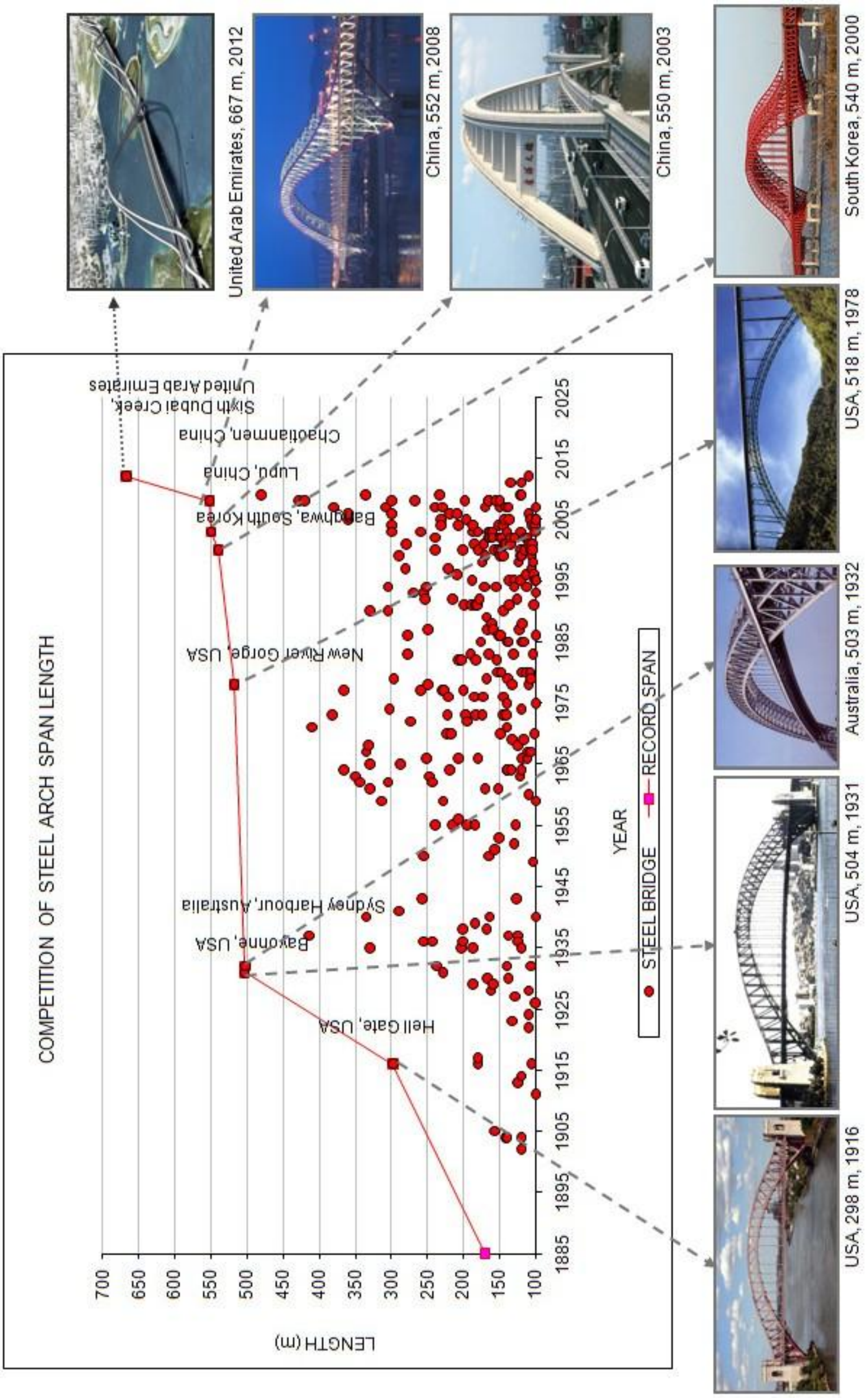


3. 3 arch bridges over 100 m built after 1900: materials used for arch bridges built after 1900 and of over 100 m
3. 4 arch bridges over 100 m built after 1900: length graphic

[5] Troyano L. F., 2006. *Terra sull'acqua. Atlante Storico Universale dei Ponti.* Dario Flaccovio Press, Palermo, Italy



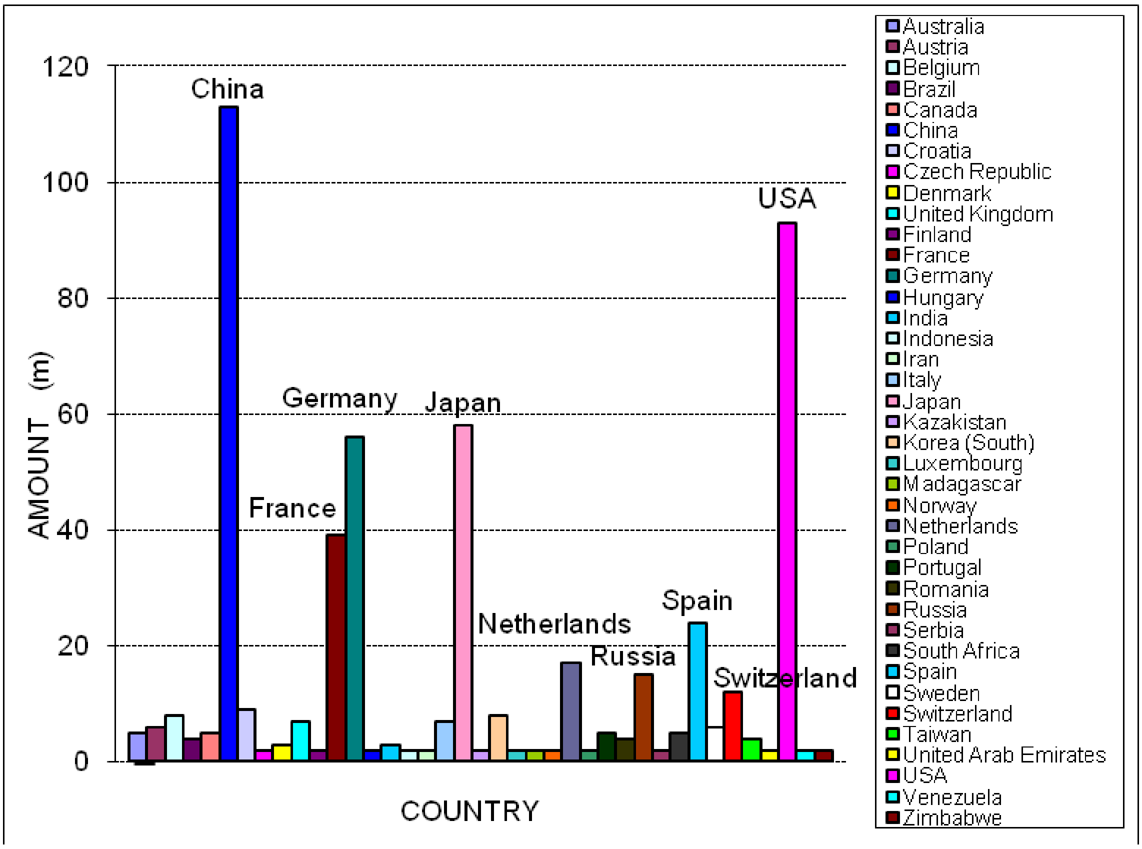
3. 5 Concrete arch bridges spanning more than 100 m as a function of the opening year



3. 6 Steel arch bridges spanning more than 100 m as a function of the opening year

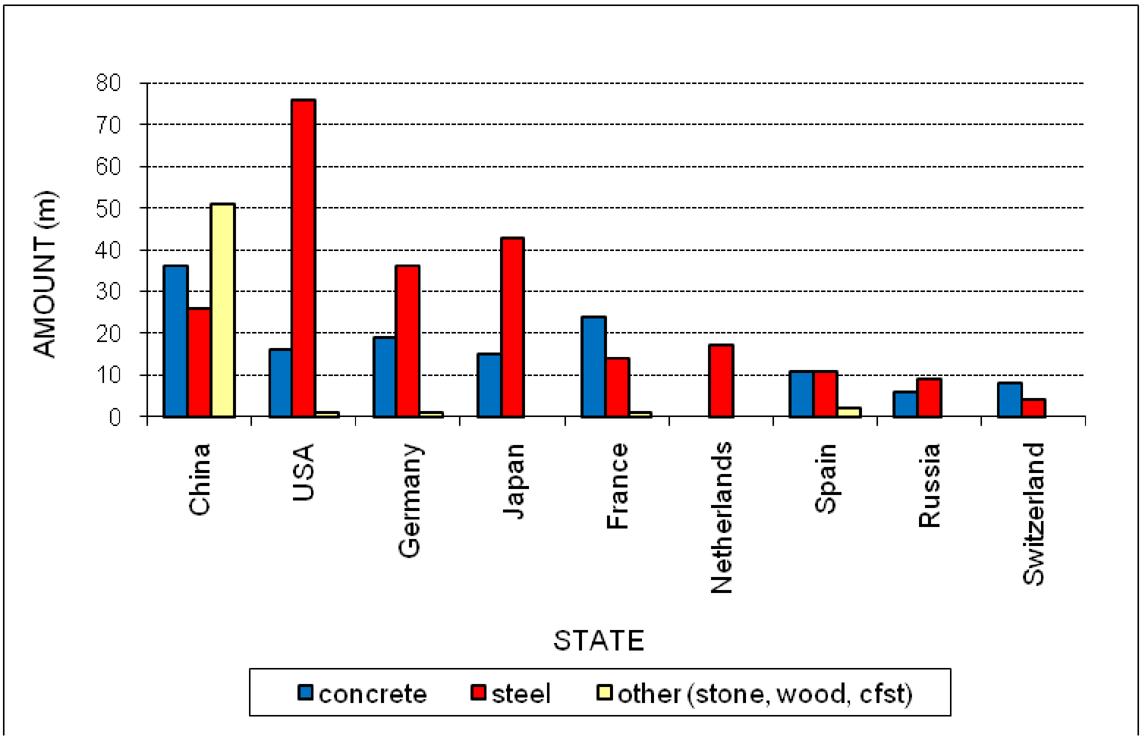
The evolution of the arch bridge is introduced in the Figures 3.5 and 3.6, where the edge lines represent the span record limit in time. There is an intensification of the arch bridges constructed in the strip between 100m - 200m span both in concrete and in steel. As we can see, only a few realizations reach spans of more than 400 m, this data underlines the daily demand of human scale projects, bridges that could overcome small and medium traffic problems. Recent erection methods permit the construction of more elegant arch bridges with longer spans. Nowadays, the most widely adopted construction method for the arch bridge seems to be the cantilever one, as seen previously. Record spans represent some exceptions that show progress in erection techniques.

With the graph 3.7, I tried to find where arch bridges are distributed in the world subdivided according the various countries: in this analysis one must take into account that each country is different, let it be in size, as China and U.S.A., but also the necessity in the construction of infrastructure links, and then the natural elements presented in each territory that could influence the construction of bridges, as water in Japan or Netherlands or, conversely, the country's position in a mountainous area such as Switzerland, and last but not least, the materials mostly used in each individual country.



3. 7 State of art in the world: arch bridge amount built after 1900 and with a span of more than 100 m in each country

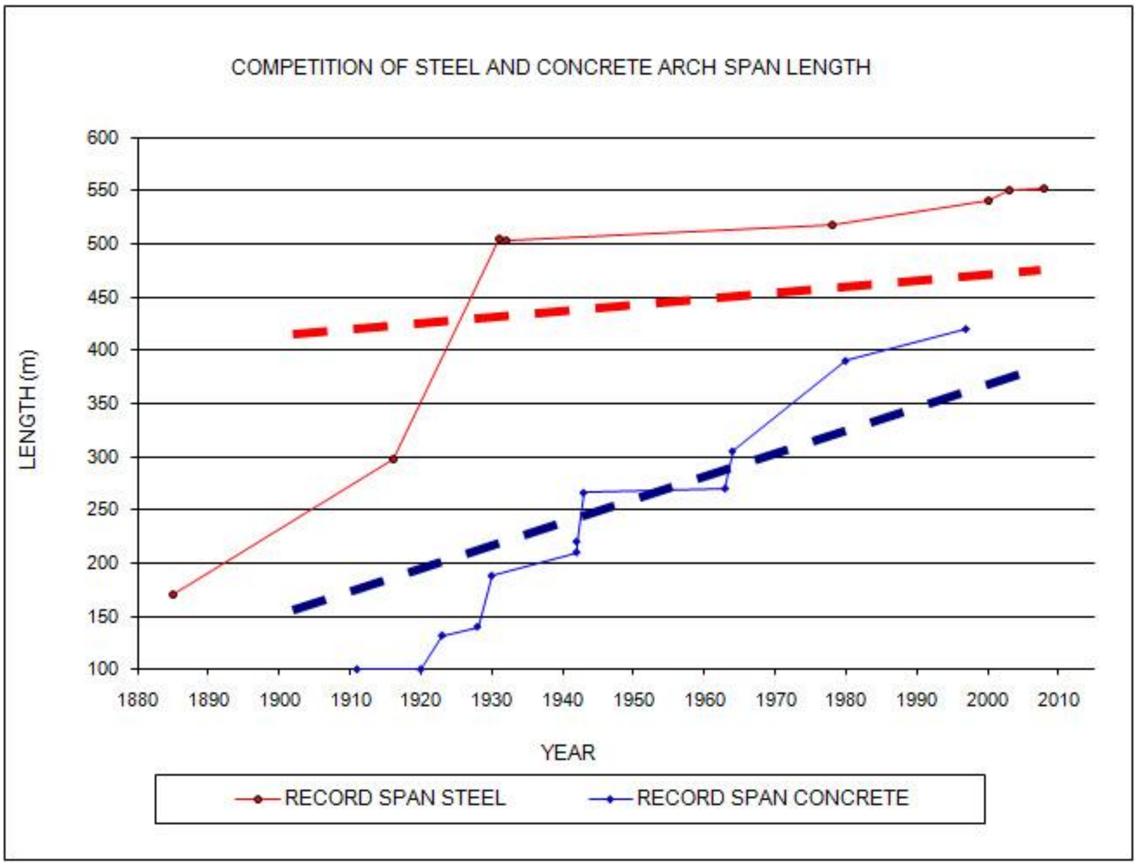
From the analysis and from the graph 3.8, we can see that steel is generally the most widely used material (to confirm the data presented above), but that its use differs according to countries. The red column of steel for the USA stands out immediately on the graph: the USA has indeed a long tradition of using steel. The old continent, on the other hand, makes a greater use of concrete.



3. 8 State of art: arch bridge built after 1900 and with a span more than 100 m: the different materials used in the country against the bridge quantity.

A bracket can be opened for China, a country that regarding its size, needs connections between vast areas and has a large number of arch bridges. Speaking about material, there is a massive use both of concrete and steel, and often they are used in composite structures, such as the examples of concrete fill steel tubes: rather than being considered a constructive method, it is a typology often used in recent years in the construction of long span bridges. This type of bridges uses steel pipes of various sizes having to do with its "lightness", and these elements are positioned as if they were elements of a Melan centering to the final position and then filled with concrete. This structural typology has advantages of simplifying the assembly construction phases, taking advantage of lightness and strength of steel, and it has the best structural behavior due to the effect of confinement exerted on the concrete (see Chapter 4 *Construction*, Fig. 4.48). In China, there are countless examples of this type which are also described in the literature and this is certainly the reason for which there is a large number of “other materials” in the graph 3.8.

Looking at the evolution of arch bridges in the world, both in concrete and in steel, we can see that the two lines over graph 3.9 represent the future trend in the use of construction materials: the higher red depicts steel and the lower blue line depicts concrete. It is easy and important to notice that the concrete trend line has a greater slope than the steel one, showing that there has been, and will always be, a greater improvement in construction technology and in the research of concrete strength. These factors will allow this material to achieve ever longer spans in the future.
The first important element that characterizes the arch bridge architecture is the use of one material or the other, even though the choice of material during the planning phase is inevitably influenced by the cost analysis. However, the total cost of a project is not completely influenced only by the material but of course also by the construction method used. The choice of material may be useful to define an interesting architectural shape or construction details.

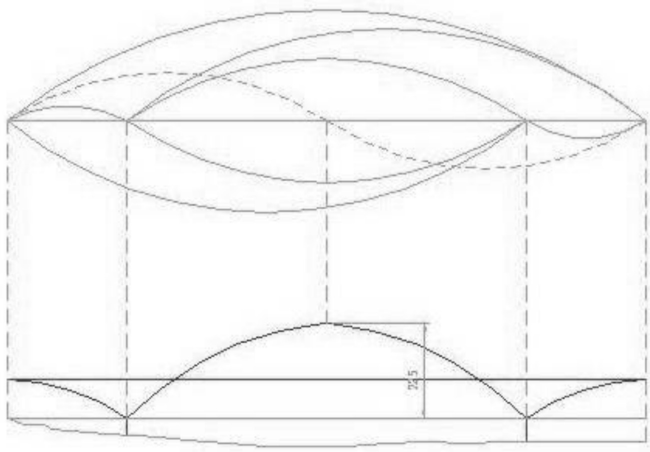


3. 9 The evolution of arch bridge typology since 1900 and with a span of more than 100 m: steel and concrete

Trend steel line   Trend concrete line

The use of concrete for the arch bridge construction has always seen more examples, reaching span longer than ever before: in fact the longest spans

represent the evolution in the construction technologies, which means the development of the tools used on the work site and the material quality. Structural considerations require that the material of the bridge should be proportioned and positioned as to provide convenience and durability. The width and arrangement of road way and motorway should suit the traffic needs. To make an even deeper investigation about materials, given the data available, concrete was taken into account: the percentage of concrete realizations is 35% for all the existing bridges built since 1900 and longer than 100 m. 90% of these structures correspond to deck arch bridges fixed at the abutments. In addition to the typological characteristics that condition the architecture of the work, a lot of factors that influence the design phase were taken into account. These factors can be mainly divided into three categories: elements of an aesthetic nature, technical-constructive problems and external factors that affect both planning phase and implementation.
Beauty does not demand elaborate ornamentation and of course it is not in any way opposed to efficiency. A good piece of work has to show characteristics such as proportion (Fig. 3.10), symmetry, rhythm, repetition and contrast. An important characteristic, necessary to achieve beauty of a building, is a good and harmonious proportion in a three dimensional space. Good proportion must exist among the relative dimensions of the various parts of a structure; between height and width; among its masses and voids, closed surfaces and openings; and between light and dark caused by sunlight and shadow (see Chapter 2 *Perception*). Proportion is to research not only in the individual parts of the building, but also between the relations of the masses: in a bridge these relations may be between suspended superstructures and supported columns. Harmony is also achieved by the relation of the same elements in the entire structure or in its various parts.



3. 10 Example of arch bridge proportion scheme

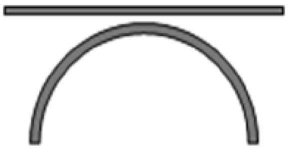
However, the realization of a good project is to think apart from the human progress: moreover the beauty of a structure could be a subjective quality and a personal feeling. A bridge must possess two general elements: structural efficiency and unity of appearance. Besides structural and typological elements, external factors have to be taken into consideration (Table 3.11), these primarily define some architectural considerations and construction difficulties.

<table>
<tr><th colspan="2">Architectural elements</th><th colspan="2">Technical elements</th><th>External elements</th></tr>
<tr><td rowspan="3">Type</td><td>Deck</td><td colspan="2">Material</td><td>Place</td></tr>
<tr><td>Half-through</td><td rowspan="3">Structure</td><td>Fixed</td><td>Obstacle</td></tr>
<tr><td>Through</td><td>Two-Hinged</td><td></td></tr>
<tr><td colspan="2">Section deck typology</td><td>Three-hinged</td><td></td></tr>
<tr><td colspan="2">Spandrel or open-spandrel</td><td>Rise</td><td rowspan="2">Rise span ratio</td><td></td></tr>
<tr><td colspan="2">Column shape typology</td><td>Span</td><td></td></tr>
<tr><td colspan="2">Connection between the pile</td><td colspan="2">Deck width</td><td></td></tr>
<tr><td colspan="2">Section arch typology</td><td colspan="2">Deck material</td><td></td></tr>
<tr><td colspan="2">Ribs number</td><td colspan="2">Construction method</td><td></td></tr>
<tr><td colspan="2">Connection between the ribs</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Connection between arch and deck</td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Span number</td><td colspan="2"></td><td></td></tr>
</table>

3. 11 Farctors influencing the architecture

Deck position

Bridges can be divided into three different categories depending on the morphological point of view. The first element that influences the shape and the architecture of a bridge is the position of the deck relative to the arch. From the analysis it emerges that the choice of one or another typology depends not only on the arch bridge design but it is also closely connected to the place where the bridge is built and with the obstacle that it may have to overcome. On the other side, the choice of the structural system is based on the research of the better and easier construction phase, but at the same time and from the architectural point of view it influences the detail of the arch.

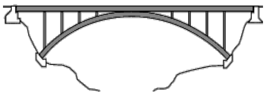
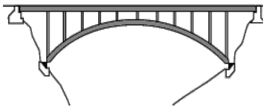
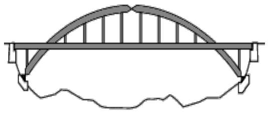
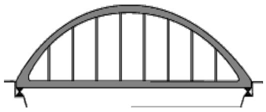
Deck arch bridge	Half-through arch bridge	Through arch bridge
		
		
Artuby Bridge Aiquines, France, 1940, 107 m span, 23 m rise , 1/ 4,65 rise span ratio, Pelnard, Considère et Caquot	**Yongdinghe N°7 Bridge** Yunnan, China, 1966, 150 m span	**Third Millennium Bridge** Zaragoza, Spain, 2008, 216 m span, 36 m rise, 1/ 6 rise span ratio, Juan José Arenas de Pablo

3. 12 Deck position typology

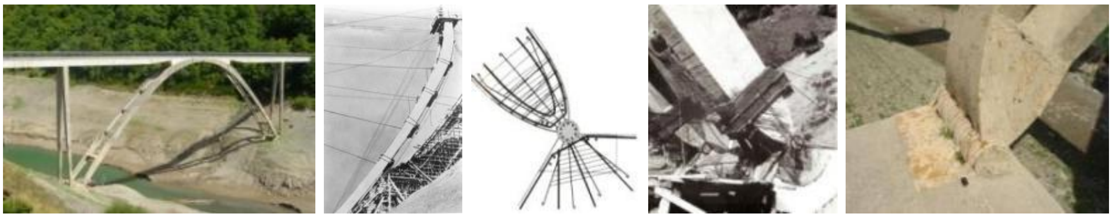
Structural Typology

The choice of the structural elements depends first of all from the construction place and its characteristics and from the construction material and its proprieties, and from the construction method and its timing of assembly. From the architectural point of view, choosing one or other typologies determines different details.

The Lussia Footbridge (Fig. 3.14), designed by Riccardo Morandi (see Chapter 4 *Construction,* Fig. 4.58, 4.59) is an example of a bridge where the structural typology becomes not only a useful element during the construction phase but an architectural detail too. Two hinges at the abutments, used in the construction, permitted the rotation of the two semi-arches till the closure at the crown.

Fixed	Two-hinged	Three-hinged	Bowstring
			
			
Fred Redmon Yakima, USA, 1971, 167 m span, 98 m rise, 1/ 7 rise span ratio	**Saratov** Saratov, Russia, 1965, 166 m span, 14,5 m rise	**Salginatobel** Grisons, Switzerland, 1930, 90 m span, Robert Maillart	**Lappeasuando** Lappeasuando, Sweden, 120 m span

3. 13 Structural element



3. 14 Lussia Footbridge, 70 m span, 1953, Vagli di Sotto, Lucca, Italy, R. Morandi.

3. 15 Viaur Viaduct, 220 m span, 54 m rise, 1902, Carmaux, France, P. Bodin

An example of a bridge with three hinges is the Viaur Viaduct (Fig. 3.15) in France. It was one of the highest railway bridges in the world upon its opening in 1902. Although it looks like an arch, the Viaur Railway Bridge is actually two balanced cantilevers joined in the middle by a hinge. A true arch effect only occurs when a train is going across the central span of the bridge.

The characteristics, that almost all the concrete arch bridges have in common, stem from the analysis of all the concrete arch bridges built after 1900 and with a span of more than 100 m: the highest quantity of concrete arch bridges are designed as deck arch bridge and with a fixed structure. Analyzing almost 150 concrete arch bridges, the highest quantity (129 bridges) are deck arch bridges.

Structural typology	
Fixed	119
Two-hinged	3
Three-hinged	2
No data	5

The main reason, that we can guess, comes from the material property and from the construction methods that permit it to be built.

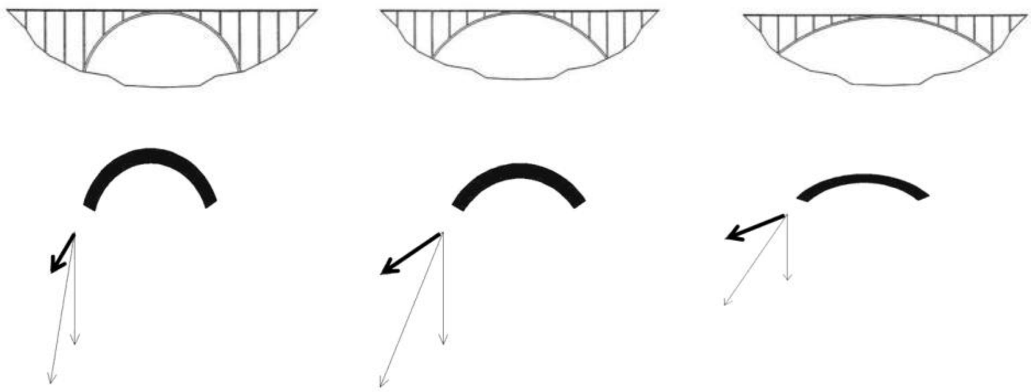
Rise span ratio

The first inevitable element that gives the architectural features at the bridge is the relationship between length and height of the bridge, called as rise-span ratio and that defines the formal and dynamic characteristics of the bridge. For example, in the classical times, the ancient roman bridges were a synonym of strength, durability and static. These features were of course emphasized by the material, the stone used at that time; on the contrary, with the use of other materials such as concrete and steel, the arch has seen a breakthrough in terms of architecture and structure, lighter and more dynamic (Chapter 1 *Design*).
From scientific references, three arch bridges typologies have been defined depending on the rise-span ratio. These values respectively are:

0,50 < f/L < 0,35 1/2 < f/L <1/3	0,35 < f/L < 0,15 1/3 < f/L <1/6	0,15 < f/L < 0,10 1/6 < f/L <1/11

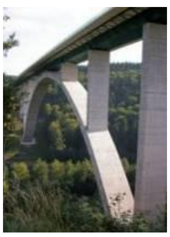
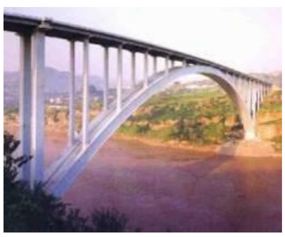
The choice of one ratio rather than another influences the arch thrust with the obviously consequences that have to be taken into consideration during the design phase (Fig. 3.16).
About the cases examined and after the premise, we can see that there are few examples of arch bridges that have a high rise-span ratio and then there are also some examples where the arch is very low.
Before going any further with an in-depth analysis of this factor, it is useful to anticipate yet another factor that influences the design and the rise-span ration of a new bridge: which is the environment, the location where a new bridge is necessary. The location considerably influences the proportion that an arch can

have between length and height: the first point consists in the resistance of the soil that must withstand the horizontal stress of the arch; the second is the width of the valley or of the river to overcome, a dimension that initially gives one of the two measures.



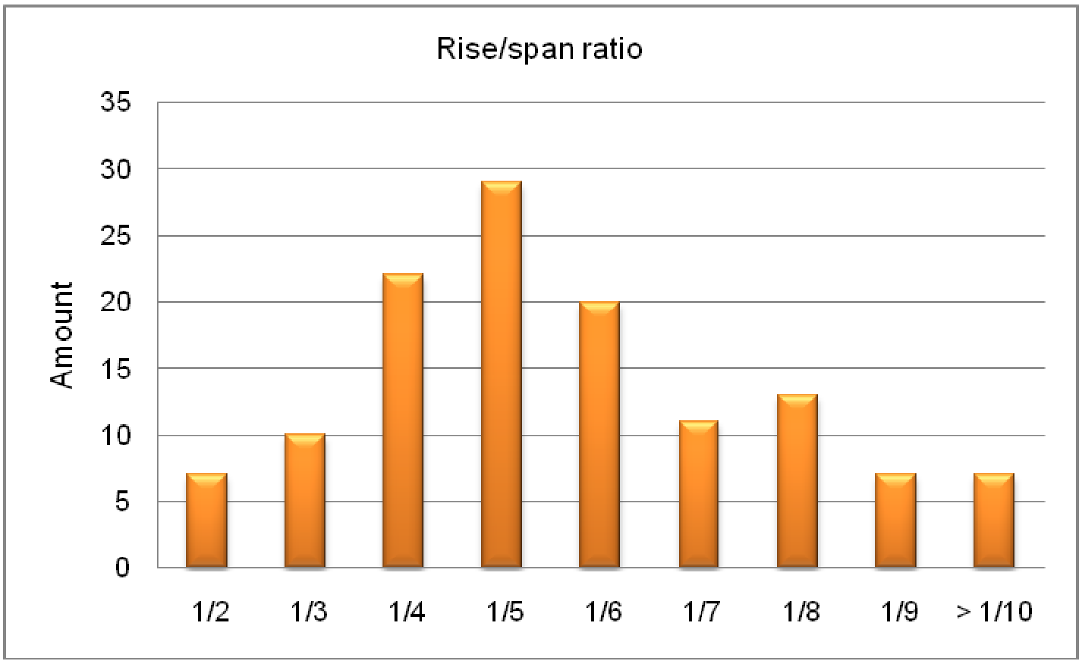
3. 16 rise/span ration influences the arch bridge architecture and structure

From this analysis it has emerged that the higher quantity of concrete arch bridges are built with a rise-span ratio of between 1/4 and 1/6. This is even more valid for deck arch bridges, instead for half-through arch bridges rise and span are independent values which do not influence the structure too much. The ratio has a importance for a good architectural observation. In general the rise-span ratio is more or less 1/6.
From all the data, we observe that the higher quantity of concrete arch bridges are built with an intermediate value of rise/span ratio. The three examples in the Table 3.17 are the longest concrete arch bridges built with different rise/span ratio.

10 bridges	65 bridges	27 bridges
0,50 < f/L < 0,35 1/2 < f/L <1/3	0,35 < f/L < 0,15 1/3 < f/L <1/6	0,15 < f/L < 0,10 1/6 < f/L <1/11
		
Wild Gera Viduct 2000, Germany, 252 m span	**Wanxian Bridge** 1997, China, 420 m span	**Jiangjiehe Bridge** 1995, China, 330 m span

3. 17 Structural element

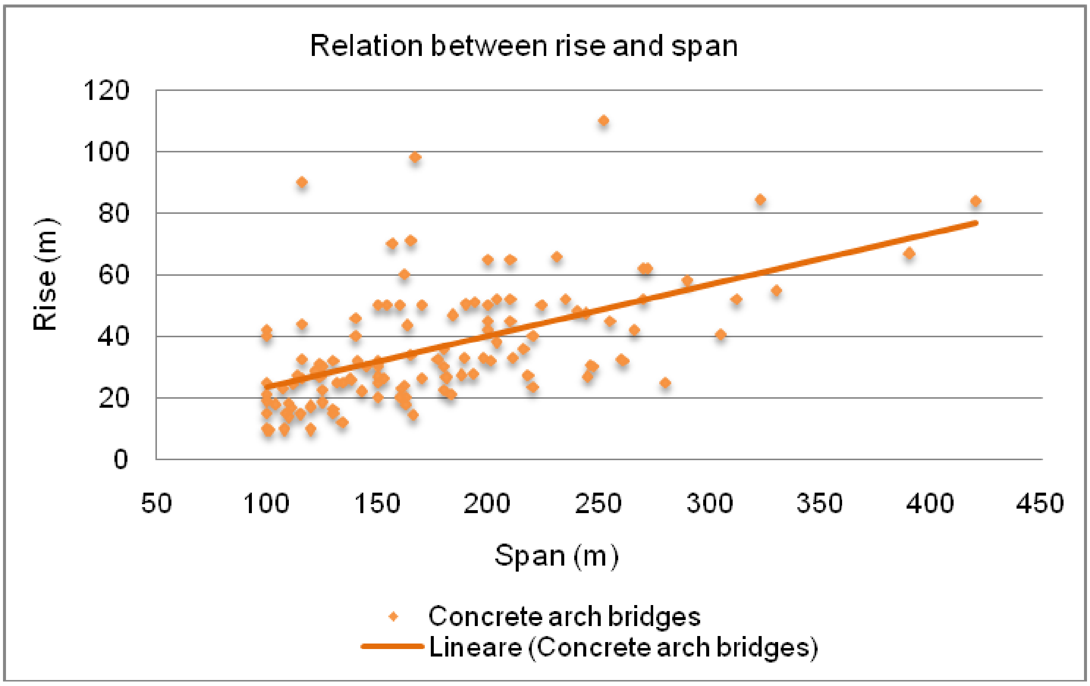
From the graph 3.18, we can see how concrete arch bridges are subdivided depending on the ratio value and that, as mentioned before, an important use of concrete arch bridges with an high value of rise/span ratio, which represents the common shape of those built in antiquity, is not so common anymore.



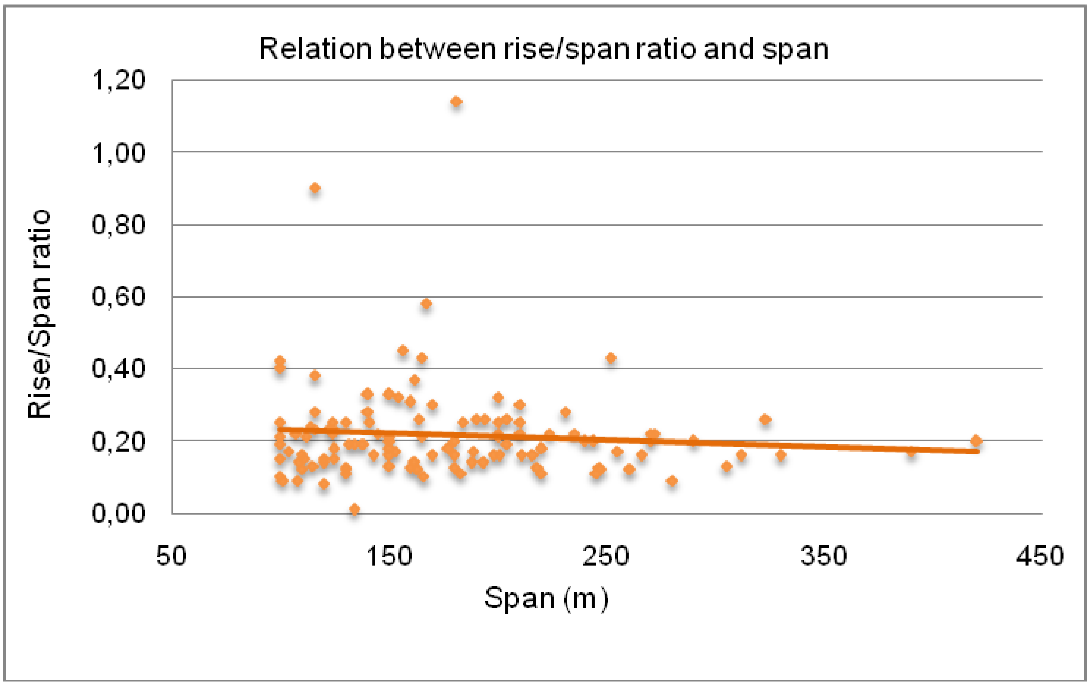
3. 18 rise/span ratio for concrete arch bridge

An interesting element is emphasized by the two graphs 3.19 and 3.20: they permit us to understand how the rise value or the rise-span ratio could influence the architectural design. With the increase of the length of the bridge there is a proportional and obvious increase in the high (greater length - greater height). On the contrary, the rise-span ratio decreases with the increase of the span. This means that the bridges with greater span will tend to have a lower configuration, rather than those of small and medium-span that have a semicircular arch architecture.
Speaking about concrete arch bridges with fixed structure and analyzing the rise-span ratio in a deeper way, we can see that the cantilever construction method is the most commonly used in every case (graph 3.21), but that cantilever and falsework construction methods have almost a similar value for arch bridges with lower ratio. This means that when the rise has a smaller value in proportion to the length of the arch, cantilevered construction method is not recommended, because it may have problems during construction, given the significant length of the semi-arch in cantilever. This expedient has to be considered depending on the location and on all the problems that may exist on the construction site: for example the creation of a very low arch bridge in the vicinity of a deep valley may not always be

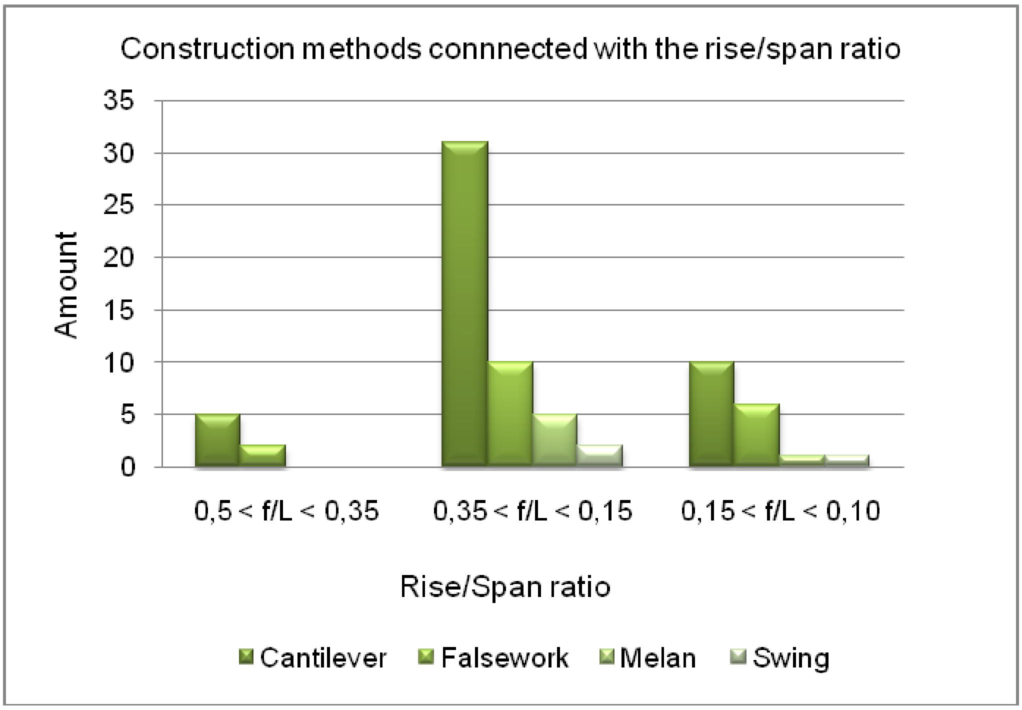
done by the centering construction method. On the other hand, a massive use of the cantilever method would be difficult for the construction of a low arch over a large river, while intermediate supports would be used to facilitate its completion.



3. 19 Relation between rise and span value



3. 20 Relation between rise/span ratio and span value



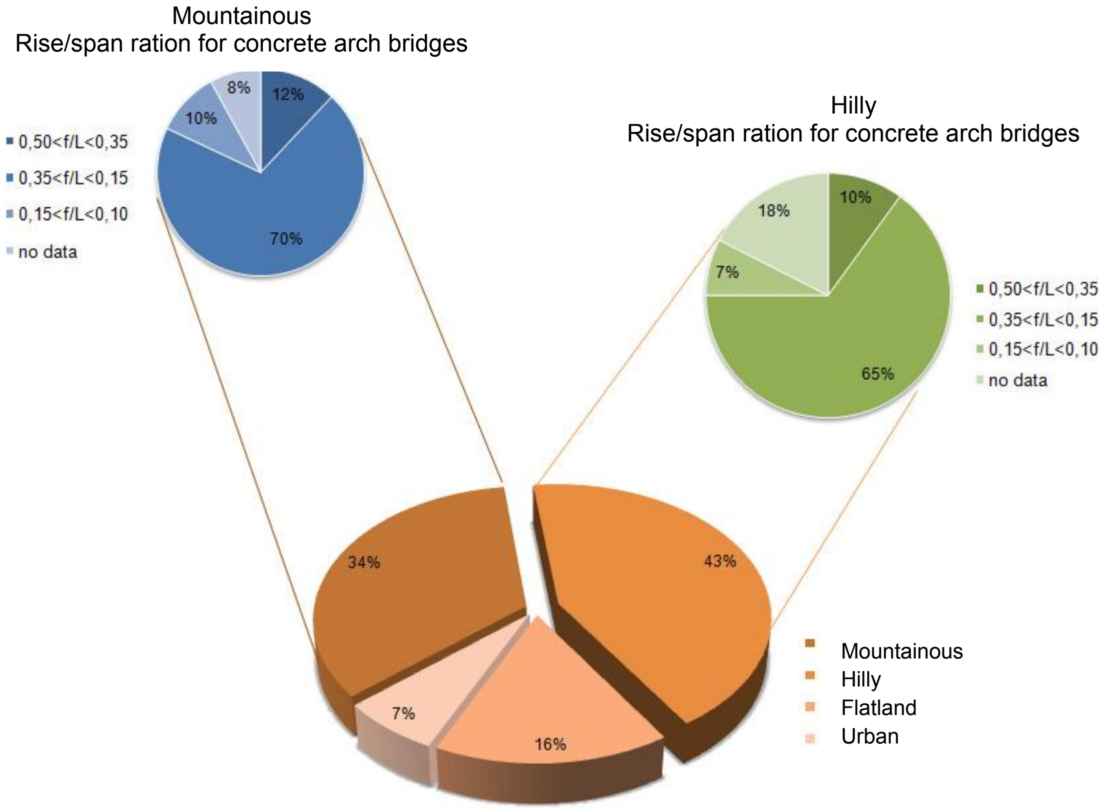
3. 21 Construction methods most used in connection with the rise/span ratio

Environmental position and Obstacles to overcome

The cantilever construction method is the most used in the building of concrete deck arch bridges. This method permits the simultaneous construction of the semi-arches from the springing to the crown or the simultaneous construction of the arch rib and the deck (see Chapter 4 Construction): the various elements could be assembled directly on site, hoisting them up by the lateral side or lifting from barges below. The cantilever method allows to overpass places and obstacles without touching them, without interfering with the surroundings, having a minor impact respect to the other construction methods.
I previously did some considerations on how the environment can influence an architectural choice. For this reason I tried to subdivide the environment in four main types: mountainous, hilly, flatland, urban. As we can see, the construction of concrete arch bridges, that are almost all deck arch bridges with fixed structure, are built in hilly or mountainous orography. The necessity of a new bridge, in general, is closely related to the obstacle presented in a certain place, these obstacles could be a deep valley, a river or a street.
It is interesting to notice that in general, as we have seen before, concrete arch bridges have a rise-span ratio between 0,35 and 0,15, but in particular, if we speak about arch bridges that have to overcome a river, the ratio is lower. In fact, if the design choice is that to make a single span cross over a wide river, it is very difficult

that the architectural shape of the arch bridge is characterized by a high ratio, because in this case the designer will be influenced by the desire to reach more linearity as possible with the water line. In the cases examined, in fact, I did not find any examples from 1900 onwards with a span of more than 100m which have a rise-span ratio higher than 1/3: the trend is to have a low ratio.

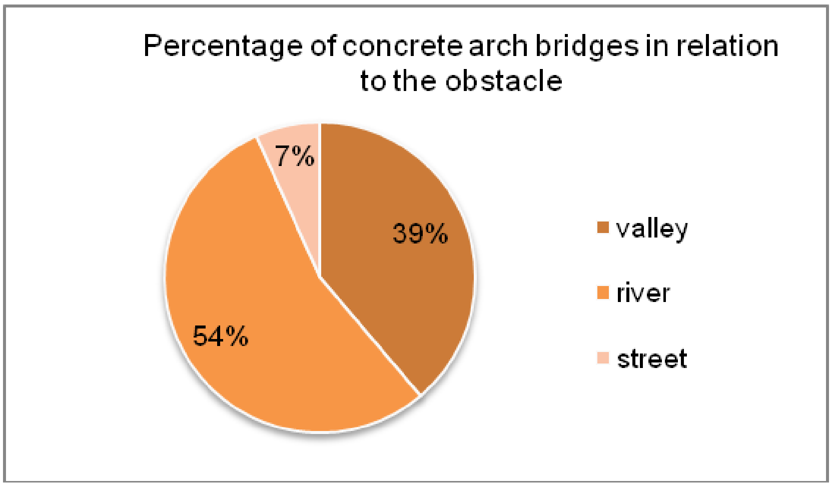
I tried to split the environment with presence of arch bridges in four distinct zones: mountains, hills, flat area and city. These areas are distributed in the chart 3.22.



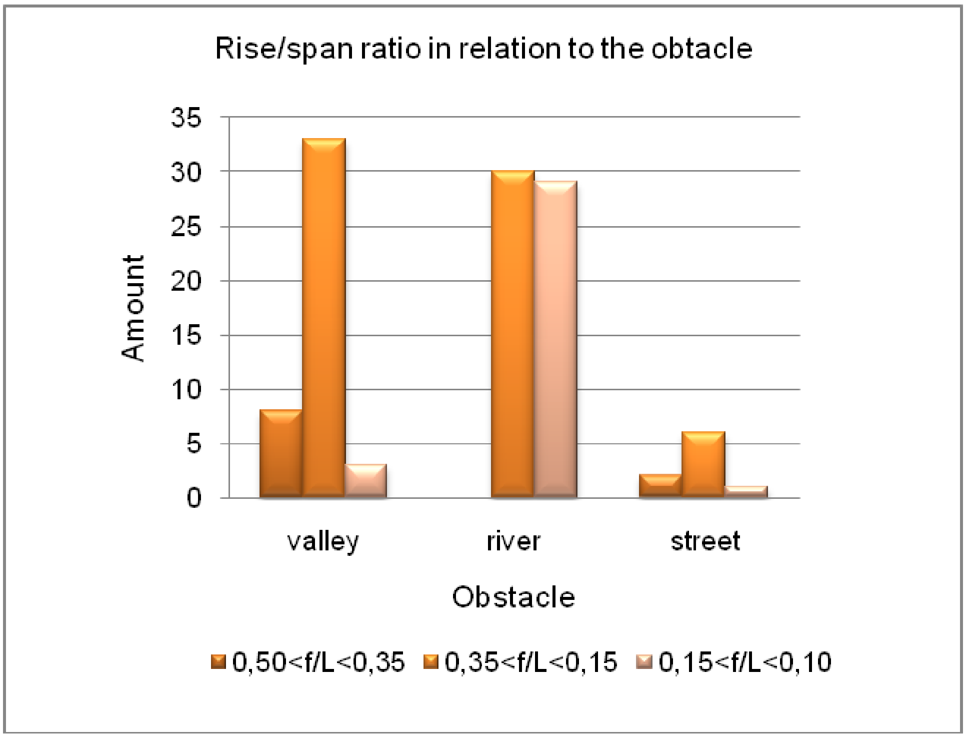
3. 22 Concrete arch bridges in relation to environmental position

The areas with significant orography, mountainous or hilly, are those that require greater use of concrete deck arch bridges and the relation between bridge span and the height from the abutments of the arch generally corresponds to a ratio between 0,35 and 0,15. The obstacle determines some architectural characteristics. Considering three different types of obstacles (valley, river, road), with the graph 3.23 it could be noticed where concrete arch bridges are used more: 54% overcome valleys, 39% rivers and the rest urban obstacles.

Summarizing and underling what has been said before, the different ratio used in the two places (graph 3.24) can be clearly seen. In particular within the environment of a river, the choice of creating a single arch bridge involves the pursuit of the formal linearity with the water line. The tendency then is to design arch bridges with a low profile, because the alternative project with high values of f/L implies a consequent heightening of the deck respect to the ground below and a major difficulty in the entrance area.



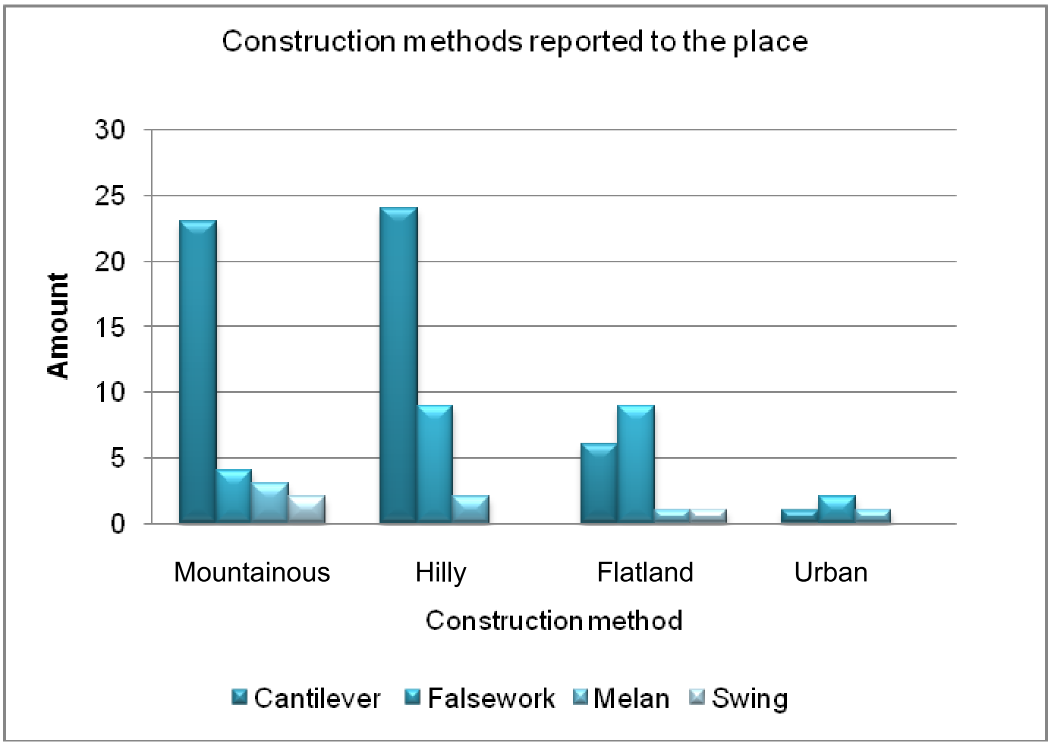
3. 23 Percentage of concrete arch bridges in relation to the obstacle overcomed



3. 24 Rise/span ratio in relation to the obstacle to overcome

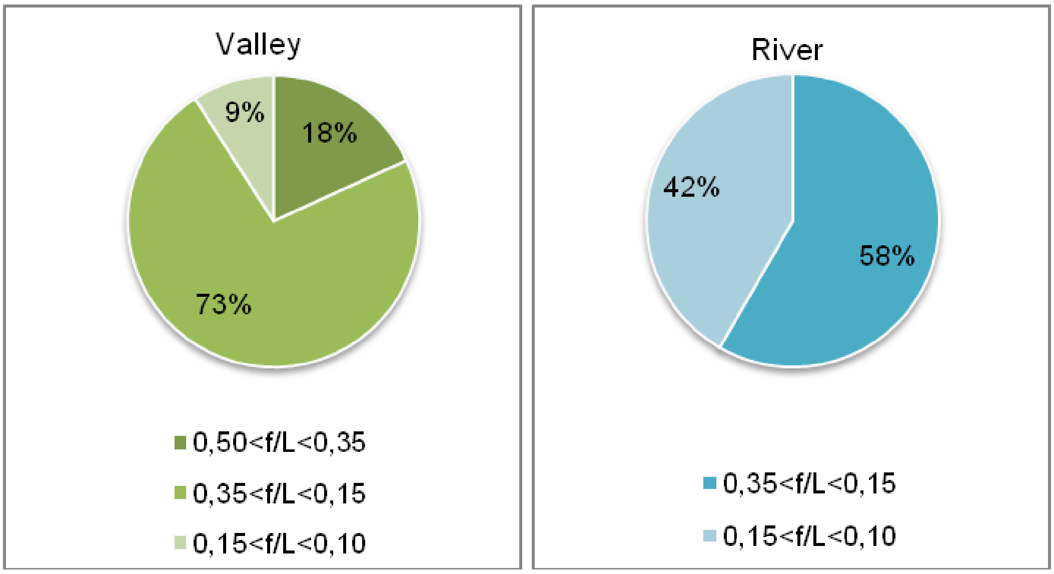
What about the construction methods? How are they related to the place, to the building site? The construction method used the most, which has been mentioned before, is the cantilever one, which is used both in difficult geographic places, like in a mountainous area with all its difficulties as to find enough space for the yard site, and in places where it is possible to use others methods, like on the hills and in flat places. In flat sites, however, there is the possibility to work directly under the arch rib placing the supports used to hold up the structure during the construction on ground or in water (graph 3.25).

What about the span? The percentage of arch bridges with longer span is reached in places where apparently the construction or the positioning of the yard site seems to be more difficult. This point confirms the importance in the choice of the construction method, but overall the real need of the bridge in that determined place. Furthermore, on places that permit an easier construction like flat land, the trend is to use more spans as to break up the whole length of the structure.



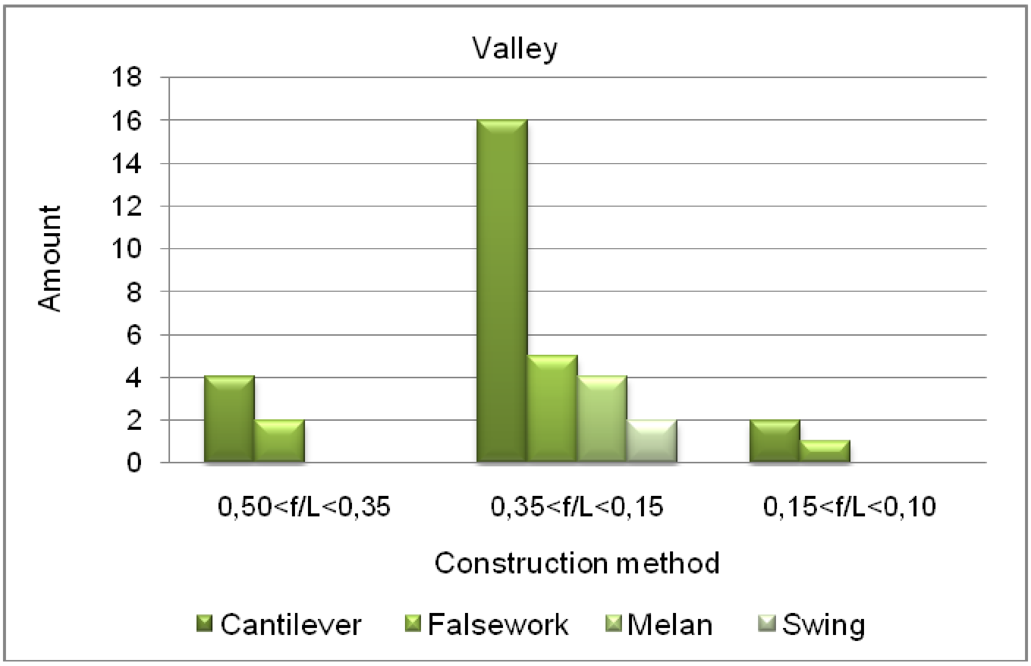
3. 25 Construction methods reported to the place

Different environments influence the architectural shape of the arch bridge: precisely the different places and obstacles define not only the rise span ratio but also the construction method used in each site. The graphs 3.26 shows what happens respectively in various situations, which kind of project, shape and construction method are mostly used.

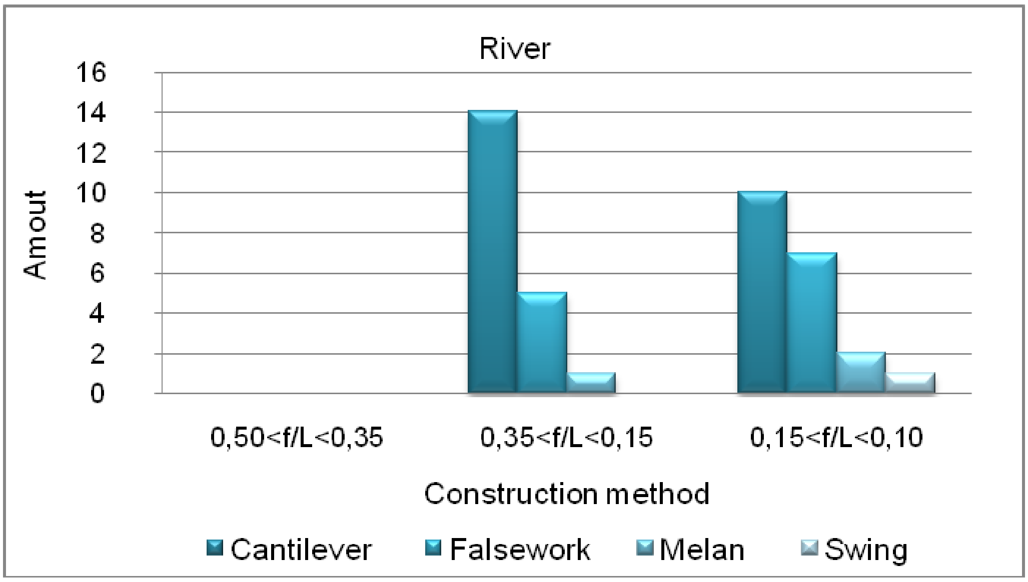


3. 26 Percentage of concrete arch bridges with different rise/span ratio in relation to the environment: valley and river

From the analysis, graphs 3.27 and 3.28, of the concrete bridges built since 1900 with a span longer than 100 m, it follows that there are no examples of arch bridges that overcome rivers and that have a rise/span ratio of 0,50<f/L<0,35.

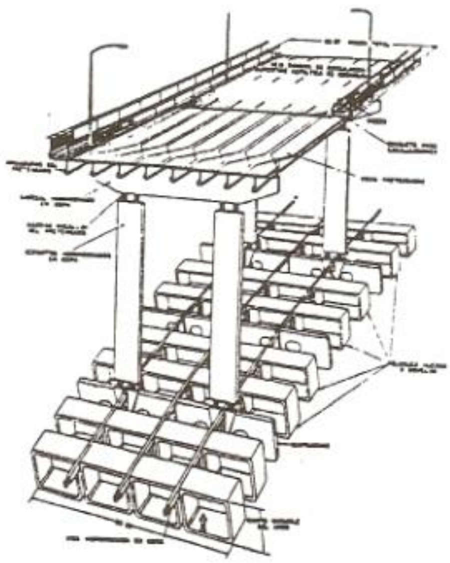


3. 27 Amount of concrete arch bridges with different rise/span ratio in relation to the environment: valley



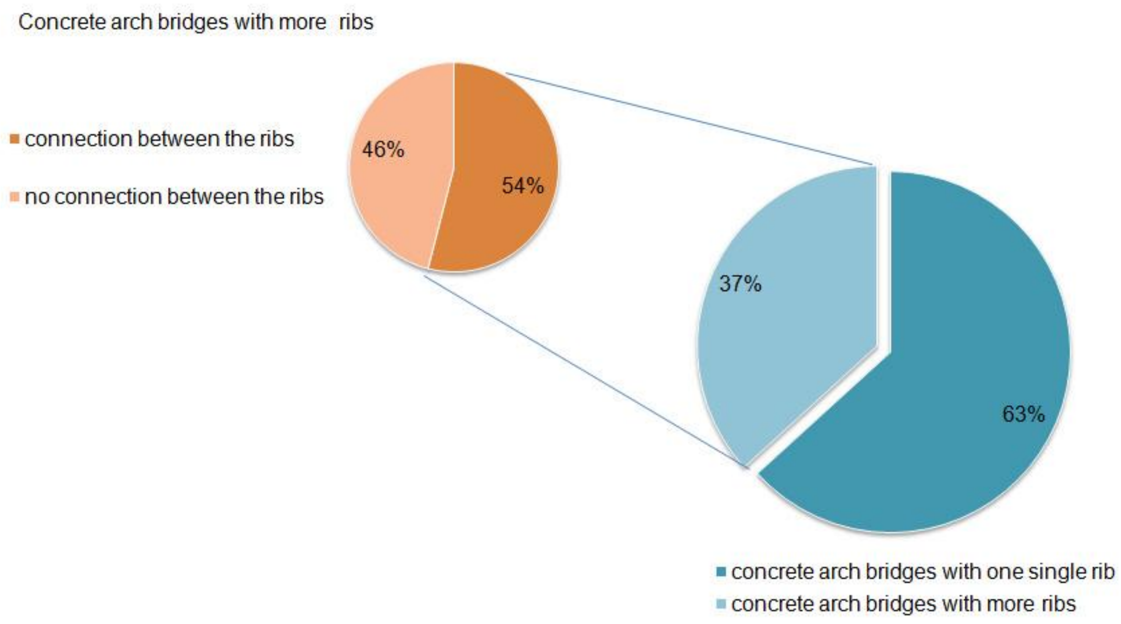
3. 28 Amount of concrete arch bridges with different rise/span ratio in relation to the environment: river

The arch ribs are obviously not the only constituent parts of the bridge, even though they are certainly the most important elements which define the architectural form. The other part consists of columns, hangers, deck, abutments (Fig. 3.29). In the case of deck arch bridges, superstructure is characterized by its section, by ribs numbers, by numbers of the spans, by connections, columns, and deck shape. Many of these elements are characterized and determined by the structural analysis of the bridge, its static and constructive demands.



3. 29 Deck arch bridge superstructure

The connection among ribs, graph 3.30, becomes a design decision that takes in consideration the stability of the structure, its rigidity in the transversal direction, but that can become an architectural element giving uniformity and completeness to the entire bridge. Though the cases show that there is not a specific law that influences the utilization of connection between the ribs.



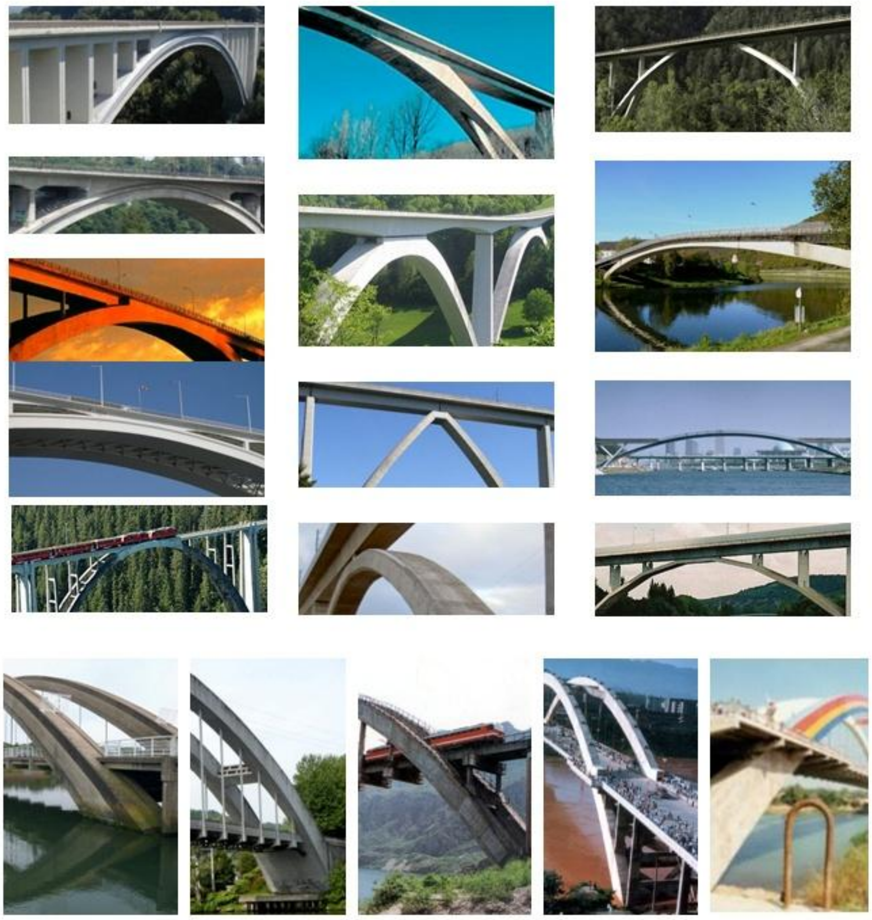
3. 30 Connection between the ribs

In the figures 3.31 we can see some examples where the use of connections can be seen.

3. 31 Examples of different connection typologies between the ribs

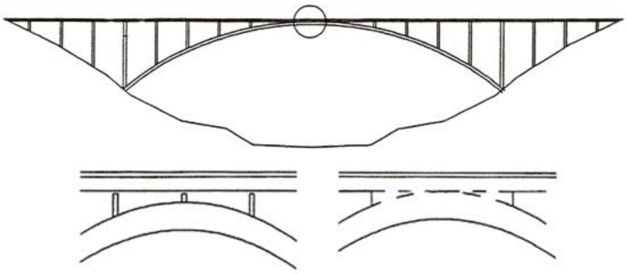
From the analysis carried out on all the concrete arch bridges we see that there are at least six types of columns used, examples of bridges without columns or with hangers, and finally the case of a spandrel arch. Some consideration concerning the use of columns must refer to all historical examples where the connection

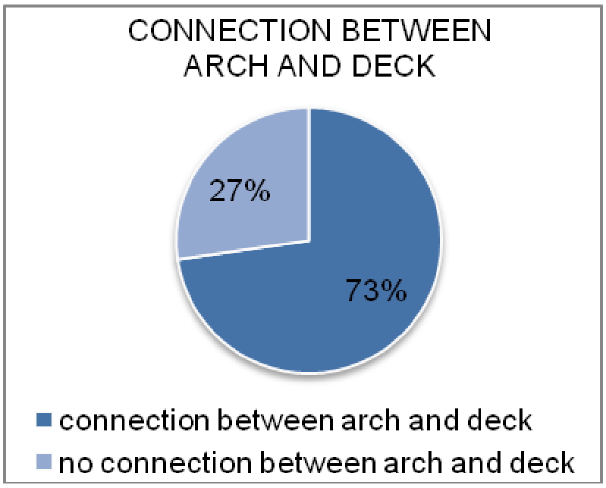
between arch and deck was performed by a full structure. The formal development of the arch bridge and the analysis of its individual components allow to clarify and emphasize the progressive architectural transformation, thanks to the constant research of material optimization. Over the years, the figure of the arch has become increasingly thin and light, and from a spandrel arch it has moved on to an open-spandrel through the use of columns that provide the support of the deck. The new achieved lightness reduces the total weight of the structure. The relationship between arch and deck becomes an important architectural element underlined by the direct connection among the elements and the shape of the columns.
The examples (figure 3.32) show how the architecture of the arch bridge can change according to the choice, during the design phase, of the different elements which can form the final project.



3. 32 Examples of different connection typologies between the arch and deck

Another element that characterizes the architectural shape of the arch bridge is the relation that there is between the columns and deck (Figg. 3.33 and 3.34). Connections can be of various types: if the deck is a continuous structure, the columns represent a support, with a “space” between the two elements. In the cases where the deck is made up of single beams, the columns take an active part in the connection with the superstructure. In both cases the columns are always embedded at the arch.





3. 33 Connection between columns and deck

3. 34 Examples of different connections between columns and deck

3.3 Italian arch bridges

The form of the arch is aesthetically pleasant and easily integrated with the surrounding environment, and its shape represents the maximum formal expressiveness of the architecture. After a long period of absence, the arch structure, which has characterized the entire history of Italian architecture ever since the Roman achievements, has regained an important role in design, especially in bridge building and in the construction of large covered spaces. The return of the arch shape in the 20th century projects was due to a formal as well as structural desire, inasmuch as the arch architecture corresponds to its structure. The arch structure resists because of its form, but it is certainly with the progress of construction techniques and with the use of new materials that this particular structure was born and became popular. A wise use of precast elements, new high strength materials and proper studies of an efficient and highly repeatable erection stage can make the arch solution competitive again, in terms of both costs and architecture[6].

At this time some of the leading figures of the cultural and technical world began constructing. They were professional who found themselves living at the time of the onset of revolutionary techniques, that opened new and unexpected opportunities in structural engineering. The collaboration between engineering and architecture is represented by their figures and their projects, giving concreteness to what would successively be called “structural architecture"[7].

The following graphs 3.35 and 3.36 show how arch bridges have evolved in Italy. In addition to observing that the higher spans hardly surpass 200 m in length, it can be assumed that some important facts and historical periods have influenced development and there are time intervals during which we have no examples of new construction. The use of different materials is a clear and explicit example of the differences between Italy and the rest of the world. Steel has recently been used in the construction of arch bridges in Italy, but it was used to a large degree in many other places around the world.

The graph 3.36 could be schematized in the timeline 3.37 that represents the historical gaps, that influenced not only the economical and social events but also the construction progress and the developments in infrastructural methods. The two world wars gave an inevitable stop to all these activities, as the construction of bridges were not, obviously, of primary importance, Moreover the economical recovery after the bellicose clashes permitted the reconstruction of everything that got destroyed and the project of new public works, like that of the national motorways, went underway.

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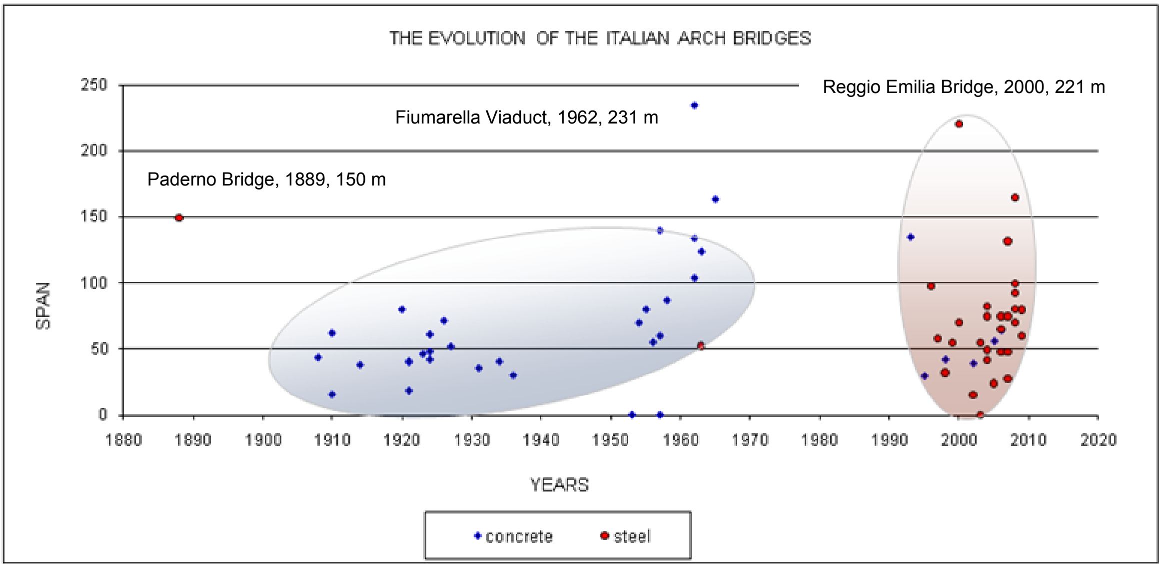
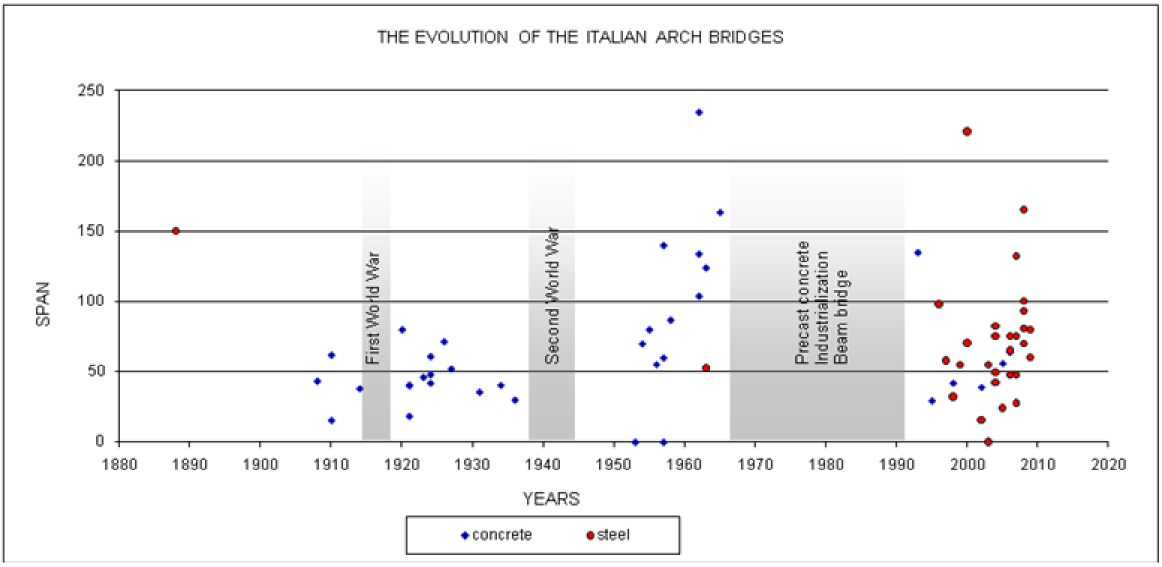
[6] Palaoro S., Siviero E., Briseghella B., Zordan T., 2010, *Concept and construction methods of arch bridges in Italy*, ARCH’10 – 6th International Conference on Arch Bridges, Fuzhou, China

[7] Siviero E., Zampini I., *Italian bridge designers in XX century*, 2nd fib Congress, Naples, Italy June 5 -8, 2006

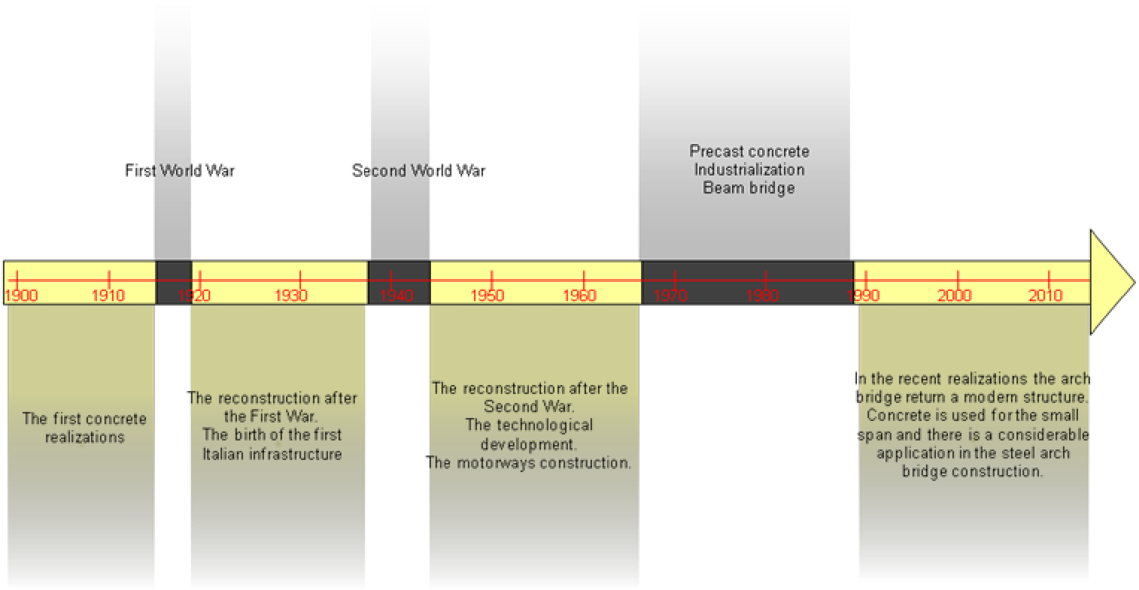


3. 35 Evolution of Italian arch bridges: concrete and steel



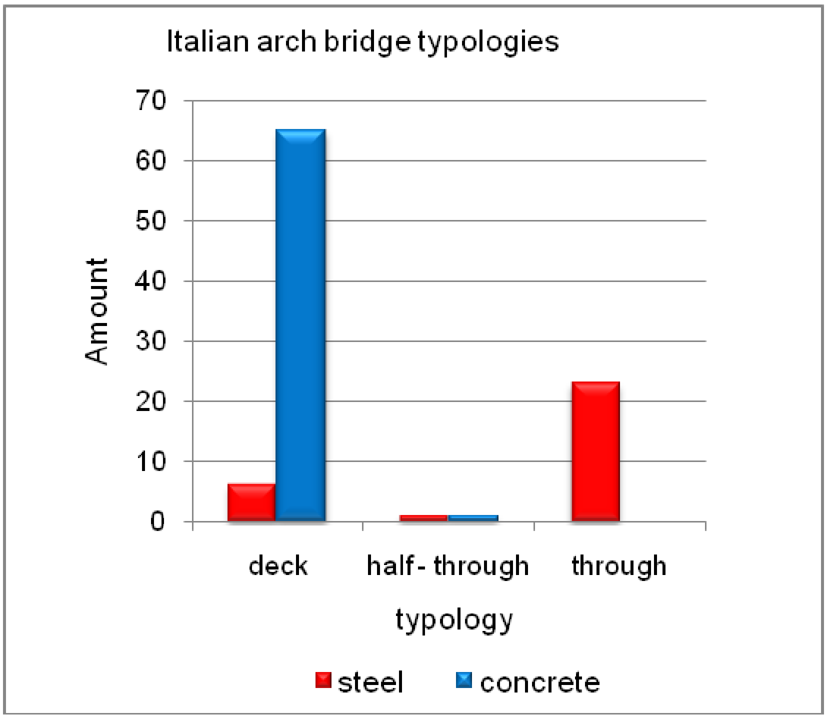
3. 36 Evolution of Italian arch bridges: historical periods

In particular, the construction of arch bridges saw another pause, a long stop lasting almost 30 years, that represented a progress period that involved all the country. The birth of precast concrete permitted the fast construction in the infrastructures with the use a mass-produced precast beams. This new material caused the standardization in the design phase.



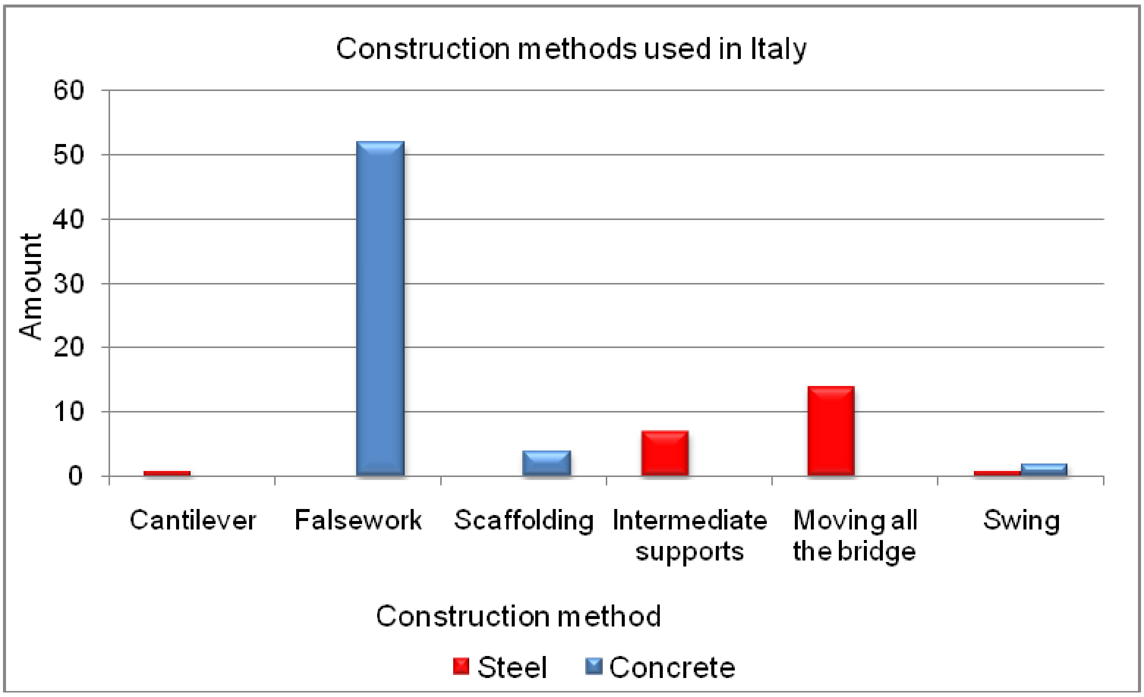
3. 37 Evolution of concrete and steel arch bridges in Italy: timeline

From the collected data about Italian bridges recovered, we see in chart 3.38 that the highest quantity of arch bridges built in concrete are deck arch bridges and that there is a greater use of bowstring type in steel.



3. 38 Italian arch bridge typologies in concrete and steel

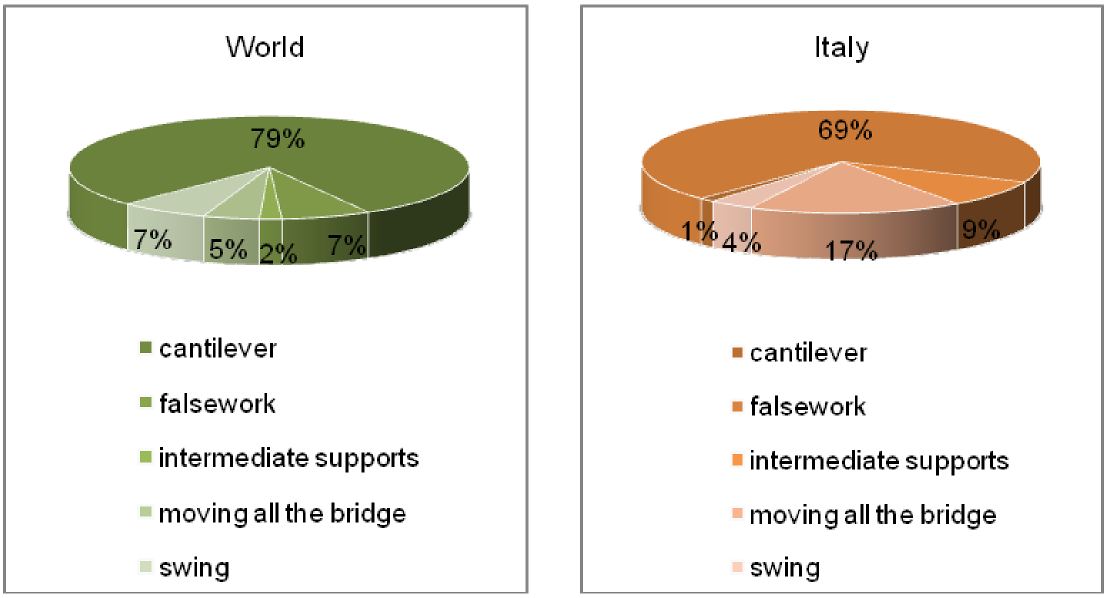
The graph 3.39 represents the construction methods most widely used for the realization of Italian arch bridges. As one can note, most of the concrete bridges built since 1900 have been realized with the use of a centering. Many new Italian steel bridges have been built using intermediate supports or with the launching of the entire pre-built bridge on a river bank and then moving the entire structure. Only a few numbers of works have been built with the cantilever and the swing construction methods.



3. 39 Construction methods used in Italy

Contrary to what happens in the rest of the world where the most widely used method is the cantilever by using temporary towers and cables, in Italy almost all arch bridges were built using falsework (graphs 3.40).

Considering the timeline chart, the historical evolution of the main Italian arch bridges stands out, considering this for each period of economical, political and social situations in the Country and the evolution of materials and constructive technologies.



3. 40 Construction methods used since 1900 for arch bridges (length L > 100 m): world and Italy

3.4 First Italian arch bridge realizations in 1900

The history of Italian arch bridges has its roots far back in time. In recent years there was a new application of the arch typology due to the development of new construction methods and details. Today Italy does not have many newly built very long arch bridges, as in other countries, but there are many important new structures with attractive aesthetics and innovative conceptual design and construction methods. Though in 19th century the new experience with materials and new technologies began a rapid evolution in construction: in Italy this period was calls the "economical boom". In those years there was a strict relationship between theoretical and practical engineering and also between design and construction.[8]
At the beginning of the 20th century, compared to the rest of the industrialized world, Italy was behind its competitors, due to the economic and historical events that had stalled Italian development. This condition persisted for a long time, especially in the southern regions. Two world wars, the autarchy of the fascist period and the Industrial Revolution were all events that, with conservative academic attitudes,

[8] Palaoro S., Siviero E., 2008*, Relazione tra forma e struttura nella recente storia dei ponti italiani.* In Atti del 2° Convegno Nazionale Storia dell'Ingegneria, Napoli, 7-8-9 aprile 2008, Cuzzolin Press, Napoli – Italy, pp.671-679.
Centro Studi C.N.I., 2006, *L'ingegneria dei ponti del Novecento. Catalogo*, Gangelmi Press, Roma

alienated the country from industrialization that was already occurring in other countries. In spite of the difficulties due to a more unfavorable situation, 20th century Italian engineering succeeded in becoming one of the new, fast evolving technologies acting as a vehicle for international exchange. The ideas of these engineers gave impetus to the renewal of engineering practices. Italy's contribution in technological innovation and its participation in international debates pushed the construction industry towards a more modern approach, narrowing the discrepancy between Italy and its competitors in Europe and in the United States. The great period of development at the start of the century was determined by the evolution of the transport system due to a greater demand for new infrastructures.[9] Around the end of the 19th century and the start of the 20th century, there was a transition from traditional constructive techniques, often based on experience and intuition, towards new methods founded upon the study of the mechanical properties of materials and their static characteristics.

Among the first to accomplish innovative works in structural concept were Arturo Danusso[10] (1880-1968), manager of the technical office of the Giovanni Antonio Porcheddu Company (1860-1937), which was the Italian representative of the Hennebique system and who was responsible for spreading the methods during the period between 1895-1933. Besides Danusso there was also Alessandro Peretti[11] (1862-1919) chief engineer of the technical office of Verona Municipality, and later on of Padua Municipality. Danusso and Peretti immediately recognized the potential qualities of reinforced concrete and promoted this fact. Designers were encouraged to tackle ambitious projects with advancing modernization and tradition coexisted with innovation throughout this time of transition.[12]

An important work that's worthy of note carried out by Danusso is the Calvene Bridge (Fig. 3.41) over the Astico River built in 1907: the bridge has a cellular structure with a span of 34.5 m and 2 m rise. With a pleasant and harmonious aesthetic line, this was one of the most interesting low arch bridges of the time and its conception opened the way for the subsequent creation in 1911 of the Risorgimento Bridge in Rome (which was discussed in Chapter 1 *Design*, see Fig

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[9] Palaoro S., 2007, *Ponti e viadotti nella storia delle autostrade italiane*, Tesi di Laurea, relatore prof. Enzo Siviero; correlatore prof.ssa Tullia Iori, 2007

[10] Iori T., *Il boom dell'ingegneria italiana: il ruolo di Gustavo Colonnetti e Arturo Danusso*, in S. D'Agostino (a cura di), *Storia dell'ingegneria*, Atti del 2° convegno nazionale, Napoli 7-9 aprile 2008, Cuzzolin editore, Napoli 2008, vol. 2, pp. 1501-1510

Favaretti G., 2000, *Arturo Danusso: tra scienza e tecnica*, Tesi di Laurea,relatore prof. Enzo Siviero

[11] Bovo S., 1998, *Alessandro Peretti, ingegnere comunale a Padova nel primo Novecento*, Tesi di Laurea, relatore prof. Enzo Siviero.

Zampini I., 2006, *Arturo Danusso, tra scienza e tecnica*, Rivista Le Strade, Ponti e Viadotti - Biografie,n°10 ottobre 2006, pp.120-126

[12] Siviero E., Zampini I., 2003, U*n secolo di storia dei ponti tra tradizione e innovazione*, i protagonisti dell'Ingegneria Strutturale italiana del novecento, Rivista Galileo n. 155 Gennaio-Febbraio 2003

1.52), anticipating the solution of Hennebique, which was later revived by many other designers.
For some time the Risorgimento Bridge, consisting of an arch with a cellular section particularly slim and light directly supporting the deck, had maintained the primacy of the concrete low arch bridge with its 100 m of span and 10 m rise.


3. 41 Calvene Bridge, Astico River, Vicenza, 1907, 34.5 m span, A. Danusso


a

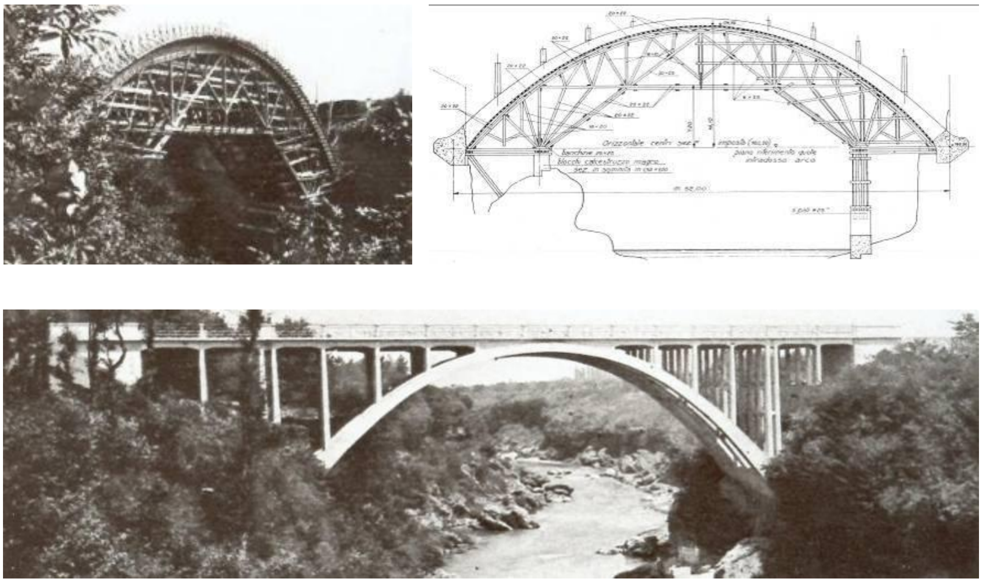
b

c

3. 42 a) Popolo Bridge, Padua, 1908, 43 m span, 4.35 m rise, A. Peretti
b) S. Massimo Bridge, Padua, 1910, 15.5 m span, A. Peretti
c) Ognissanti Bridge, Padua, 1921, 38 m span, A. Peretti

Alessandro Peretti's works in Padua from 1900 to 1919 were significant achievements for the development and the expansion of the city. The opening of new roads established new zoning and aesthetic needs.
His bridges in Padua (Fig. 3.42) proved the passage, which took place within a few years, for the different construction techniques and traditional formal design of bridges using reinforced concrete to define the structure. He used the new technique combining reinforced concrete with bricks in the Popolo Bridge and the S. Massimo Bridge and then for the entire structure of the Ognissanti Bridge. The Popolo Bridge, built in 1908, consists of a reinforced concrete arch which is strong and low, with a span of 43.52 m and 4.35 m rise. It was a daring construction for the time, which permitted the crossing of the river with a single span without intermediate piers. The S. Massimo Bridge built in 1910 is a reinforced concrete arch with a span of 15.5 m with abutments and tympanums in bricks covered with cement plaster, which mimicked stones at the abutments. The Ognissanti Bridge, designed in 1914 and realized in 1921, a mixed arch-beam system, is a low reinforced concrete arch with lighted tympanums and with a span of 38 m; the deck

is based on cross-walls connected at the arch. In the first two bridges, shape and structure are still separated, but in the third the concrete structure expresses the image of the bridge, through the real functions of the structural material.
In the 20th century, new experiences with materials and new technologies triggered rapid evolution in construction: due mainly to the use of concrete, because in Italy the technical development of steel was blocked until the end of the 19th century. After the First World War, there was an intensive phase of study done on reinforced concrete and a lot of new structures were built with this new material. In other countries, both in Europe and in America, there was a frequent use of steel and therefore a fast development regarding this material that in Italy, on the contrary, did not find applications.[13] At the start of the century, the great period of bridge development was determined greatly by the evolution of the road transport system, which was extended by the requirement of new infrastructural construction. Almost all achievements during this period were carried out with centering construction method. At this time the prevalent type of almost all bridges present in Italy was the arch. The Brembo Bridge (Fig. 3.43), designed by Luigi Santarella[14] (1886 -1935), is an example. It is a slightly oblique bridge relative to the direction of the river and consists of a central arch made up of five ribs; the curve is almost parabolic and measures 52 m in span and 14 m in rise.[15]



3. 43 Brembo Bridge, Bergamo, 1927, 52 m span, L. Santarella

[13] Siviero E., Zampini I., 2008, *Ponti italiani del Novecento: un secolo di storia tra tradizione e innovazione*, In *De Pontibus. Un manuale per la costruzione dei ponti*, Il Sole 24 ORE S.p.A. Press, Lavis (TN), pp. 255-341
[14] Santarella L., 1930, *L'architettura nei ponti italiani in cemento armato*, Rivista Industria Italiana del Cemento, luglio 1930, pp. 14-20
[15] Santarella L., Miozzi E., 1924, *Ponti italiani in cemento armato*, Hoepli Press, Milano

Reinforced concrete finally emerged in Italy during the period between the two world wars and was favored by some people in the scientific and technological fields which in turn helped contribute even further to the technical and scientific innovations. One example is the bridge over the Biedano river in Viterbo, built in 1937 (Fig. 3.44). Designed by Giulio Krall (1901-1971), it is a deck arch with a span of 91 m and a rise/span ratio of 1/5. This bridge is light and daring and well integrated into the landscape.

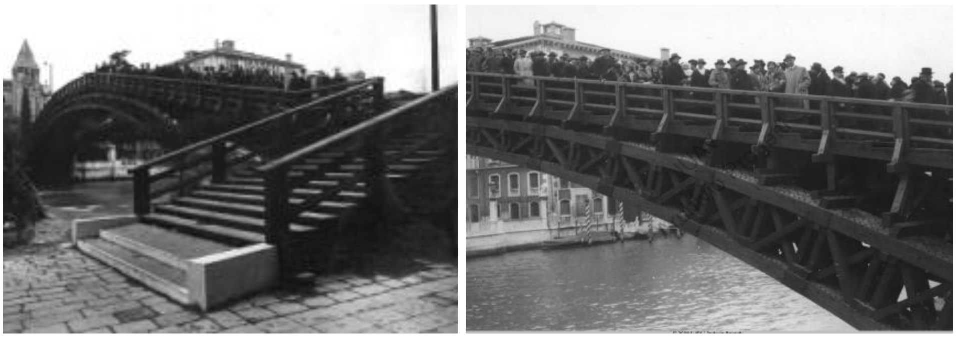
3. 44 Biedano Bridge, Viterbo, 1937, 91 m span, G. Krall

The reconstruction phase allowed for the carrying out of many important works: Eugenio Miozzi[16] (1889 -1979) was one of the eminent engineers of the time that used reinforced concrete to rebuild the bridges destroyed during the war. He was an Engineer of the Civil Genius of Udine and Belluno from 1918 to 1926. From 1927 he was Chief Engineer of the Civil Genius of Bolzano. From 1930 Miozzi was Chief Engineer of Venice Municipality were he designed the most important infrastructures that characterize the city even to this day (Fig. 3.45): the Libertà Bridge, that connects the city-island with the mainland; the Scalzi Bridge, that is in front of the railway station; and the Accademia Bridge, built as a temporary timber footbridge which can be admired and used even today.[17] To make the architectural line aesthetically pleasant, designers did not hide but rather emphasized its structure, combining elegance with stability and resistance. These were concepts clear to Miozzi, Danusso and Krall, whose bridges testified this change.[18]

Towards the 30's, Miozzi discovered a new type of structure which was very audacious for its time. The achievements of this period were works that represented a change in technology of reinforced concrete. His patent and his perfection of a pretension system made him one of the greatest planners of his time.

[16] Siviero E., Zampini I., 2008, *Eugenio Miozzi, un ingegnere tra tradizione e modernità*, 2° Convegno Nazionale *Storia dell'Ingegneria,* Napoli 7-8-9 aprile 2008, pp. 991-1000
Zampini I., 2006, *Eugenio Miozzi, ingegnere tra tradizione e modernità*, Rivista Le Strade, Ponti e Viadotti - Biografie, n°5 maggio 2006, pp.120-124
Culos L., 1998, *Eugenio Miozzi e i suoi ponti*, Tesi di Laurea, relatore prof. Enzo Siviero
[17] Santarella L., Miozzi E., 1924, *Ponti italiani in cemento armato*, Hoepli Press, Milano
[18] E. Siviero, I. Zampini, 2005, *Italian bridge designers in XX° century*, Fib Symposium "Keep Concrete Attractive" 23-25 May 2005, Budapest, Hungary

a



b

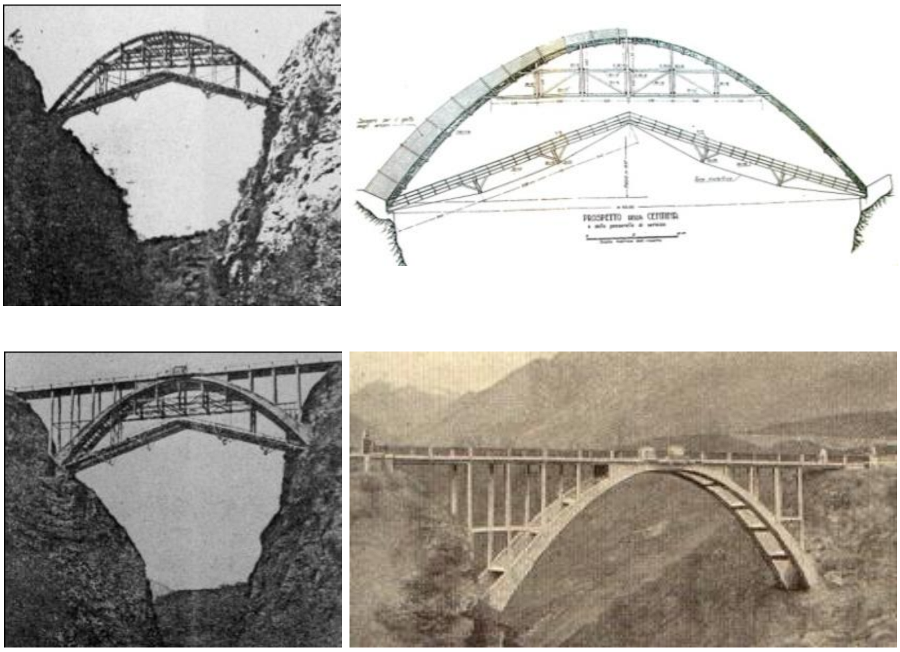
c

3. 45 a) Libertà Bridge, Venice, 1931-33, total length 4 km, E. Miozzi
b) Accademia Bridge, Venice, 1932, 48 m span, E. Miozzi
c) Scalzi Bridge, Venice, 1932-34, 40 m span, E. Miozzi

For the Vittoria Bridge in Belluno (Fig. 3.46) built in 1926, Miozzi revisited the typology of the Peretti's Popolo Bridge: an arch-beam system with a span of 71.6 m and 9.27m rise with a series of 22 piers used to support the road deck.
Miozzi tried to check the media fiber during the design phase, creating an analytical procedure for the rotation of the arch segments allowing for an axial line lower at the crown while higher at the abutments, to avoid excessive deviation between the geometrical line and the pressure curve in order to reduce the maximum stress. Miozzi also applied this system for the Scalzi Bridge in Venice with the pretension of the metal core contained within the Istria stone exterior.

3. 46 Vittoria Bridge, Belluno, 1926, 72 m span, E. Miozzi

More or less during the same years, the Vittoria Bridge over the Pioverna River in Cremeno (Fig. 3.47) erected in 1922-23 by Arturo Danusso, is an arch bridge linked to the deck by very light and slim columns, underling the development of the reinforced concrete technique. The two fixed ribs have a span of 53.5 m and a rise of 19.73 m and converge to make them even more stable, and connected to each other with horizontal elements.



3. 47 Vittoria Bridge, Cremeno, 1922, 53.5 m span, A Danusso

Giulio Krall (1901-1971) was a great structural planner. He achieved many merits in conceptual development due to his innovative contributions, synthesis and scientific rigor. Manager of the technical office at Ferrobeton from 1935 to 1960, he created audacious structures by adopting innovative construction methods, bringing

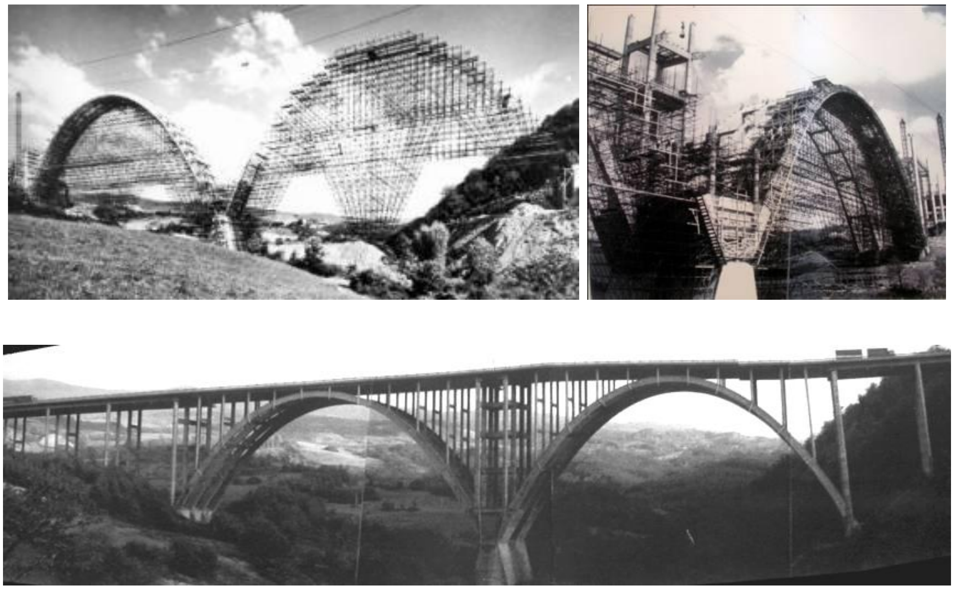
important contributions to the evolution of these systems. His contribution is greatly recognized in the conceptual development of physics, mathematics, mechanics and engineering and for the development of solutions in engineering characterized by innovative ideas, synthesis and scientific thoroughness. He proved to be the most prominent example in engineering of the century in the direct correlation between mathematical sciences, planning and experiences on the field.
One of the most innovative concrete arch bridge of the period was the Africa Bridge over the Tevere River in Rome, built in 1930. With this structure, Krall wanted to represent the arch-beam features of the Risorgimento Bridge of Hennebique. The bridge is a hyperstatic cellular arch-beam with a span of 96 m and 10.8 m rise. Later on, after the war, Krall built yet another bridge with this typology, the Mezzo Bridge over the Arno River in Pisa in 1948-50 (Fig. 3.48). The engineer Carlo Cestelli Guidi (1906-1995) also participated in this competition. The winning project by Krall was a single span arch bridge 72 m long. This solution was very daring for the time having a static behavior intermediate between an arch and a beam, fixed at the both ends.

3. 48 Mezzo Bridge, Arno River, Pisa, 1948-50, 72 m span, G. Krall

3.5 Italian arch bridges built after the Second World War

After the Second World War, the Italian designers dedicated themselves to the post-war reconstruction, which involved all sectors of the economy and industry but especially the severely affected road and railway infrastructures. During this historical period the main problem was to establish a planning system, that would open at the door to the country’s progress towards a modern economic and social composition as well as fixing a development program of infrastructures that would allow a radical renewal.
The intense building activity due to the reconstruction of roads, infrastructures and industrial fittings, facilitated the evolution of reinforced concrete technology, that began before the war. The use of the pretension system spread quickly in

prefabricated construction: its success in the world of construction was due to an increase in economic production and greater speed[19].



3. 49 Merizzano Viaduct, Sun Motorway, 1960, 87 m span, G. Krall,

In Italy the reconstruction of the country after the Second World War was an opportunity to try and bring Northern Italy and Southern to more or less the same level of development, connecting them with an infrastructural system: the construction of the motorway led to the building of many new bridges carried out with new materials and techniques, allowing to reach ever longer spans and thinner structural sections[20]. The Autostrada del Sole (or Sun Motorway) can be regarded as a true site of arch bridges[21]. Consisting of sixty-seven viaducts, each one unique and designed by twenty-seven different designers which were built between Bologna and Florence in stretch of less than 90 km. An important example is the Merizzano Viaduct, designed by Giulio Krall, with two twin arches spanning 87 m each (Fig. 3.49).

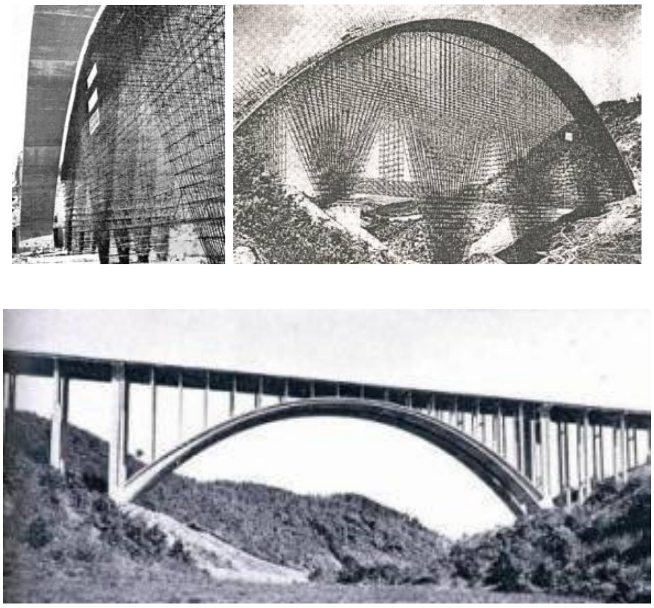
[19] Vanoni D., 1962, *Applicazione del Cemento Armato Precompresso sull'Autostrada del Sole con particolare riferimento al tratto Milano-Firenze*, Rivista Industria Italiana del Cemento, maggio 1962, pp.279-300

[20] Iori T., 2006, *L'autostrada del Sole*, in Storia dell'Ingegneria, Atti del Convegno Nazionale; Napoli, 8-9 marzo 2006, a.c.d. Alfredo Buccaro, Giulio Fabricatore, Lia Maria Papa, Tomo II

[21] Palaoro S., 2007, *Ponti e viadotti nella storia delle autostrade italiane*, Tesi di Laurea, relatore prof. Enzo Siviero; correlatore prof.ssa Tullia Iori, 2007

Vanoni D., 1967, *I grandi ponti sull'Autostrada del Sole*, Estratto da Costruzioni in cemento armato – Studi e Rendiconti, pp.165-207

The viaduct over the Aglio River (Fig. 3.50), with 164 m span and 44 m rise, designed by Guido Oberti[22] (1907-2003), is a thin arched structure which because to its slenderness managed to reached levels of boldness for the time. The bridge was built with the use of huge tubular ribs made by Dalmine. The adopted construction solution was a particular centering structure, that once the first bridge was made it was moved for the cast of the second arch, without having to be disassembled and reassembled saving considerably in time and labor. "*The Aglio Viaduct, that the engineer is honored to have designed, is a significant confirmation of the capacity of Italian designers and of the large static, aesthetic and economic possibilities offered by reinforced concrete*", Oberti (1960).[23]



3. 50 Aglio Viaduct, Sun Motorway, 1958-60, 164 m span, G. Oberti

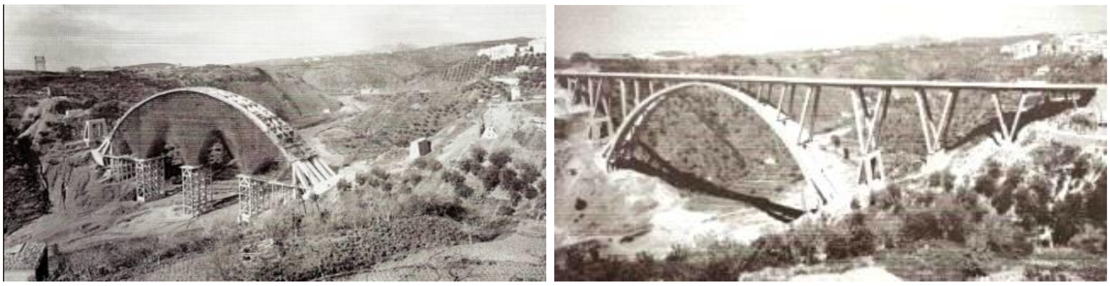
In Italy, the economic recovery brought about a climate of technological optimism that is clearly evident in the work of the major designers: Pier Luigi Nervi (1891-1979), Giulio Krall (1901-1971), Riccardo Morandi (1902-1989), Adriano Galli (1904-1956), Carlo Cestelli Guidi (1906-1995), Silvano Zorzi (1921-1994), Sergio Musmeci (1926-1981) were among the most important designers of bridges and viaducts. Some of them contributed to the formulation and the spread of prestressed concrete in the early postwar years.

The discovery of the prestressed concrete and the consequent prefabrication of structural elements permitted building to be less expensive and much faster. The motorway construction endorsed the erecting of many new bridges, built with these

[22] Zerio C., 2000, *Guido Oberti e l'indagine sperimentale*, Tesi di Laurea, relatore prof. Enzo Siviero

[23] Oberti O., 1961, *Autostrada del Sole, Viadotto sul Torrente Aglio*, Rivista Industria Italiana del Cemento, gennaio 1961, pp.15-24

new materials and techniques, allowing to reach ever longer spans and thinner structural sections.
One protagonist of these new structures and of the use of prestressed concrete was the engineer Riccardo Morandi[24] (1902-1989). When Morandi began to design in 1935 he took as his reference point, in the field of reinforced concrete construction, Eugene Freyssinet and Robert Maillart. It was a particular period in which the experimentation was valuable to assert the various new technologies. He was not only involved in the design phases, but also in the construction process on site. The first bridges designed by Morandi between 1945 and 1955 were all arch bridges. He often used the prestressed concrete technique, and he always took into account the aesthetics.
One of his works in Italy is the Fiumarella Viaduct[25] (Fig. 3.51), built in Catanzaro for the motorway. It has a main span of 231 m and 66 m rise. Built in 1962 it is still the longest Italian concrete arch bridge. Its total length is of 500m with two concrete ribs and it was built with the centering construction method.[26]

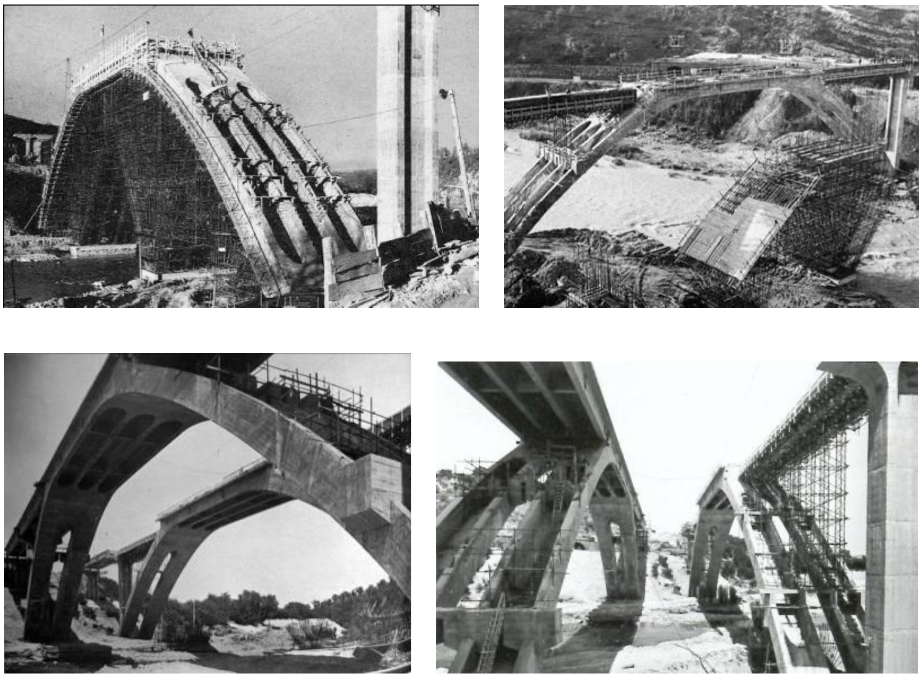


3. 51 Fiumarella Viaduct, Catanzaro, 1962, 231 m span, R. Morandi

Silvano Zorzi (1921-1994)[27] had strong technical and scientific capacities that permitted him to be significant and one of the better designers of bridges and viaducts in Italy. In his projects he searched for the most rational constructive methods thanks to the improvements in technology. For the motorway he built two arch bridges over the Arno river: the Incisa and the Levane Bridges. They are both arched-portal casting *in situ*. The Levane Bridge has a central arch of 144 m span, while the Incisa has two twin bridges offset by 15 m with a slim structure that is accentuated by the bifurcation of the piers. Zorzi's bridges all have one essential

[24] Mason C., Ravagnan B., 1991, *Riccardo Morandi e i suoi ponti*, Tesi di Laurea, relatore prof. Enzo Siviero
Masini L.V., 1974, *Riccardo Morandi*, De Luca Editore, Roma
[25] Morandi R., 1961, *L'arco del viadotto della Fiumarella presso Catanzaro*, Rivista Industria Italiana del Cemento, luglio 1961, pp.341-352
[26] Boaga G., Boni B., 1962. *Riccardo Morandi*, Comunità Press, Milano
[27] Casucci S., Lincetto S., 1995, *Silvano Zorzi e i suoi ponti*, Biblioteca di Galileo, Padova
Lincetto S., 1994, *Silvano Zorzi quarant'anni di progettazione di ponti e viadotti*, Tesi di Laurea, relatore prof. Enzo Siviero.
Villa A. e Martinelli E., 1995, *Silvano Zorzi, ingegnere 1950-1990*, Electa, Milano

structure and a considerable span: the structural solution adopted by him is an arched-portal without placing piers into the river bed. The hyperstatic solution, respecting the classical arch structure, implies a lower weight and a minor pressure on the abutments allowing to support small failures on the foundations, without compromising the entire stability of the bridge. The Incisa bridge over the Arno River (Fig. 3.52), designed by Silvano Zorzi and Giorgio Macchi[28] (1930) has a particular yet interesting technical solution, where the ordinary reinforced concrete (provided in the project) is replaced by an arched-portal in prestressed concrete. This solution has influenced the architectural design of other bridges in the area also. The piers have a double T shape, which emphasizes how it is possible to express a bridge with a pleasing aesthetic without having to hide the structural needs with unnecessary artifices.

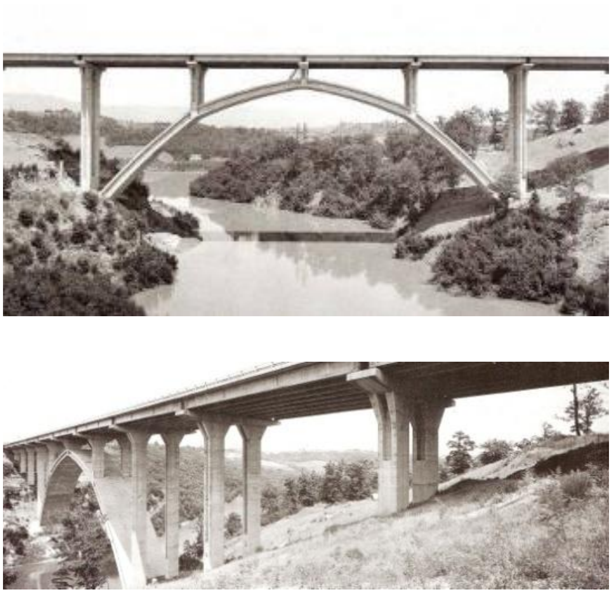


3. 52 Incisa Bridge, Sun Motorway, 1962, 104 m span, S. Zorzi

In the twin bridges at Incisa (Florence), spacing 15 m, Zorzi used a fixed prestressed concrete arched-portal and supported beams, prestressed also on the lateral side.

At Levane (Fig. 3.53), to overpass the Arno River, a reinforced concrete arched-portal structure was adopted. The piers support the deck made by prestressed concrete. The arch has a polygonal shape, and the sides of the polygon are slightly curved to compensate for the effects of its own weight.

[28] Scappini D., Ruffo E., 1998, *Giorgio Macchi: scienziato e costruttore*, Tesi di Laurea, relatore prof. Enzo Siviero



3. 53 Levane Viaduct, Sun Motorway, 1962-63, 134 m span, S. Zorzi

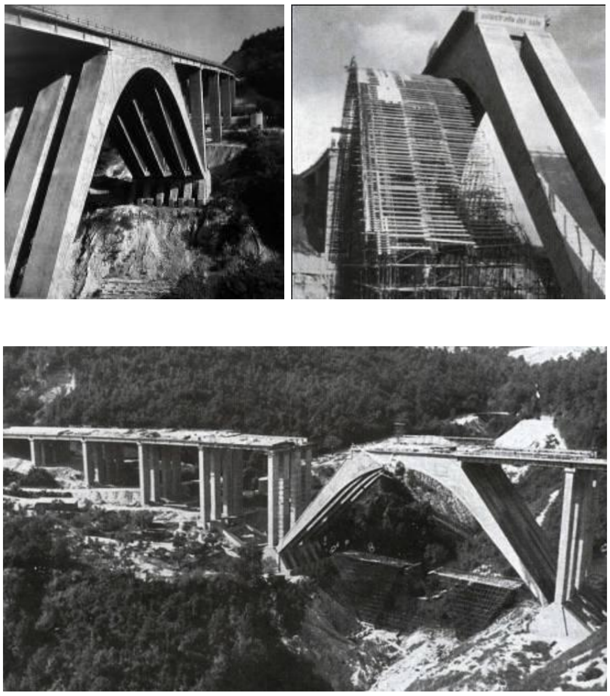
The work of Carlo Cestelli Guidi[29] (1906-1995) in the field of research has been focused on the development of technical skills, on the investigation of innovative themes and on experimental inquiry about geotechnics, foundations, prestressed concrete, structural safety fields. Cestelli Guidi used his projects to verify and study the structural behaviour, combining theory, experimentation and design in a constant process of mediation among the various possible interpretations, maintaining balance however between tradition and innovation, between traditional technologies and new techniques, imposed by new construction methods and by prefabrication.

He was among the first to guess the potential applications of the prestressed structures, and from his earlier projects, in which he frequently used the Gerber beam and the arch bridge structure, he accomplished the continuous beams with the cantilever construction method.

The St. Giuliano Viaduct (Fig. 3.54) is an arched-portal structure with a total length of 376 m. The solution adopted, considering the significant slope of the valley, was to use two prestressed concrete twin arches for the two independent roads. The viaduct is composed of a deck, positioned on supports with an interval of 34 m. The central piers are inclined to firmly set up a portal with the deck that spans 100 m. The cast of the portals was executed segment by segment through means of

[29] Baessato D., 2001, *Carlo Cestelli Guidi e i suoi ponti tra ricerca e progetto*, Tesi di Laurea, relatore prof. Enzo Siviero
Cestelli Guidi C., 1947, *Il conglomerato precompresso, teoria-esperienze-applicazioni,* Edizioni della Bussola, Roma
Cestelli Guidi C., 1957, *Aspetti della progettazione dei ponti ad arco*, Rivista Industria Italiana del Cemento, maggio 1957, pp.115-119

tubular centering, made only for the half width of the deck and then after the construction of the first portal shifted to the subsequent execution of the other half bridge. The inclination of the piers, that form the portal with the deck, is of a 45° angle.



3. 54 S. Giuliano Viaduct, Sun Motorway, 1958-61, 100 m, C. Cestelli Guidi

The Fiumarella Viaduct designed by Riccardo Morandi, with the S. Giuliano Viaduct realized by Carlo Cestelli Guidi, and the bridges over the Arno River at Incisa and Levane by Silvano Zorzi are among the last large concrete arch bridges built in Italy up until the more recent ones were built. In fact, as one can seen in the timeline graph, there is a relatively long period where no arch bridge building took place, which changed again due to the fast construction by means of prestressed concrete beams.

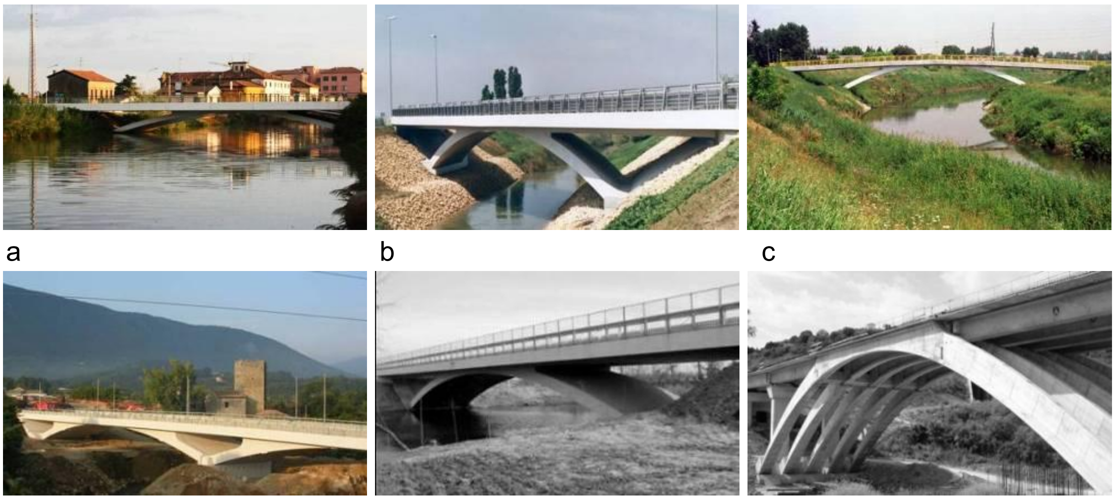
3.6 Contemporary designers: recent concrete realizations

The building of arch bridges has been dramatically reduced in recent decades in favour of other construction types. The reason for this tendency is prevalently economical and technological, due to the fact that during the erection process the arch needs a provisional formwork to be sustained, which consistently increases the building expenses and the need of manual labour. This is particularly true for small

and medium spans, where the beam solution is the simple and economic alternative.
However, considering that small and medium spans represent the vast majority of the bridges dislocated over the Italian territory it is mandatory that good designer finds a structural solution which is both economically feasible and that fits in well with the environment. In order for the arch solution to become competitive again, the requirements during its building process must be reconsidered, reducing the onerous formwork with the help of precast elements and new high strength materials. The problem of constructing an arch derives from the different static schemes between the construction phases and its final use. The search of innovative techniques and the careful study of structural behavior during the erecting stages allowed the arch solution to become competitive once again after several decades of little use, which has been mainly due to economic reasons.
These considerations do not only apply to big spans, that represent particular or unusual cases which therefore have the necessity of innovative constructive processes, but also for less important works, such as small and medium spans. Consequently a careful research of innovative construction techniques and an in-depth study of behaviour through the transitional phases of assembly would permit the arch bridge solution to be competitive once again for the building of small and medium spans. The architectural elegance of the arch, with such different static schemes between the construction and service phases, provides symbiotic harmony with the surrounding environment through its architectural features, emphasizing the poetry of the arch shape in engineering and technological interpretation.
Today Italy cannot boast as many recently built very long arch bridges as in other countries, but there are many new important structures with an attractive appearance and innovative conceptual design and construction methods. The arch bridge over the years has enjoyed a new renaissance, especially through the use of prefabricated elements that have enabled rapid and cheaper construction. The improvement of construction methods, the use of materials with high resistance, that consent the reduction in dimensions of the sections, and the development of prefabrication now make these temporary works less burdensome, with beneficial economic and safety consequences as well as possible reproducibility on a large scale.

The research in aesthetic and typological issues, with an approach based on the principles of the Structural Architecture, is aimed at the design quality, and today these factors are considered as important aspects of the actual design. One of the greatest performers and popularizer of Structural Architecture is Enzo Siviero (1945). The focus on a harmonious integration of the new constructions into the environment has a major interest for the formal aspects with the reuse of the structural shapes of the past, such as the arch. As we have seen, the use of the arch was put aside for long time because of the complex and expensive construction requirements respect to the girder type, though today it is proposed yet again, thanks the increased opportunities offered by new materials and new technologies. For centuries the arch structure has had a primary role in the historical evolution of the bridge (see Chapter 1 *Design*) and that justifies all its interpretations in the contemporary and modern way as well as the greater structural efficiency of the arch and its superior aesthetic value.[30]

For some Italian arch bridge examples in prestressed concrete see Chapter 4 *Construction*: the Battaglia Terme Bridge (Padua, 1994), the St. Urbano Bridge (Padua, 2001), the San Nicolò Bridge (Padua, 1998) and the Sgurgula Bridge (Rome, 2005), all designed by Enzo Siviero, the Piave Vecchia Bridge (San Donà di Piave, Venice, 2002) designed by Flavio Zanchettin, the Mazzocco Bridge (Pescara, 2007) designed by Mario Paolo Petrangeli (Fig. 3.55).



a b c

d e f

3. 55 a) Battaglia Terme Bridge, Padova, Italy, 1994, 29,5 m span, E. Siviero
b) St. Urbano Bridge, Padua, Italy, 2001, 39 m span, E. Siviero
c) Bicycle and Pedestrian Bridge at Ponte San Nicolò, Padua, 1998, E. Siviero
d) Sgurgula Bridge, Rome, 2005, 56 m span, E. Siviero
e) Piave Vecchia Bridge, San Donà di Piave, Venezia, 2002, 45 m span, F. Zanchettin, E. Siviero
f) Mazzocco Bridge, Pescara, Italy, 2007, 70 m span, M. P. Petrangeli

Here we look at the San Donà Bridge[31] (Fig. 3.56), designed originally by Enzo Siviero with a prestressed concrete arch system, and successively revisited by the two engineers, Bruno Briseghella and Tobia Zordan, with a mixed solution in concrete and steel. This bridge is located in a strategic area just outside the city of

[30] Siviero E., Zampini I., Giovanetti E., 2003, B*ridge buildings in Italy, present and future*, Internationales Brückensymposium. Aktuelle Entwicklungen im Brückenbau, Technische Universität Darmstadt, Darmstadt, Germany, 1-2 October 2003

[31] Oliveri S., Siviero E., Zanchettin F., 1999, *Il ponte sul Piave della variante alla statale 14*, Rivista Le Strade n. 5, maggio 1999.

Venice, is a large scale version of the bridge type mentioned before; it has a total length of 500 m, comprising of five segmented arch bays, with spans of axes that vary from 90 to 100 m and with a maximum arch rise of 7.3 m. This example is important to understand how a project could change for different reasons in a lapse of time but without changing its architectural characteristics. In the first phase of the project, in fact, the deck was in precast elements and should have assumed a chain function to prevent the negative effects connected to traction.
According to the first project, to limit the number of supports it was necessary to use large prefabricated elements resulting in an increase in the weight of the bridge. After placing the elements, the deck reinforcement is post-tensioned and the structure assumes the characteristic bowstring configuration, with the arch thrust partially absorbed by the bridge deck.[32]

3. 56 San Donà Bridge, Venice, 2008, 500 m (L = 4x100 m), B. Briseghella, E. Siviero, T. Zordan

The interruption of its construction was due to the introduction of a new regulation, the O.C.P.M. n° 3274, concerning seismic design and seismic classification of the National territory. This fact, since the original project was characterized by a massive box girder concrete deck on pile foundations (thus not conceived for horizontal loads at first), gave rise to the necessity of starting with an updated design aimed at achieving a much lighter composite steel and concrete box girder deck. The new deck was connected to the already built piers by means of non conventional steel-to-concrete connections ensuring hogging moment resistance at

[32] De La Grennelais E., Di Marco R., Siviero E., Zanchettin A., 2006, *The bridge over the River Piave in San Dona' di Piave, Venice,* 2nd fib Congress, Naples, Italy June 5 -8, 2006

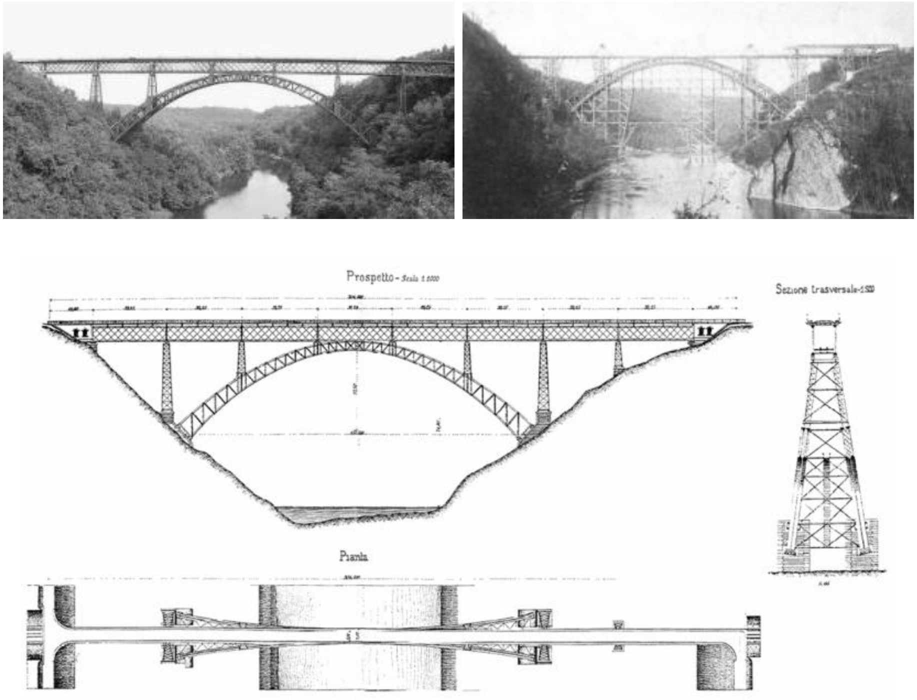
the supports. The new design of the deck is characterized by sophisticated aesthetics and by an optimized distribution of structural material obtained through an iterative design-and-check process that, starting from a FE model of the structure with a full bottom flange of the box girder would lead to a layout with the material taken away from the zones with reduced levels of stress. At the beginning of the process, a model with a continuous and full steel bottom flange was created; in the end, two wide elliptical holes were created in the lower flange of the steel box girder. The ultimate solution obtained sees the use of two materials, concrete and steel joined together, a structure that simultaneously makes a symbolic connection between the bridge and nature, resembling to a certain extent the “immobile flight of a seagull”. [33]

3.7 Italian steel arch bridges

Unlike what happened in Europe and America, where there was a gradual evolution of steel bridges, in Italy there was a block in the development of steel-related technologies that were been used by the end of nineteenth century producing good results in bridges and industrial building.[34]
One of the symbols of industrial development at the time was the Paderno railway bridge[35] (Fig. 3.57), built between 1887 and 1889 according to the project of Jules Röthlisberger. The bridge took the form of the Garabit Viaduct made four years earlier in France by Gustave Eiffel and consists of a single iron span of 150 m that supports, through seven iron piers, the deck that has two levels, one for the railway and the other for the roadway. The structure is completely joined by nails, and does not use welding. Because of its technical features, the bridge is considered a masterpiece of Italian industrial engineering, and one of the most remarkable structures made in 19th century.
As mentioned above, significant development of steel use did not take place in Italy during the 20th century, because it still had a very high production cost and, apart from occasional structures built by engineers who had foreseen and studied the enormous potential of steel, though steel was widely used in bridge building from the end of World War II onwards, and only recently it is used more frequently than concrete. After World War II there was a rapid development of Italian steel

[33] Culatti M., Attolico L., Danieli N., Garghella P., *Ponti ad arco in calcestruzzo*, Rivista Strade e Autostrade 2-2006
[34] Gori R., 1995, *I ponti storici in ferro in Italia: una proposta per un inventario strutturale*, in *Studio e recupero del ponte*, a.c.d. Siviero E. con Casucci S. e Gori R., Architettura e strutture – Collana diretta da E. Siviero, n°8, Ed. Biblioteca di Galileo, 1995, pp.75-119
[35] Gentile C., Saisi A., 2010, *Dynamic monitoring of the Paderno iron arch bridge (1889),* ARCH’10 – 6th International Conference on Arch Bridges, Fuzhou, China, 2010, pp.22-37

constructions[36] and in the last few years engineers have used steel as frequently as concrete.



3. 57 Paderno Bridge, Paderno D'Adda, 1889, 150 m span, J. Röthlisberger

Thanks to the continuous research work carried out on Italian bridges and their historical development by prof. Siviero and by the Bridge School of IUAV University, in recent years seminars for young Italian bridge designers have been organized. The designers have responded to the invitation with pleasure presenting their recent realizations.[37] BridgeItaly Colloquium may be considered to be an important starting point for the study and collection of the last major projects on Italian territory.[38]

A clear example of a modern Italian steel work is the arch bridge in Albenga Fig. 3.58), designed by Luca Romano (1964). The steel structure is an arch that carries a box girder, thus forming a tied arch. The bridge spans 98 m with a rise of 21 m, and the deck is supported by cable. It was necessary to build the bridge in a short

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[36] De Miranda F., 1990. *Aspetti attuali della evoluzione dei ponti a struttura d'acciaio.* Journal Costruzioni metalliche, Number 4, July – August 1990, pp.249-266

[37] S.Palaoro, 2007, *Workshop BridgeItaly. First Edition 2007*, "Le Strade", 7-8 July-August 2007, pp. 124-125
S.Palaoro, 2009, *Bridge Italy, Progettisti a confronto, Seconda Edizione 2008*, "Le Strade", 6 June 2009

[38] Licordari A., 2009, *Ponti e passerelle: giovani progettisti italiani*, Tesi si laurea, relatore prof. Enzo Siviero, corrrelatori Stefania Palaoro, Fabrizia Zorzenon, 2009

time and the erection was optimized by working simultaneously in shop and on site. Repetition of the elements and the bolted assembly permitted rapid fabrication and construction on site with the use of temporary structures.[39]

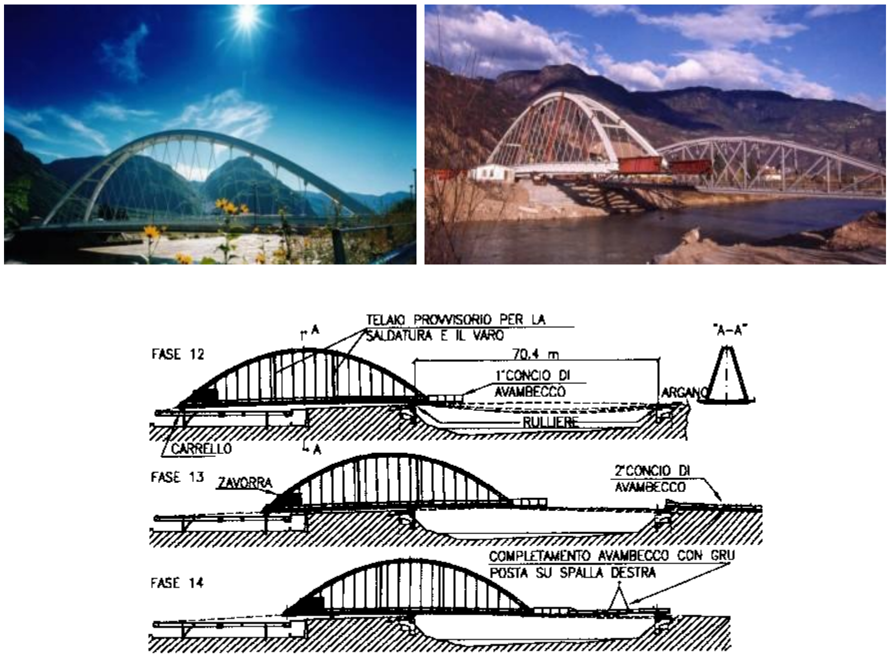
3. 58 Albenga Bridge, Albenga, Savona, 1996, 100 m span, L. Romano

The Arch Bridge in Pozzuoli (Fig. 3.59), by Luca Romano and Pierangelo Pistoletti (1948), is a bowstring structure, 58 m long. The suspension of the deck is obtained through tension rods every 3 m, connected to the inclined arches. Arches are 12,5 m high at the crown. The deck has a thickness of only 80 cm to allow extra height for the underlying archaeological site.

3. 59 Pozzuoli Bridge, Pozzuoli, Napoli, 1997, 58 m span, L. Romano, P. Pistoletti

[39] Romano L., 2001, *Structural Analysis and Construction o fan Arch Bridge in Albenga, Italy*. Journal of the International Association for Bridge and Structural Engineering (IABSE), Volume 11, Number 1, February 2001, pp.47-52

The need for a new bridge in Vadena near Bolzano because there was the presence of an old iron bridge, outdated by the new viability requirements, saw the design by Mario Valdemarin (1938) e Giorgio Romaro[40] (1931) of a Langer structure. The bridge is composed of tubular steel arches with a rectangular section inclined towards the centre and with a span of 70.4 m. The two arches are connected to the top by transverse elements. The bridge is used by vehicles, pedestrians and cyclists. The launch technique did not allow to put temporary piers into the riverbed so it was carried by an additional structure, positioned in front of the bridge (as illustrated, Fig. 3.60).



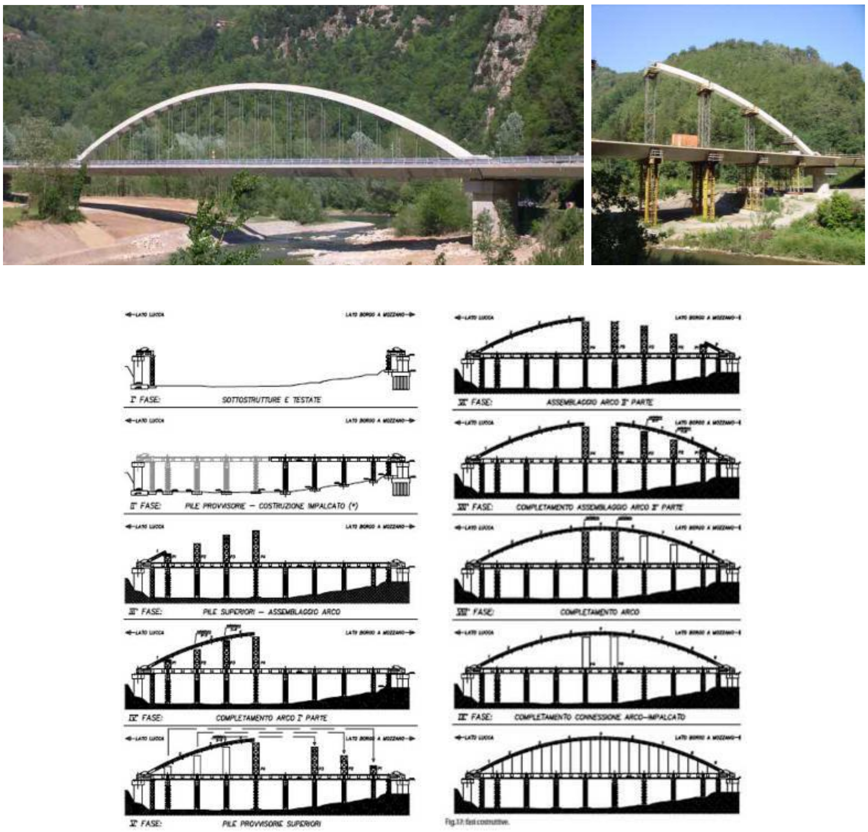
3. 60 Vadena Bridge, Bolzano, 1997, 70,4 m span, M. Valdemarin, G. Romaro

Another good example of a steel bridge is the arch bridge over the Serchio River near Lucca (Fig. 3.61), by Massimo Viviani (1959), built in 2007. The arch is a bowstring structure with a span of 132 m. The deck is in prestressed concrete; in fact for small and medium span bridges this is a good solution to reduce the construction cost. The arch is composed by welded ribs.[41]

[40] Romaro G., 2001, *Quattro vari per due ponti di ferro a sud di Bolzano*, Rivista Galileo, Novembre 2001, pp. 8-11

[41] Viviani M., 2008. *Il nuovo ponte sul Serchio a Lucca*. Journal Costruzioni metalliche, Number 4, July – August, pp.40-48.

Viviani M., 2007, *Il nuovo attraversamento del fiume Serchio*, in Costruire con l'acciaio, ricerca scientifica e tecniche costruttive, a.c.d. Ghersi A., Dario Flaccovio Editore, 2007 pp.695-700



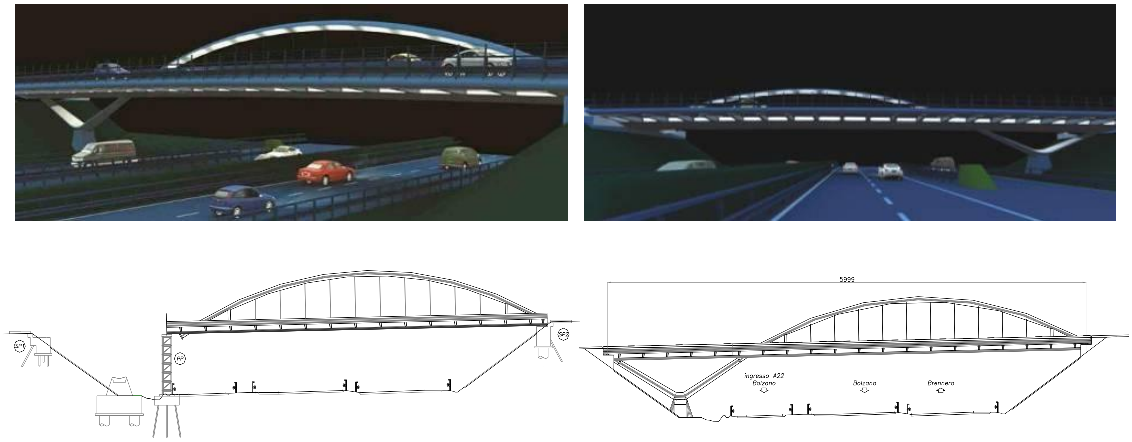
3. 61 Serchio Bridge, Lucca, 2007, 132 m, M. Viviani

The bridge over the Bernardino River near Verbania (Fig. 3.62) designed by Mario De Miranda (1954) is a Nielsen structural type, constructed in 2003. This structure typology gives stiffness at the arch-deck union. The typical “network” arrangement of the cables was used to minimized the structural weight and for aesthetical reasons.[42]

3. 62 San Bernardino Bridge, Verbania, 2003, 85 m span, M. De Miranda

[42] De Miranda F., Gnecchi Ruscone E., 2008, *Il ponte ad arco sul torrente San Bernardino a Verbania*, in journal Strade & Autostrade, n.4

The overpass of the A22 motorway near Egna (Fig. 3.63) designed by Antonio Capsoni (1964) with a span of 45 m, is a bridge marked by a shallow tied arch element going below the deck on one side. The deck was made with a mixed steel-concrete scheme. The adopted solution was considered optimal from both an aesthetic and a static-constructional point of view. The design of the upper structure is completed by the presence of a concrete podium placed where the lower compressed chord rises up toward the western abutment. It was carried out with a longitudinal launching and with the use of a provisional pier.



3. 63 Overpass for the A22 motorway, Egna, Trento, 2004, 45 m, A. Capsoni

3. 64 Piove di Sacco Bridge, Padua, 2008, 70 m span, E. Siviero

The bridge over the River Brenta in Piove di Sacco[43] (Fig. 3.64), designed by Enzo Siviero, is in good relationship with the river. It is characterized by a simple shape constituted by two inox steel arches with a tubular section linked by steel elements at two thirds of the span. The bridge is characterized by an apparent simplicity of form and function. The system of the arches sustains a slender deck. In the central part, the deck is supported at the third parties on the total length by four steel tie rods. The bridge was designed as a “door” for the nearby city.

An important example, for the Italian arch bridge evolution, is represented by the Reggio Emilia Bridge[44] (Fig. 3.65) designed by Santiago Calatrava (1951) was erected in 2000 and it is still the longest Italian steel arch bridge with the span of 221 m (for more illustrations see Chapter 2 *Perception*, Fig. 2.25).

3. 65 Reggio Emilia Bridge, Reggio Emilia, 2000, 221 m span, S. Calatrava

[43] Mestrelli P., Moraglio I., Pistoletti P., Berto C., Ometto G., Lazzari M., 2007, *Ponte ad arco sul fiume Brenta: progetto e montaggio*, in Costruire con l’acciaio, ricerca scientifica e tecniche costruttive, a.c.d. Ghersi A., Dario Flaccovio Editore, 2007 pp.633-640
Siviero E., Attolico L., Culatti M., D’Aguanno V., 2005, *Arcate metalliche per ponti di piccola e media luce*, Rivista Strade e Autostrade 6 novembre/dicembre 2005
[44] Romaro C., Romaro G., 2007, *Le prime opere d’arte realizzate su progetto Calatrava in Italia sono ponti. Parte 1: Viadotto Calatrava a Reggio Emilia. Parte 2: il ponte Calatrava a Venezia*, in Costruire con l’acciaio, ricerca scientifica e tecniche costruttive, a.c.d. Ghersi A., Dario Flaccovio Editore, 2007, pp.671-686

The central bridge, crossing over the A1 motorway and the high-speed railway line, is set as one of the key elements for its plan position and size. The arch is supported through pairs of rods, which unload the weight to the abutments. All the elements are in painted white steel, except the abutments that are in reinforced concrete. The bridge has two lanes going in both directions and cycle paths.
Even the assembly phase was interesting, which provided for the first-stage of the deck construction, with the arch segments lying above it. The second-stage consisted in the lifting of the arch ribs using provisional piers and connecting them at the deck by means of ropes, and finally stretching the cables.

Another one of Calatrava's achievements is the Costituzione Bridge[45] (Fig. 3.66). The construction of the IV bridge over the Grand Canal is most certainly the symbol of the change, adding to what was first a modernity and functional part (for more illustrations see Chapter 2 *Perception*, Fig. 2.30).

3. 66 Costituzione Bridge, Venezia, 2008, 80,8 m span, S. Calatrava

The bridge is located a few meters away from the Scalzi Bridge built by Miozzi in the 30's (see Fig. 3.45 c) and allows a quick connection between Piazzale Roma and the railway station. The work is obviously a pedestrian bridge because of its

[45] Briseghella B., Siviero E., 2010, *The Fourth Bridge over the Grand Canal in Venice: From Idea to Analysis and Construction*, Journal Structural Engineering International, *volume 20 number 1 february 2010*
Romaro G., Romaro C., Miazzon A., Rampin L., 2008, *Il IV ponte sul Canal Grande a Venezia*, Rivista Costruzioni Metalliche, Settembre-Ottobre 2008, pp.38-48

nature and because of the specific needs of the city itself. It has a unique static model, based on a segmental pushing arch with controlled and compensated thrust. It has a 80.5 m span and 3.6 m rise with a width of 9 m in the middle and 6.5 at the abutments.
Also interesting in its phase of assembly, with the placement in the first phase of the lateral segments and the subsequent assembly of the central one.
The Costituzione Bridge becomes a new gateway for lagoon city of Venice, a new doorway to the mainland that represents a symbolic exchange between past and future development.

3.8 Final Considerations

A bridge has the main structural function of connecting two elements that are divided by an obstacle, but at the same time it is also an architectural form. The best bridge designs occur when attention is given to both shape and correct use of structure. The arch is the best solution to express conceptual simplicity, which should be a characterizing mark of any bridge. The use of the arch for the carrying out of big infrastructures dates back to Roman times, as demonstrated, for example, by the beautiful aqueducts which are still present in a vast part of Italy and Europe. Italy vaunts a long tradition in the construction of arch bridges. The history of bridges and viaducts represents the progress in construction techniques and structural typologies. Improvement of construction cannot be based just on formal elements, but also on technological elements.
The latest Italian realizations seek "work completeness", taking into consideration all the costs and the entire life cycle, with particular attention given to the construction details, during the design phases. The intent of the new planning is to return to the traditional shaped arched structures, using modern construction techniques and new materials.

As can be seen from the vast bibliography, even to this day there is a particular interest in any new achievements and it is especially underlined the importance it has taken over the years at the Venetian School of Bridges. The IUAV University of Venice has always been distinguished for its commitment, aimed at integrating and approaching architecture and structure.

A unique sensitivity of the structural architecture theme emerges, thanks to the organization of lectures with professors and designers, of international conferences and debates, with the discussions of various levels on bridge design and on historical and contemporary architectural and structural designers.

This educational philosophy aims to demonstrate that the structural aspects can be learned by architects with outstanding results and takes its inspiration in the important Masters proposed by the IUAV since the mid 20th century. In the University of Venice there is in fact a cultural heritage, left over the years by teachers who have helped to spread the design culture and the dialogue between engineering and architectural disciplines, not only in the construction field but also through their teaching.

Giulio Pizzetti (1915-1990), Franco Levi (1914-2009), Giorgio Macchi (1930), designers and teachers at the IUAV University of Venice, promoted the concept of "total design" by means the synergy of the techniques and composition disciplines. The scientific activities performed in recent years by prof. Enzo Siviero are outstanding, not only for the research carried out on the classical theme but also for the develop of an interdisciplinary teaching method. The continuous dialogue between engineering and architecture, defined as "Structural Architecture", is intended to raise the quality in construction and also in cultural terms. The revaluation activity of the most important accomplishments of the structural engineers, achieved in the degree thesis, permit to find a design culture that can express the harmony between form, structure and function. The contact with the past gives the possibility to acquire a larger design dimension and to achieve more creative knowledge and to revaluate the importance of the intuitive thinking, justified by the static. The revisiting of history allows us to acquire a cultural design process of the bridge, that opens out to the future. For this reason it is an important ethical duty of the designer to find the meaning of each project in their own cultural roots, recognizing the significance of aesthetic value. This could be a lesson for the future bridge engineers and architects.

CHAPTER 4: CONSTRUCTION
Construction methods

A bridge should be studied and built like a cathedral,
with the same care and using the same materials.
Michelangelo Buonarroti

4.1 Introduction

Every resistant structure has a shape, but when considering the arch we can say that the structure is a shape in itself. Hence the arch continues to resist due to its shape, which is also its greatest advantage and its biggest inconvenience: because in order to be able to function as an arch, it needs to be complete. Therefore, all partial structures that may arise during the construction of the arch have little to do with final structure: in fact, the construction of arches stem from this difficulty. Throughout history we can see different uses of construction methods, created through the different uses of materials and with the evolution of the technologies applied on the work site.[1]

The construction methods could be subdivided into two fields: the first collects the use of auxiliary structures that support the arch until it is completed: the second represents the building of the arch by means of partial structures, using different resistant structures, until closing it at the keystone, which is when the arch begins to work.

Every construction method will be presented with a brief description and some important examples realized in Italy, China and in the World.

4.2 Scaffolding construction method
Centering:

Centering (Fig. 4.1) is the classical construction method for arch bridges, and it has been widely used in the construction of historical bridges, in particular for the implementation of the ancient stone bridges made of stone blocks. The voussoirs were of small size compared to the total span of the entire bridge, so the centering method is a necessary tool to support all the elements before the structure is completed and closed at the crown. This method is still used today and it is often applied in the construction of small and medium span arches, but as far as large-span arches are concerned, the cost of the centering almost equals the cost of the bridge itself.

Up until the earlier decades of the last century scaffolding was made of wood, whereas in the 50’s the construction was accomplished by metal scaffolding. Very often the scaffolding itself is an architectural and engineering effort that can be highly suggestive and challenging as far as projects are concerned. Nevertheless,

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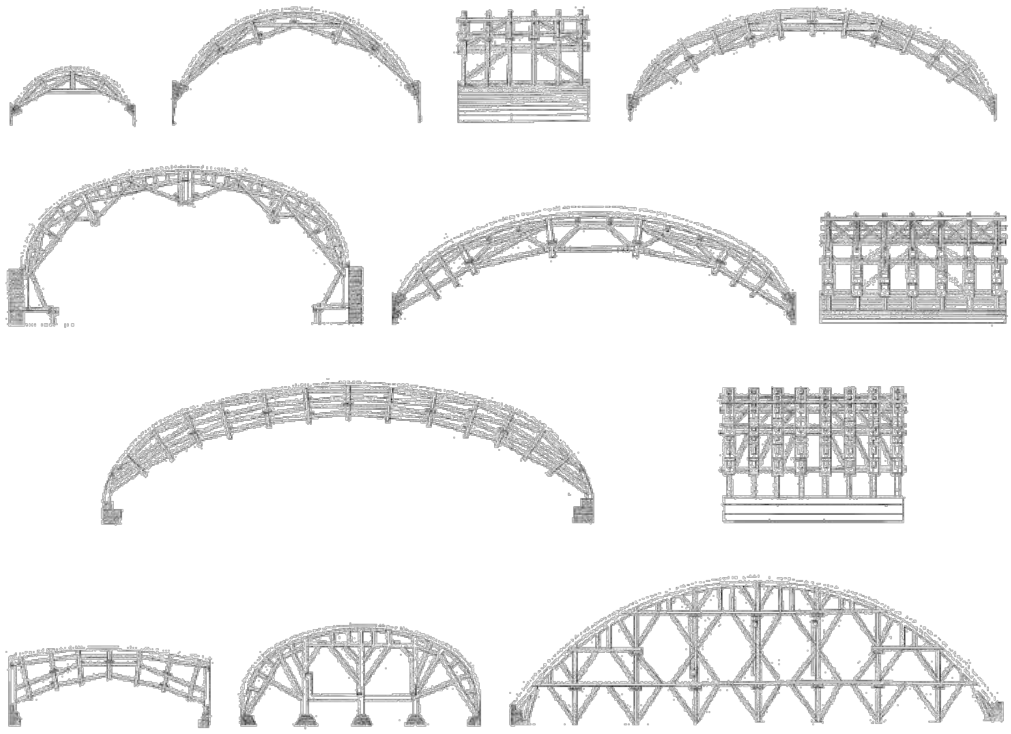
[1] For further information on this theme also see: Casciati L., *Ponti e Viadotti, Metodi costruttivi*, 1992, pp.171-202, in *Costruzioni oggi e domani*, a.c.d. E. Siviero, Architettura e strutture – Collana diretta da E. Siviero, n°1, Ed. Centro Editoriale Veneto, Padova, 1992

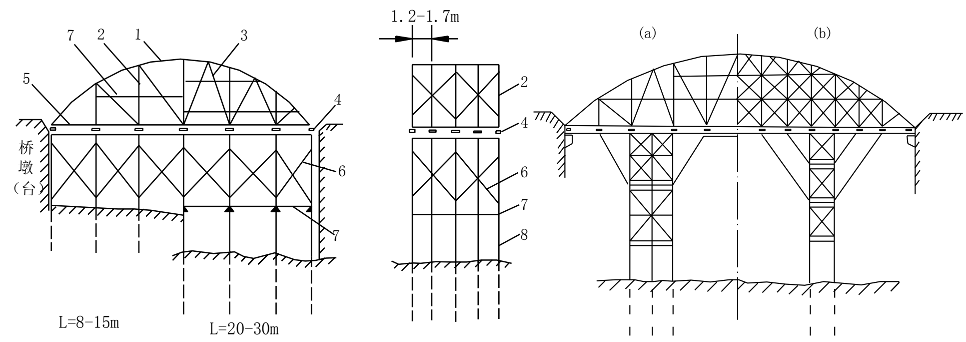
the scaffolding construction and the cost of work in the assembly and disassembly, soon became increasingly expensive.



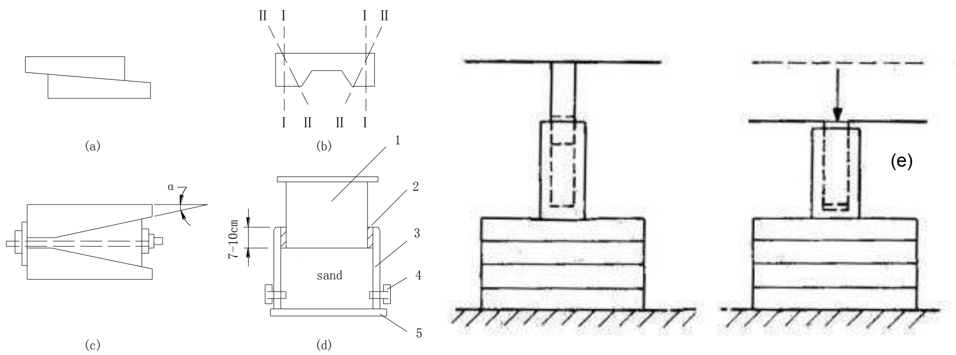
4. 1 Examples of different scaffolding typology

The scaffolding has to support the entire structure and all the tools of the yard during the construction phase. Therefore, the construction structure might have some problems if loaded wrongly. The temporary structure must be carefully designed because it must be easy to assemble in the erection phases and to dismiss during the removal process, and sometimes it could be reused for the construction of another part of the structure, or of an entirely new bridge for instance the construction of a second arch span.
The centering may have different shapes depending on the surrounding environment: the presence of a deep valley, a river or a flood threat. Each project has its own particular centering, that is designed for the specific project. Generally, the centering is composed of two distinct parts: the top arch and the bottom falsework, and between these two parts the dismantled equipment is installed. The top centering is composed of arched beams, columns and transverse connections and the bottom structure has piles and horizontal supports. To improve the lateral stability horizontal and inclined supports are used. This type of structure requires a lot of material to be set up. Timber or steel waste can be reduced using a strut-

framed centering (Fig. 4.2), that is merely a simplification of the common one and in this case making it possible to have more free space on the yard.[2]
The dismantled equipment (Fig. 4.3) could be of many types depending on the bridge dimensions. For small bridges chocks or benches could be used, and hydraulic jacks, pistons and sand cylinders could be used for large bridges.



1-arched beam, 2-column, 3-diagonal strut, 4-dismantled equipment, 5-tied rob, 6-inclined support, 7-horizontal support, 8-pile
4. 2 Full span centering and strut-framed centering



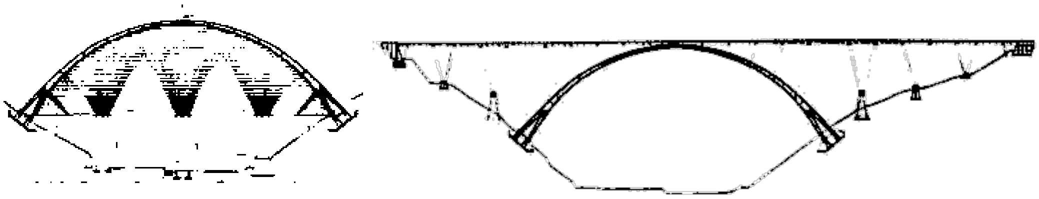
a. chocks
b. bench
c. composite chock
d. sand cylinder: 1.piston; 2.tamp with asphalt; 3.metal (or wood) cylinder; 4.dump sand hole; 5.padding plate
e. jack system
4. 3 Types of dismantling equipment

Italy

Since 1970 this construction method had been practically abandoned and the building of arch bridges were replaced by the use of prestressed concrete beams, which were cheaper and faster to assemble. In recent years, the arch shape has

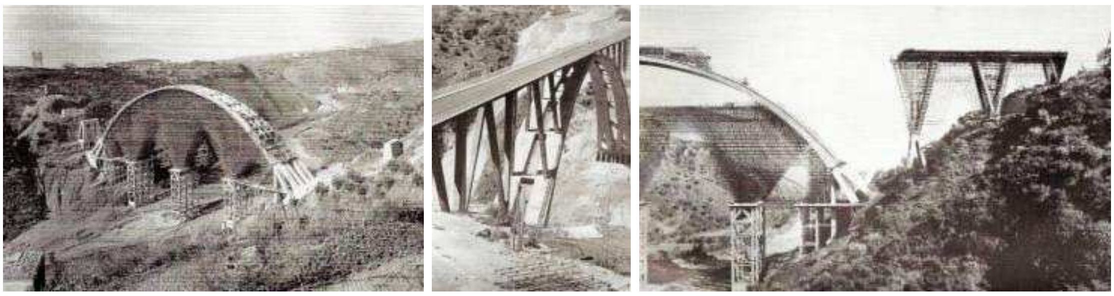
[2] Chen B., 2009, *Construction methods of arch bridges in China*, Proceedings of the Second Chinese-Croatian Joint Colloquium, Construction of arch bridges, Oct. 5-9 2009, Fuzhou, China, p.70

regained new architectural value and it has been readopted in a modern way and with the use of new materials, especially for the construction of small and medium spans.



4. 4 Fiumarella Viaduct, Catanzaro, Italy, 231 m span, 1962, R. Morandi
Centering and final bridge drawings

An important example is represented by the Italian viaduct over the Fiumarella River (Fig. 4.4), in Catanzaro city. It is one of the most renowned accomplishments of Riccardo Morandi[3] (1902-1989) and it is the longest concrete arch bridge in Italy. It was a daring feat for Italy, and it is the synthesis of the many works carried out by one of the greatest Italian structural designers.
The Fiumarella Viaduct (Fig. 4.5), opened in 1962, is the symbol of the city and it is a bridge with a single carriageway road, built on a single arch. It was set up through a resistant scaffolding structure, created by temporary concrete and steel tubes. It was one of the tallest temporary structures ever accomplished: it was more than 120 m high. The arch consists of two independent semi-arches and has a 10,50 m wide box structure at the crown and 25 m at the spring. It has a 231 m span.[4]



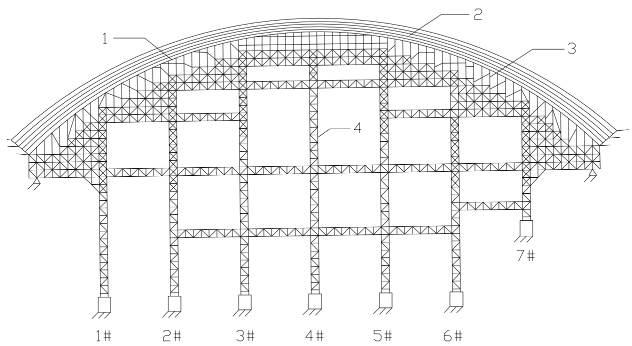
4. 5 Fiumarella pictures: construction phase and state of art
Fiumarella Viaduct, Catanzaro, Italy, 231 m span, 1962, R. Morandi

[3] Cetica P.A., 1985, *Riccardo Morandi ingegnere italiano*. Firenze, Alinea.
[4] Boaga G., 1988, *Riccardo Morandi*. Bologna, Zanichelli.

China

A Chinese example would be the New Danhe Bridge (Fig. 4.6)[5], that is a super-large bridge on the Jincheng-Jiaozuo Expressway, spanning over the Danhe River in the west of Taihang Mountain in Jincheng City of Shanxi Province, built with stone. The bridge was completed and opened to traffic on September 2000. The main arch span is 146 m and it is the widest spanned bridge in the world using stone material.

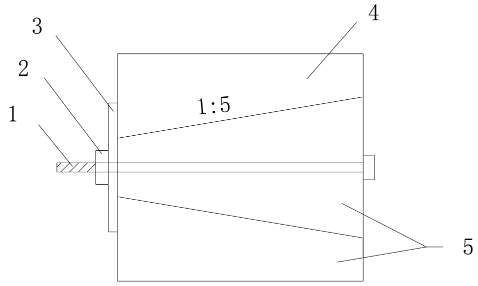
4. 6 Danhe bridge pictures: construction phase and state of art
New Danhe Bridge, China, 146 m span, 2000



1. Bow wood and formwork; 2.main arch ring; 3.wood bent frame;
4. Steel arch cantering
4. 7 Arch centering of New Danhe Bridge

[5] Hu C. W., Hu D. L., Liu S. L., Zhou W., 2001, *The Longest Stone Arch Bridge in the World*, Proceedings of the Fourth International Conference on Arch Bridges, Sept. 19-21, 2001, Paris, France, pp. 667-672
Chen B., *Construction methods of arch bridges in China*, Proceedings of the Second Chinese-Croatian Joint Colloquium, Construction of arch bridges, Oct. 5-9 2009, Fuzhou, China, pp. 74
Major Bridges in China, 2003, China Communications Press, Beijing.

The New Danhe Bridge is a good example of an arch bridge built on centering that was approximately 80 m high (Fig. 4.7 and 4.8). The spatial steel bent centering was assembled with steel universal elements, composed of nine groups of 16 m high bearing piers and tie girders. The width of the deck is 24,80 m and the rise of the main arch is 32,44 m (1/4,5 of the main span).



1. high-strength bolt; 2.nut; 3.steel apron plate;
4. Hard wood soaked with vinegar; 5. Waxed hard wood
4. 8 Dismantling equipment of New Danhe Bridge, Composite chock

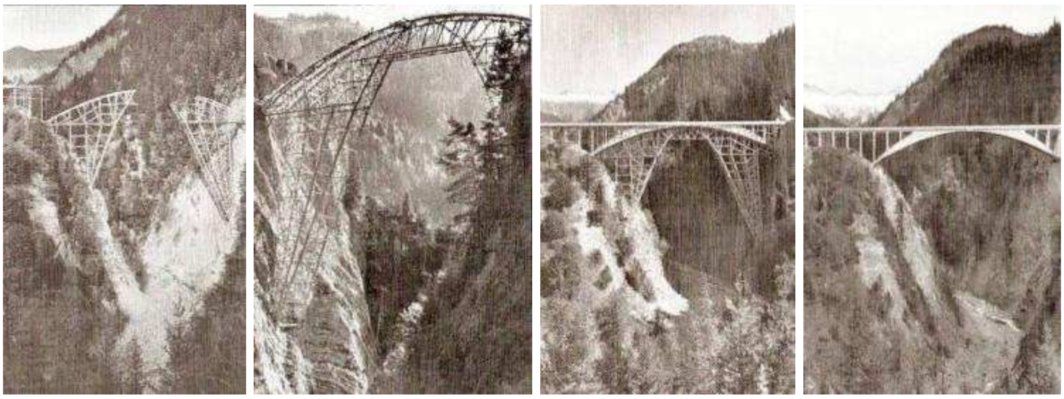
World

Robert Maillart (1872-1940) had previously designed a three-hinged arch bridge over the Rhine at Tavanasa in 1904. Along the 51 m span of the Tavanasa Bridge, the arch is thinnest at its crown and at its springing points, thickening in-between to reflect the shape of its bending moment diagram. This bridge was destroyed by an avalanche in September 1927. Maillart entered a competition the following year for the bridge at Salginatobel (Fig. 4.9), with a three-hinged arch spanning 90 m that used the same overall form as seen at Tavanasa. Maillart's design was the least expensive.[6]

This project is, probably, one of the most famous bridges in the world. The reasons are to be found in the attention that the engineer given to structure: David Billington reported that "*discipline of structural efficiency is the primary basis for creation*".[7] This is mirrored brilliantly in Maillart's bridge, the project is the union between the nature of the arch and the efficiency of the structural system. At the same time, it is a good example of architecture collocated into the environment. The choice of a wood centering like construction method requires a careful design of the formwork (Fig. 4.10).

[6] Billington D. P., 2003, *The Art of Structural Design: A Swiss Legacy*. Princeton University Art Museum. Princeton, USA.
Laffranchi M., Marti P., 1996, *Robert Maillart's curved concrete arch bridges*, Journal of Structural Engineering, ASCE, October 1996

[7] Billington D. P., 1983, *The Tower and the Bridge*. Princeton University Press, Princeton, USA.

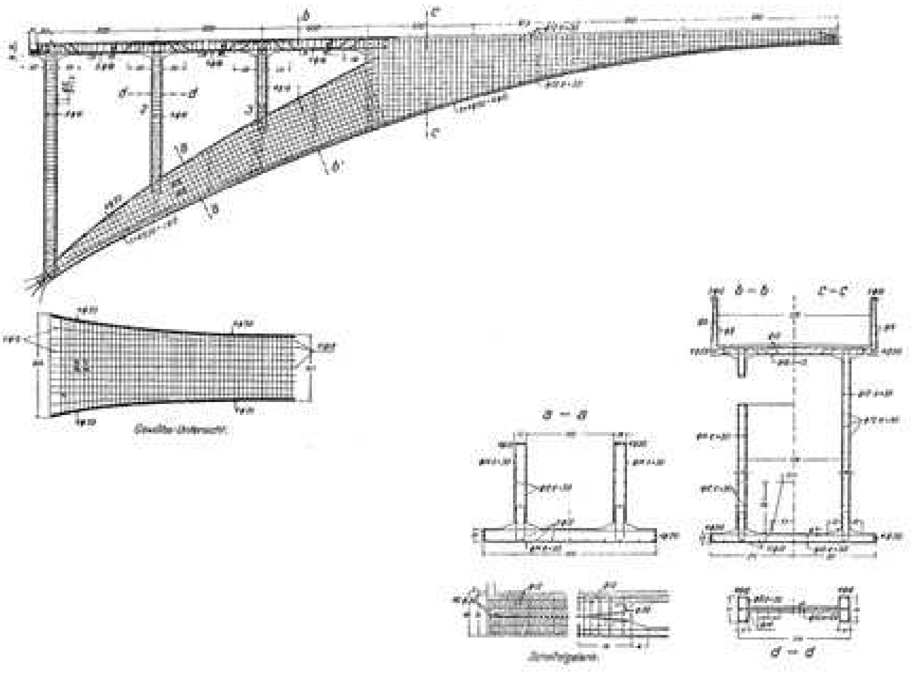


4. 9 Salginatobel bridge pictures: construction phase and state of art
Salginatobel Bridge, Switzerland, 90 m span, 1930, R. Maillart

The Salginatobel[8] arch bridge is 133 m long in total, and its main element is a hollow concrete box girder over the central part of the arch (Fig. 4.11). The roadway is 3,5 m wide, supported on reinforced concrete piers above the ends of the arches. Reinforced concrete has proved to be a malleable construction material, taking the strength of concrete in compression and the strength of steel in tension. The arch plate which decreases in thickness towards the centre and the arch supported walls that increase in length but decrease in thickness from the springing points towards the centre as the greatest moment is experienced at the quarter span points.

4. 10 Salginatobel bridge pictures: construction phase and state of art
Salginatobel Bridge, Switzerland, 90 m span, 1930, R. Maillart

[8] Tapping A. J., 2007, *The Salginatobel Bridge*, Proceedings of Bridge Engineering Conference 2007, 4 May 2007, University of Bath, Bath, UK

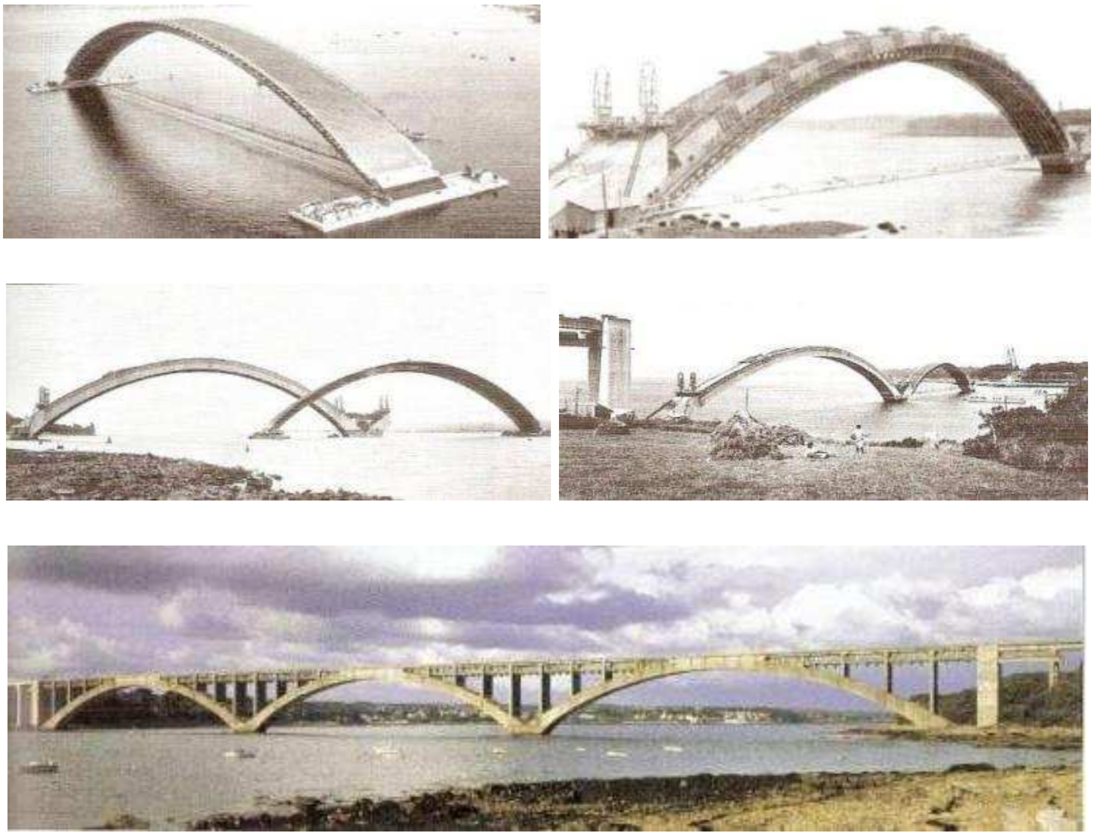


4. 11 Salginatobel structure and sections at the spring and at the crown
Salginatobel Bridge, Switzerland, 90 m span, 1930, R. Maillart

Eugène Freyssinet (1879-1962) was one of the most prominent engineers in the world, a brilliant inventor and creative builder and he is best known for his work on prestressing, but during his career he completed many significant structures, including the Plougastel Bridge (Fig. 4.12), consisting of three 180 m spans with a 27,5 m rise. The section is a hollow box cross-section. The upper deck was used as a roadway and the lower one was foreseen to be railway.[9]
The bridge was concreted on a timber centering, built onshore and tied from end to end for stability reasons and it was supported on two barges under the arch feet, by which it was transported from one arch to the other. The scaffolding was used three times for the whole arch spans and was transported over water by means of barges. Once the first concreting was finished, the centering remained supported on the barges in order to be moved to the next position. The formwork used for casting the three arches was the greatest and the most daring wooden structure used in construction history, with its 10 m in width and 170 m in length.
This bridge is one of the engineering masterpieces of all times, basically due to its construction procedure. According to Billington[10] "*it was the elegance of his*

9 Troyano, L.F., 2004, Procedures for the construction of large concrete arches. In *Arch Bridges IV Proceedings – Advances in Assessment, Structural Design and Construction:* 53-63. Barcelona: CIMNE, 2004.
10 Šavor Z., Bleiziffer J., 2008, *Long span concrete arch bridges of Europe,* 1st Chinese-Croatian Colloquium on Arch Bridges in Brijuni Islands, 10-14 July 2008

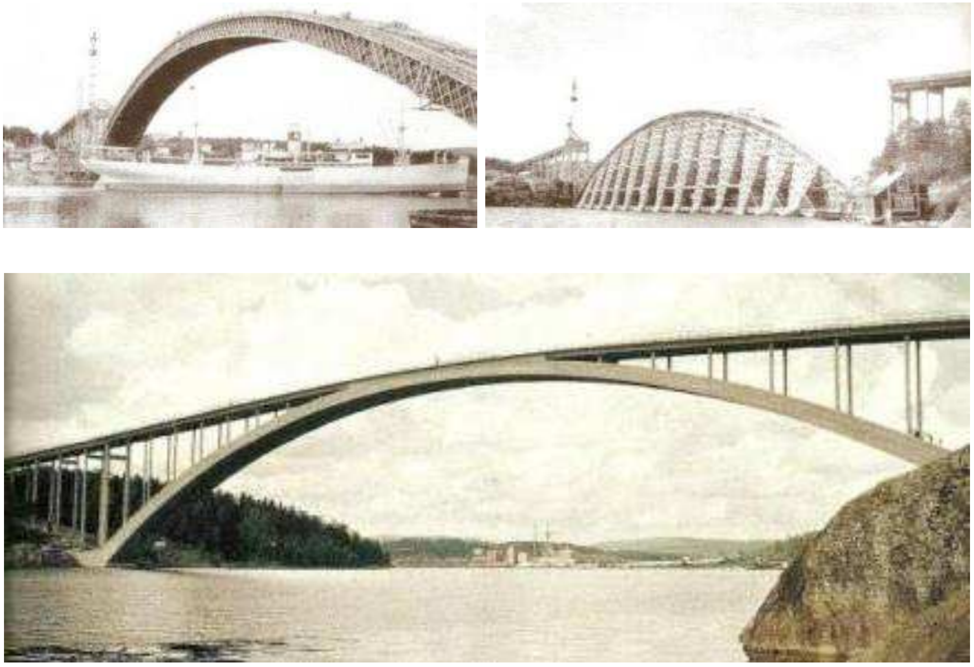
construction procedures both visually and in concept [that] *made Freyssinet world-famous both to engineers and architects*."



4. 12 Plougastel bridge photographs: construction phases and the state of art
Plougastel Bridge, France, consisting of three arches of a 186 m span, 1930, E. Freyssinet

The Sando Bridge (Fig. 4.13) was built in 1943 across the Angerman River in northern Sweden. It is a thin reinforced concrete arch with a span of 260 m and a rise of 39 m above the river. For the construction of the Sando Bridge a similar centering like one used in the the Plougastel bridge was used, but it collapsed during the casting process. The new centering had of much more traditional design, with very close spacing of piers supporting the formwork. Despite the tragedy, Sando Bridge is still a masterpiece of structural engineering.[11]

[11] Pérez Fadón Martínez S., *Arches: Evolution and Future Trends*. In *Arch Bridges IV Proceedings – Advances in Assessment, Structural Design and Construction,* Barcelona: CIMNE. 2004, pp.11-25.
Troyano L.F., 2004, *Procedures for the construction of large concrete arches*. In Arch Bridges IV Proceedings – Advances in Assessment, Structural Design and Construction, Barcelona, CIMNE, 2004, pp. 55-66.



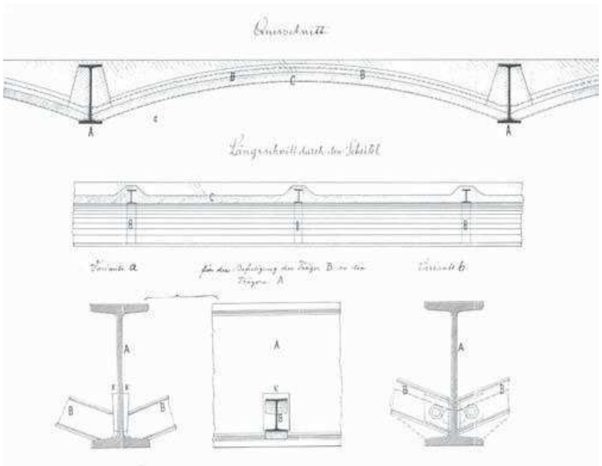
4. 13 Sando Bridge, Angerman River, Sweden, 240 m span, 1942

4.3 Melan scaffolding:

The Melan system was patented in 1892 (Fig. 4.14) with the particular feature of combining steel arch ribs, or so-called rigid reinforcement, with concrete vaults. During the innovation phase, the Melan system was primarily used for constructing suspended floors, and only later on was it used for bridges. Although it represented only one of the many suspended floor systems in use for buildings, the Melan system found favour among a number of clients and structural engineers because of its very high load-carrying capacity.[12]

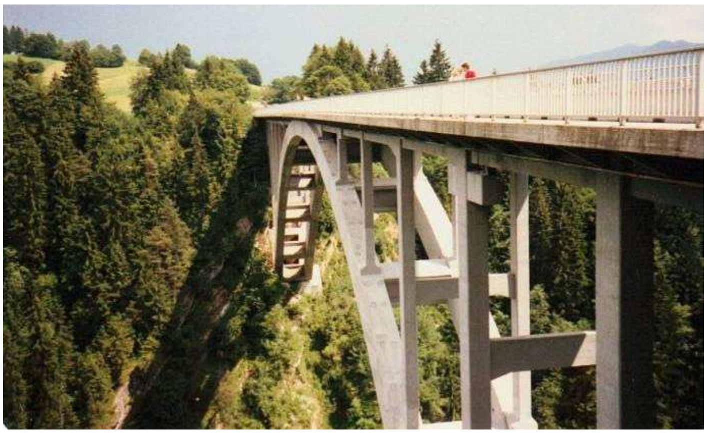
To avoid the difficulty, the scaffolding method had new developments and constructive innovations, Josef Melan (1854-1941) achieved metal scaffolding that had a double function: both as scaffolding and reinforcement of the final structure. This method uses parallel metal "I" beams embedded in concrete along the line of the arch intrados. It consists of building a steel lattice arch first, which serves as the scaffolding truss, but also the second function as a reinforcement of the definitive arch. The disadvantage was that the amount of steel employed for the initial arch is greater than the reinforcement required by the concrete arch.

[12] Eggemann H., Kurrer K. E., 2009, *On the International Propagation of the Melan Arch System since 1892*, Proceedings of the Third International Congress on Construction History, Cottbus, May 2009



4. 14 Drawing from Melan's patent and example of a Melan scaffolding

The most famous bridge, built with this scaffolding method, is the Eschelbacher Melan Bridge in Austria (Fig. 4.15), built in 1929 with a 130 m span and 31.8 m rise. It includes two spaced concrete ribs. This method came quickly into widespread use, thanks to its cost-effectiveness and fast construction and even due to the fact that timber centering for arch construction could be omitted.[13]

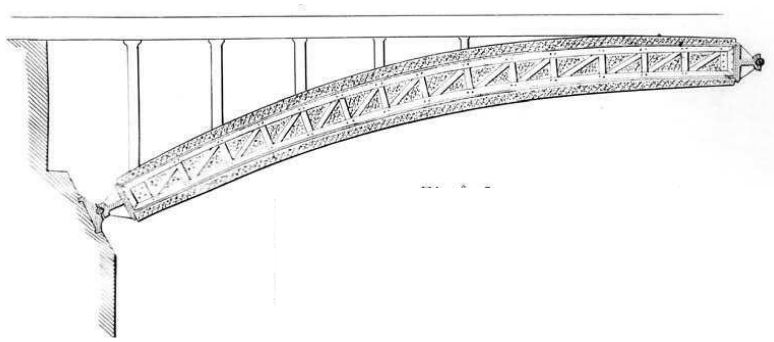


4. 15 Eschelbacher Bridge, 1929, 130 m span

The Melan method was largely abandoned after 1940s, but the end of the 20th century was marked with the completion of several long-span arch bridges, with either steel truss arches embedded in concrete, filled with concrete, or both. Any of these procedures facilitated the construction and increased the load-carrying capacity, thus providing competitive bridge designs with 200 - 400 m spans. In

[13] Šavor Z.; Bleiziffer J., 2008, *From Melan Patent to Arch Bridges of 400 m spans.*, 1st Chinese-Croatian Colloquium on Arch Bridges in Brijuni Islands, 10-14 July 2008, pp. 349-356.

some great arches the centering consisted of a steel arch made of a steel section that had a span with the same dimensions as the definitive one (Fig. 4.16).



4. 16 Bridge section built with Melan scaffolding

Originally appreciated for its high load-carrying capacity, the Melan system was soon to be used for its technological advantages in practical operations on site. These advantages led to a significant improvement in the economy and in the organization of bridge building: firstly in the increasing of the prefabrication throughout the factory fabrication of the steel Melan arches led to a new level of control of the engineering in the building process; and secondly the replacing of the timber centering by steel Melan arches reduced the costs of labour and materials. For example, consider a mountainous region, where the eventual use of the centering method produces high costs and risk of flooding. The third point consists in the speed of construction on site.[14] The economical advantages of the arch bridge based on the Melan system compared to conventional reinforced concrete arch bridges are indicated during the planning and design phases. This is particularly evident when bridging deep valleys and when long spans are required. A special form of design became a special form of construction: the history of the evolution of the Melan system from 1892 to the present day is a good example of the change from the structural/constructional to the technological paradigms in bridge-building.

Italy

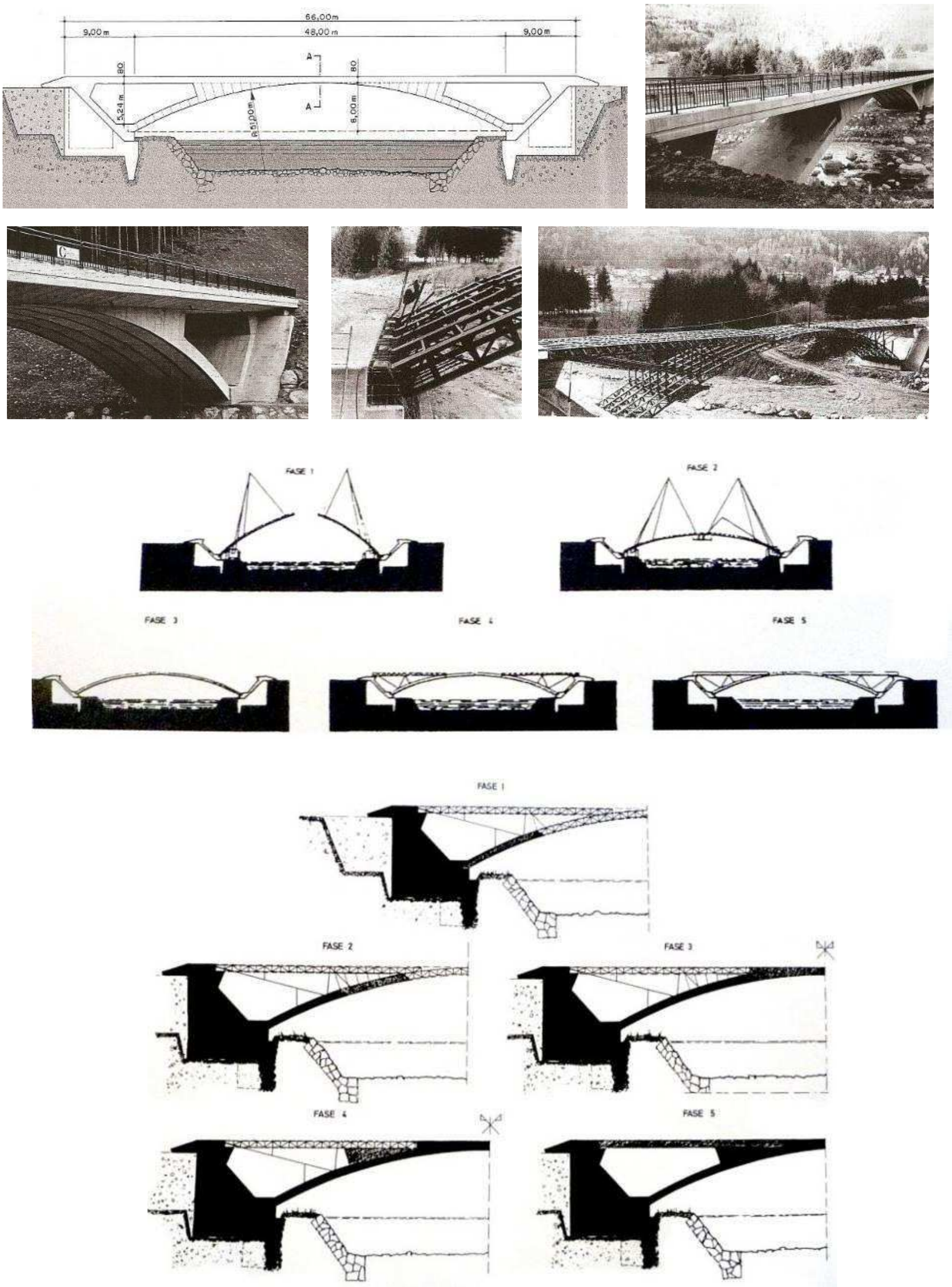
One bridge realized in Italy with this method is the one over the Sarca River, near Villa Rendena in the Trentino region, built in 1996 (Fig. 4.17); the Italian engineer Armando Mammino (1950)[15] was responsible for the design. In this case the risk of

[14] Eggemann H., Kurrer K. E., 2009, p. 523

[15] Mammino A.,1996, *Il ponte ad arco sul fiume Sarca in Villa Rendena, Trento*, L'industria italiana del cemento, 66(715), 1996, pp. 780-791

Mammino A., *Il ponte sul fiume Sarca in Villa Rendena: un primo esempio di progettazione*, p.177-199, in Mammino A., *Il progetto strutturale: filosofia e storia recente,* 1995, Architettura e strutture – Collana diretta da E. Siviero, n°7, Ed. Biblioteca di Galileo.

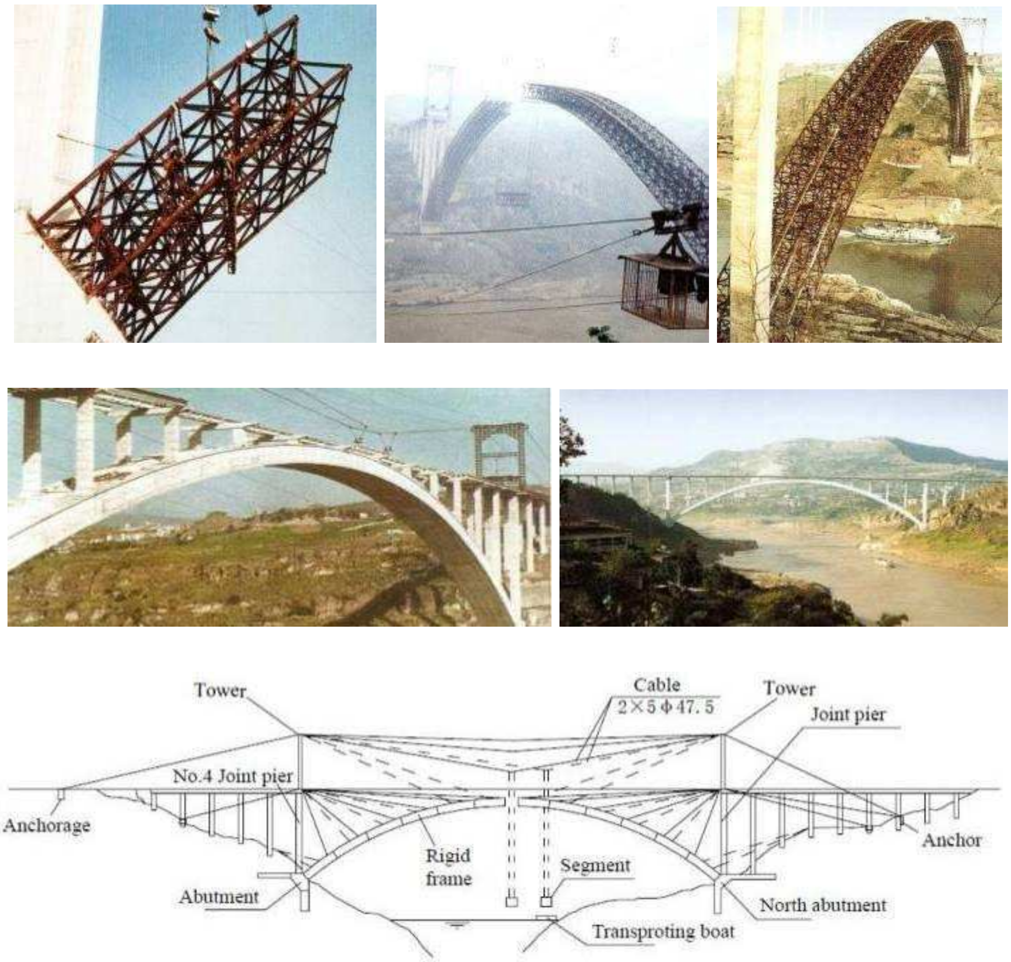
flooding was critical for the choice of structure. The bridge had a total length of 66 m, and the arch span was of 48 m.



4. 17 Arch Bridge on Sarca River, in Villa Rendena, Trento, 48 m span, A. Mammino
Construction phases: positioning of the Melan centering and melding of the concrete process

China

But it was in China that the Melan method saw its true revival with the construction of long-span concrete arch bridges with rigid reinforcement, as well as concrete filled steel tubular arches.[16] The arch bridge, in reinforced concrete, with the record span is the Wanxian Bridge (Fig. 4.18), over the Yangtze river in the vicinity of the Three Gorge Dam in the Sichuan Province in China finished in July 1997, with a span of 420 m. The arch axis is a catenary curve with a rise to span ratio of 1/5.[17]



4. 18 Wanxian Bridge, Yangtze River, Wanzhou, China, 420 m span, 1997

[16] *Major Bridges in China*, 2003, China Communications Press, Beijing, China

[17] Yan G.M., Yang Z.H., 1997, *Wanxian Yangtze Bridge, China. Structures in Asia*. Structural Engineering International, 3/97

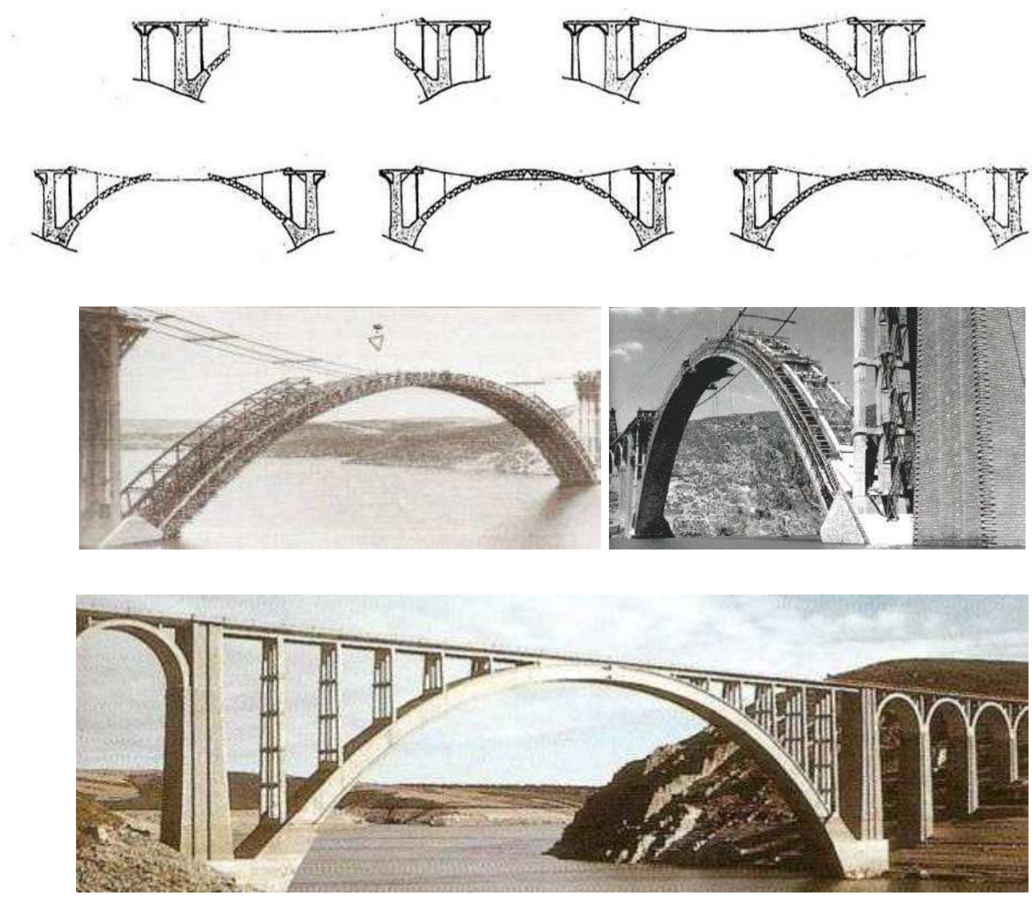
Li W., Fan W., Sun Y., Liu J., 2001, *The Wanxian bridge: the world's longest concrete arch span*. Proceeding for the 3rd International Conference on Arch Bridges : 673-676. Paris: France, 2001.

Xie B., 2008, *Wanxian long span concrete arch bridge over Yangtze river in China*, 1st Chinese-Croatian Colloquium on Arch Bridges in Brijuni Islands, 10-14 July 2008

A trussed arch of hollow sections was erected first and then filled with concrete. The CFST structure was built using the conventional cantilever technique. The stiffened truss frame is then encased by subsequent concrete placements to become the main reinforcement of the completed arch section. Concrete placement had to be simultaneous on all six working sections starting from the first segment. Where concrete was incorporated with the metal structure, thus forming a mixed structure.

World

The most impressive historical bridge erected utilizing the Melan method is the Martín Gil Railway Viaduct[18] (Fig. 4.19), built in 1942 across the Esla River, in Zamora, Spain. The original design was a concrete arch, 209 m in span and 65 m in rise, to be constructed on timber centering.



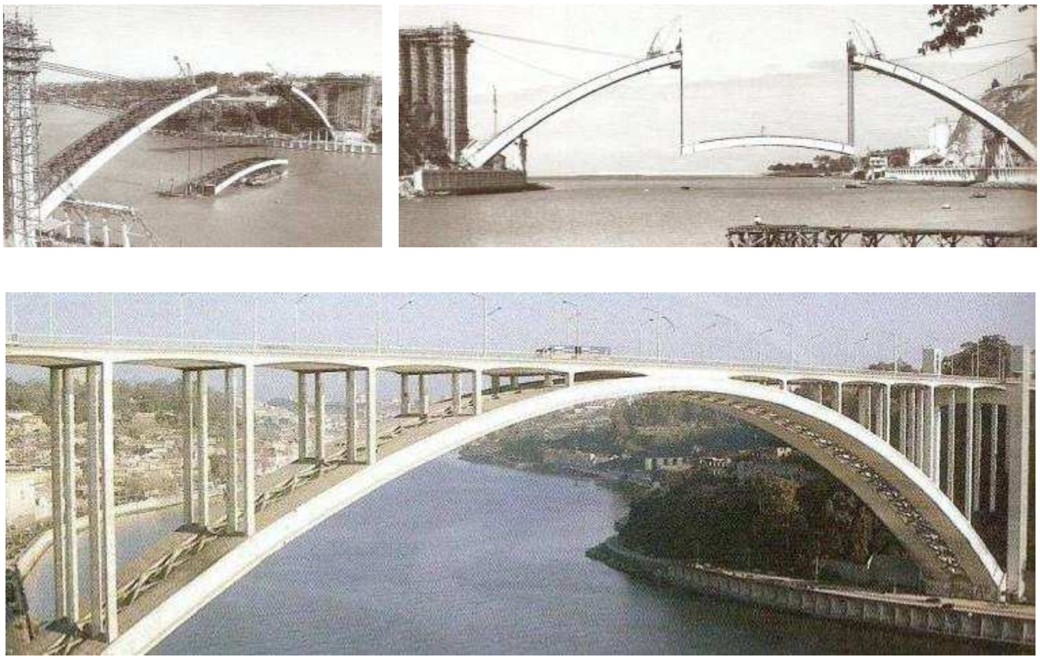
4. 19 Martin Gil Viaduct, Esla River, 209 m span, 1942, M. Gil, E. Torroja

Eduardo Torroja (1899-1961) decided to use the Melan method instead of the already constructed timber centering that was deteriorated due to the suspension of

[18] Castellon F., Villalba C., Salazar A., Torroja E., 1943, *Viaducto Martín Gil*, Revista de obras públicas., Trenes de Zamora, *1942-1943.*

construction works during the Spanish Civil War. Its assembly was extremely ingenious: it was accomplished with a metal centering frame which was then sunk in the casting with a bearing function to all effect. The arch was constructed in segments, going from one end to the other. This was performed in such a way that for concreting of a segment the concrete of the preceding segments was in composite action with rigid reinforcement therefore reducing the required amount of reinforcing steel.[19]

The Arrabida Bridge[20] (Fig. 4.20), designed by the engineer Edgar Cardoso (1913-2000), has a total length of 493 m and an arch span of 270 m and a rise of 52 m. It was inaugurated in 1963. It is composed of two twin arches, each one comprising a double caisson of reinforced concrete. In addition, the caissons are connected by reinforced concrete cross-trussed.[21]



4. 20 Arrabida Bridge, Duero River, Oporto, Portugal, 270 m span, 1963, E. Cardoso

[19] Šavor Z.; Bleiziffer J., 2008, *From Melan Patent to Arch Bridges of 400 m spans*., 1st Chinese-Croatian Colloquium on Arch Bridges in Brijuni Islands, 10-14 July 2008, pp. 349-356.

[20] Troyano L.F., 2006, *Terra sull'acqua, Atlante storico universale dei Ponti*, Dario Flaccovio Editore, Palermo, Italia

Pérez Fadón Martínez S., 2004, *Arches: Evolution and Future Trends*. In *Arch Bridges IV Proceedings – Advances in Assessment, Structural Design and Construction,* Barcelona: CIMNE. 2004, pp.11-25.

[21] Appleton J., 2001, *Arrabida bridge. Inspection and assessment*, presented at ARCH'01. 3ème conférence sur les ponts en arc., Paris 19-21 Set. 2001 pp.29-34

Soares L.L., 2003, *Edgar Cardoso: engenheiro civil,* Faculdade de Engenharia da Universidade, Porto, Portugal, pp. 271-291

The bridge was built using a metal self-resistant steel centering for each of the arches covering the entire span. The shuttering comprised of three longitudinal beams connected together by trusses horizontally and vertically. The end sections of the arch were constructed first, using scaffolding and backstays anchoring them to the shore pier. Then the central section was winched into place from the semi-arch ends. The shuttering platform was first situated downstream from the initial twin arch, when concreting maneuvered upstream into place to concrete the second twin arch. Finally, it was positioned between the two twin arches to concrete the truss connection.

4.4 Cantilever construction method[22]

The cantilever is probably the method most commonly used and it consists in the simultaneous construction of the semi-arches, from the abutments to the crown, using auxiliary structures that hang the arch until it is finished. The cantilevering construction method is subdivided into different types depending on the auxiliary structures used in the yard, on the arch typology and on the characteristics of the place.

Eugene Freyssinet is acknowledged as the pioneer of the cantilever method. He designed three bridges in Venezuela for the Caracas-La Guaira highway, which were erected between 1950 and 1953. Parts of these arches, next to springing, were made as cantilevers stayed by cables, while the central part was erected on scaffolding, supported by previously completed elements.

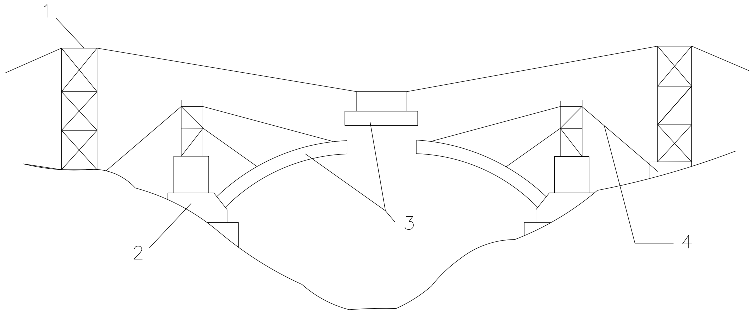
Cable stayed-cantilever:

This method needs requires a lot of tools on site, such as pylons or towers and cables (Fig. 4.21), which permit the construction from the springing to the crown. Pylons can be built on the piers at abutment. The cables stayed hold the cantilever arch with rear stays, anchored to the ground or to approach bridges.[23]

Concrete arch bridge can be built using this method and the arch rib can be cast *in situ* segment by segment, and can also be assembled by precast segments. The steel arch rib, on the other hand, can be prefabricated and then hoisted in the final position.

[22] Žderić Ž., 2008, *Cantilever erection of arch bridges*, Proceedings of the First Chinese-Croatian Joint Colloquium, Long arch bridges, 10-14 July, 2008, Brijuni Islands, Croatia, pp. 337-342

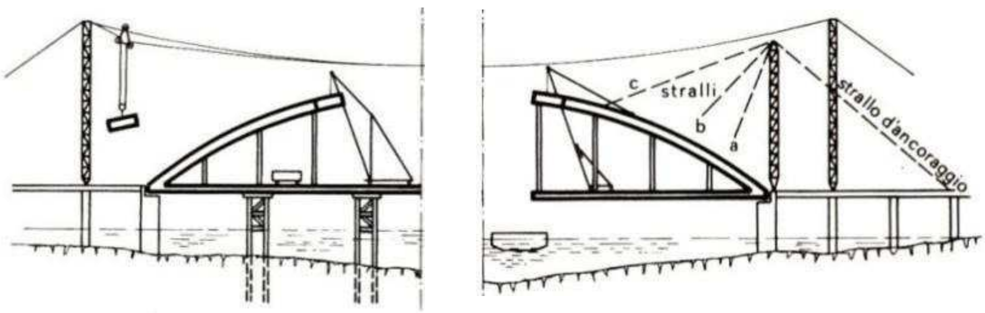
[23] Chen B., 2009



1. Cableway; 2.abutment; 3.arch rib segment; 4.stayed cable;
4. 21 Cable-stayed Cantilever method with cable crane

Cable-stayed cantilever for bowstring construction[24]

After the construction of a sufficient numbers of provisional piers, the construction of the deck starts (Fig. 4.22), and successively the arch finds supports on each element of the suspension, with eventual braces. On completed the arch, the disarmament can be started by working with boxes of sand or jacks, installed at each provisional supporting. The process is relatively simple, but can result to be costly in proportion to the difficulties of construction of the provisional piers, and is unsuitable for arch bridges with suspension ropes.



4.22 4.23

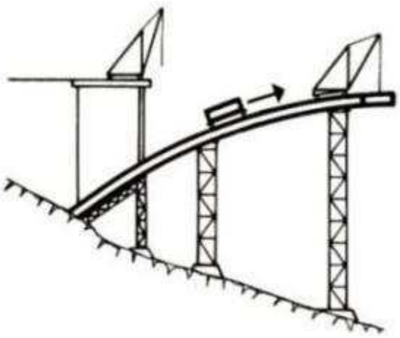
4. 22 Cable-stayed Cantilever method for bowstring type by means intermediate supports
4. 23 Cable-stayed Cantilever method for bowstring type by means towers and ropes

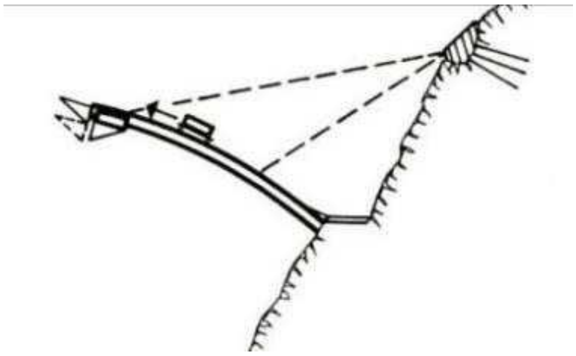
With the second system for bowstring type, provisional supports are not required (Fig. 4.23). The horizontal components of the arch thrust and the reaction of the anchorage are in equilibrium because the deck is under compression. The assemblage continues with the free cantilever method, building the arch and deck either simultaneously or at another time. In this case there is less stress both for the arch and for the deck, while the transportation and lifting blocks become more complex.

[24] Nascè V., Dal Pont E.,1975, *Tecniche di montaggio*, CISIA, Milano, Italy

Cable-stayed cantilever for deck arch bridges construction[25]

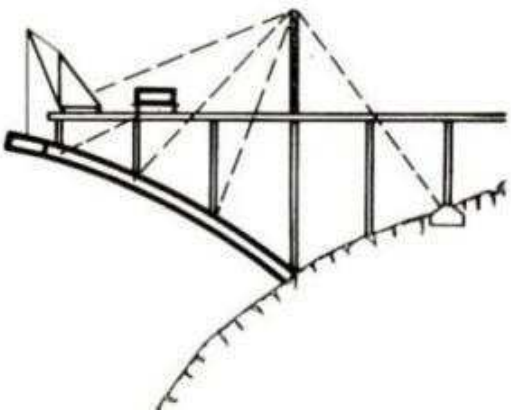
Deck arch bridge can be built in the same way as bowstring bridges, from below with provisional elements (Fig. 4.24), or from above with cables (Fig. 4.25). In deep valleys or in places with difficulties regarding the foundations structures, the cable system is obviously more convenient. The pylons must inevitably be of great height, even though the posterior anchorage of the pylon is to be taken to the foundation, to avoid bending stresses to the access viaduct piers. For arch bridges set on sloping valleys, cables can be directly anchored to the rock by means of rods or special steel tubes.





4. 24 Cable-stayed Cantilever method for deck arch bridge by means intermediate supports
4. 25 Cable-stayed Cantilever method for deck arch bridge by means rods.

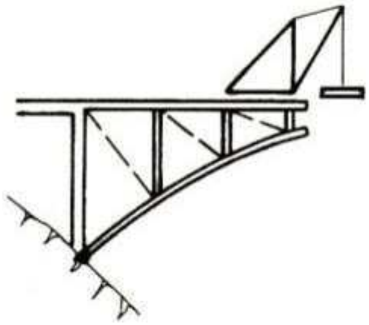
Even for deck arch bridges the construction of the deck can be contemporary or subsequent to the arch. Provisional diagonals can be used between the two struts during the construction phase, so that the structure works as a scaffolding lattice girder (Fig. 4.26).



4. 26 Cable-stayed Cantilever method for deck arch bridge by means diagonals.

[25] Nascè V., Dal Pont E., 1975

Free cantilever construction:
The cantilever method using only provisional diagonals can be built in free-cantilever (Fig. 4.27): the bridge is mounted as a cantilever beam lattice advancing symmetrically from either side.
While the arch supports the assembly efforts (removing the effect of equipment, the reactions at the abutments have approximately the same values of use), the struts are subjected to a strain proportional to the span of the entire arch instead of their distance, and the deck should be designed with a longitudinal direction and with joints able to resist to the high concentrations of assembly.



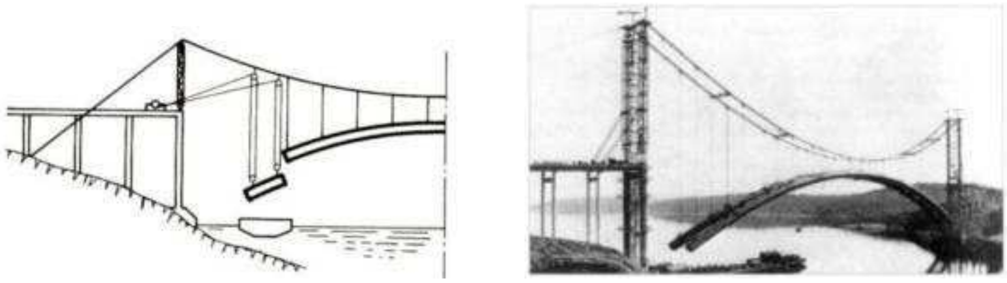
4. 27 Free Cantilever method for deck arch bridge by means diagonals.

The horizontal reaction at the deck level can be supported by the abutments or by the foundations. Tension forces in the structure above the arch are transmitted to the abutments by means of appropriate temporary elements, and from there they can be transmitted into the ground.
The construction procedure, in which the arch and the superstructure above the arch are being built at the same time, should achieve two major advantages: inclusion of structural elements above the arch into the load-bearing system during the construction period as well as shortening the period of construction.

Cable-stayed cantilever construction as in a suspension bridge
Another method that can be used in the cantilever system is the assembly of the arch bridge as a suspension bridge. The various segments are brought by boats under their final assembly position, then raised with the help of hanging cables.

This method was used for the construction of the Askerofjord[26] Bridge in Sweden (Fig. 4.28), which spans 278 m, and built in 1961. However, this method posses many more difficulties than the other one; attention must be paid to the stability of the work done under the wind action and for the registration of the suspension during assembly.

[26] Troyano L.F., 2006, *Terra sull'acqua, Atlante storico universale dei Ponti*, Dario Flaccovio Editore, Palermo, Italia



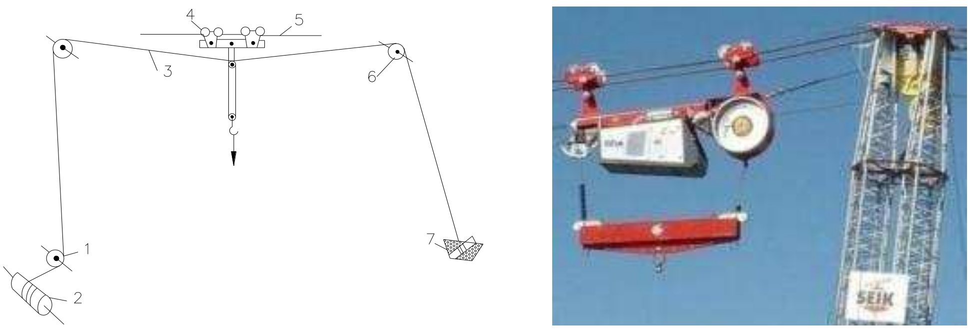
4. 28 Cable-stayed cantilever construction as in suspension bridge and Askerofjord Bridge, Sweden, 278 m span, 1961.

Transport and lifting:

An arch rib is built from the spring to the crown to form two halves arches. Auxiliary structures are necessary during the construction, because the arch cannot be an efficient bearing structure before its closure. Cables and pylons are used to hold the cantilever arch advancing from spring to crown.

Cable:

In the cable-stayed cantilever method, steel strand rope, spiral rope and wire strand, etc, can be utilized as the cable stayed and back cable, with winches or hydraulic jacks being the devices used for adjusting the cable force. The choice of materials, rope diameter and the amount of main cables used should be decided accordingly by calculation.



1. Steering pulley block; 2.winch; 3.hoisting rope; 4.crane position;
5. main cable; 6.pulley block; 7.anchorage
4. 29 Hoisting system

The hoisting system (Fig. 4.29) mainly consists of the hoisting tackle block, hoisting cable, hoisting windlass, and guiding tackles.[27] The hoisting cable goes through the hoisting block which has the same lines as the main cables.

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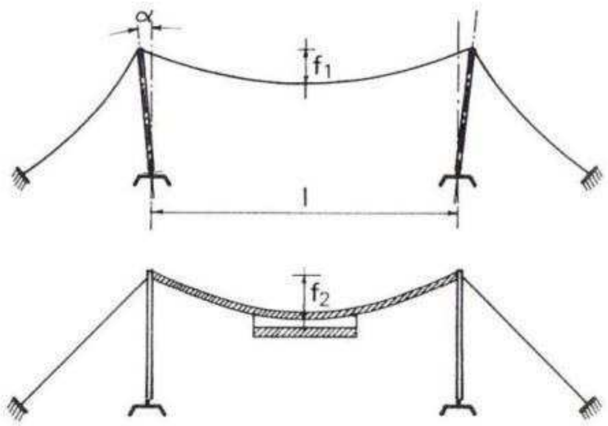
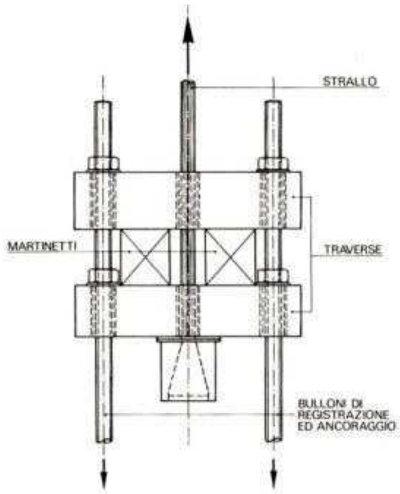
[27] Han Y, Wang J.Y. & Feng Z., 2008, *Two span cable crane in erection of large scale arch bridges,* Long arch bridges, Chinese-Croatian joint colloquium, Brijuni Islands, 10-14 July 2008

The pulling cables are arranged along the forward and backward direction of the traveller, which are generally pulled by a single cable. If the two-point hoisting is utilized the two travellers should be connected by steel rope which is spaced at the same distance with the two hoisting positions. The pulling cables are driven by their own windlass at the two side banks. As the pulling undergoes at one side, the pulling cables at that side should be tensioned while the ones on the other side should be loosened. When the hoisting centre is close to the pylon, the double-cable method can be used, which means that a corner block with one gear or some secondary pulling equipment can be set in front of the traveller. [28]

The stay cable and the back cable can be anchored to the pylon independently. They can be separated cables that are both anchored to the anchorage beam at the top of the stay pylon. They are tensioned at the top of the pylon and can control the force directly from there, but the tension in this high tight space at the top of the tower causes some difficulties for workers.

The other way would be to adopt spandrels on the top of the pylon and have the cable anchored at one end of the erected arch that goes through and over the spandrels and turns around to become back cable which is finally anchored to ground anchorage.





4. 30 Hoisting system
4. 31 Recording device

Using suspension geometry, the cable-stayed cantilever structure is influenced both by thermal and elastic variations and with the lengthening of the wires due to the continuous increase of load Fig. 4.30): for this reason the anchor piers must have a recording device (Fig. 4.31) that should disarm the precedent wire after the subsequent installation.

[28] Chen B., 2009

Pylon and tower:

The pylon or tower for the stay cables is a temporary structure and can be made by universal steel members like the Bailey frame or the CFST columns.

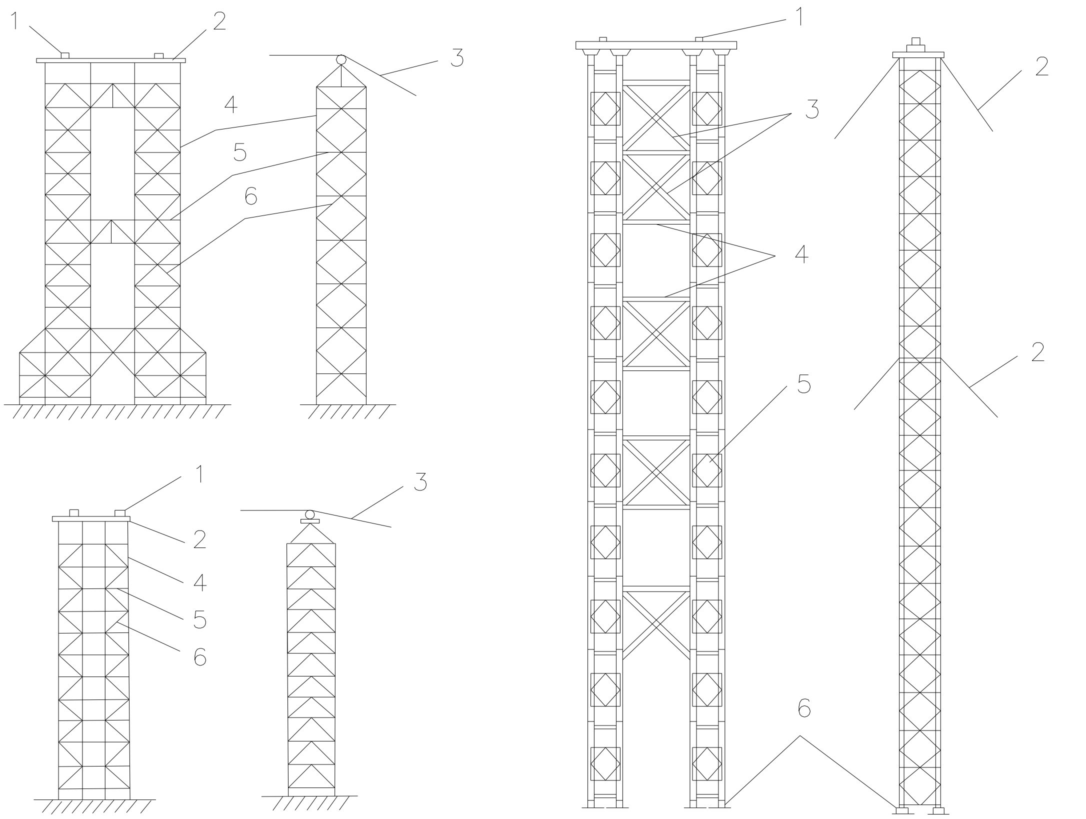
When the arch rib segments are hoisted up by the cable crane, the stay pylon and the main tower of the cableway can be set separately or can unit forming one. The cableway tower and stayed pylon have a similar structure, however the former one is higher.

The stayed pylon (Fig. 4.32) is fixed to a foundation in order to have sufficient stiffness for the aligment of the cantilever arch and to gurantee its safety against buckling, while the higher cableway tower can oscillate having hinges in its base to prevent large bending moment induced during the erection phase and its stability is provided by wind cables. If the stay pylon and the cableway tower are separated, the stay pylon generally stands on the spandral column on the arch seat, while in the case that they are united as one single tower, the cableway tower will stand over the top of the stay pylon with hinges.

4. 32 Stay pylon

The main tower of the cable crane consists of the tower tops, the tower bodies, the foundation, and the wind cables (Fig. 4.33). The universal member, Bailey truss or steel pipe members, are mostly used in forming the pylon. For a two-span cable crane system, the centre tower is often established in the river, where transversal wind cables are difficult to set, so the stability of the centre tower is the key issue. A detailed design based on the hoisting capacities, the wind resistance requirements and the ground bearing capacities must be carefully calculated and designed before the installation of the crane while the centre tower is always established and strengthened on the permanent piers.

Wind cables are the key issues for the hinged main tower in its stability against buckling. During the assembly of the main tower, at least two groups of wind cables should be installed with an angle of 30°- 45° from the ground, each set consisting of four ropes. After the completion of the main tower, formal wind cables should be installed at the top of the tower. Not only providing stability for the main tower but also carrying the various forces during the hoisting as well as controlling the displacement of the tower top. Therefore, the wind cables are an important component of the tower structure and should be considered and constructed very carefully.



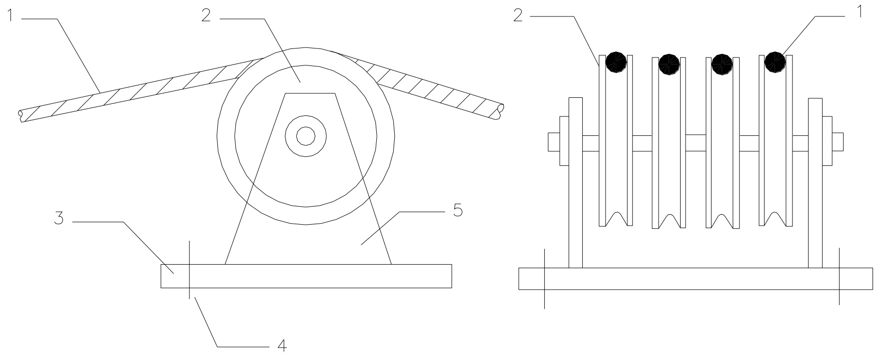
(a) Universal members (b) Bailey truss

In (a): 1.cable saddle; 2.beam cap; 3.main cable; 4.vertical prop; 5.transverse brace; 6.inclined brace;

In (b): 1.cable saddle; 2.wind cable; 3.main inclined brace; 4.transverse brace; 5.bailey truss; 6.support

4. 33 Main tower of Cable crane system

Saddles for main cables (Fig. 4.34), hoisting cables as well as stayed cables are set at the top of the cable tower. The main cable saddle that is generally adopted is the single pulley type with race width and depth slightly larger than the diameter of the main cable. The pulley has a diameter which is more than 15 times wider than the diameter of the main cable. The anchorage of the cable crane system transmits the forces from all of the cables towards the ground.



1. Main cable; 2.pulley; 3.padding plate; 4.braced bolt; 5.bearing plate;
4. 34 Main cable saddle

Before the formal hoisting, the cable crane system should be completely checked thoroughly in addition to a necessary trial hoisting. During the trial hoisting, continuous examination of the following items should be executed: the displacement at the top of the pylon, the sag and the forces of the main cable, the dynamical situation, the working behaviours of the pulling cable, the hoisting cable and the anchorage of the main cable. The communication, command delivery and the synchronization among various working groups should be checked during the trial hoisting. Analyses and improvement measures should be proposed after the trial hoisting has been carried out.[29]

Crane:

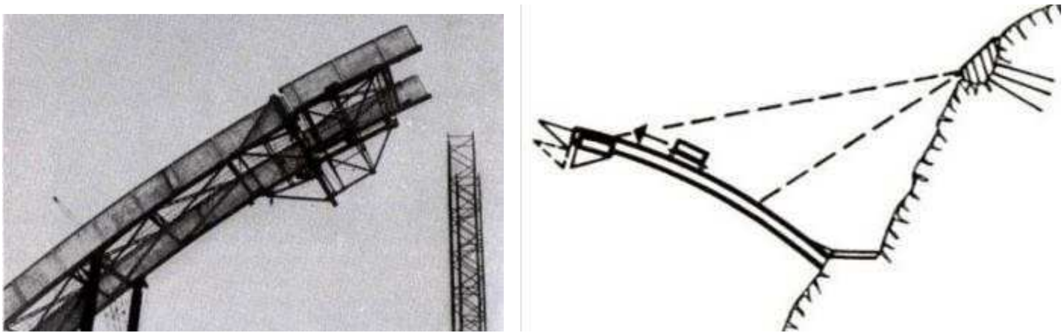
By means of lifting the Blondin and the cableway crane have the advantage of not burdening the arch with their weight while providing both sides to insure a parallel building.

The derrick, used in the cantilever construction, can lift blocks weighing more than even a 110 t; it can be installed directly onto the deck and onto the arch using a base frame adaptable to the variable slope of the extrados.

The position of the blocks could be performed by a carriage moving platform, as can be seen in figure 4.35.[30]

At its front end the carriage is supported with stays and anchored in bank piers, whilst on its rear end it is supported with prestressed bolts on the preceding segment. When the concrete is hard enough, hydraulic presses are used to carriage the slides to a new position. This procedure is repeated until the arch is eventually finished. The carriage system after the first two segments is a simply supported beam with an overhang. Loads from the segment concrete are transmitted to the preceding segments. Compression force is transmitted to hydraulic presses as the tensile force is transmitted to prestressed bolts.

[29] Chen B., 2009
[30] Nascè V., Dal Pont E., 1975



4. 35 Derrick system

Barge:
When a bridge is built to overpass a river, the transport becomes easier by means of barges that can offer more advantages such as not having weight restrictions, and freeing the construction of the bridge from access viaducts and positioning the yard at the foot of the bridge. When the installation begins from springs, the segments can be transported to the final position by using mobile carts (Fig 4.36).

4. 36 Barge

China
An example of a concrete arch bridge constructed with the free-cantilever construction method is the Jiangjiehe Bridge (Fig. 4.37), in Weng'an, Guizhou, China, with a span of 330 m and 55 m rise, completed in 1995. The shape of the Jiangjiehe bridge is a concrete truss arch and it was built using free-cantilever method. This style of arch bridge has become very popular throughout China with its signature "N" shaped spandrel openings. The upper chord and the inclined

member are prestressed during the cantilever erection. The deck contributes to the strength of the whole bridge acting as an upper chord.[31]

4. 37 Jangjiehe Bridge, Weng'an, China, 330 m span,1995

As an example of the cantilever construction method using cables and towers the Lupu Bridge[32] is one (Fig. 3.38). It was opened in 2003 with a main span of 550 m. It is 32 m longer than the former record holder, the New River Gorge Bridge in the Fayetteville, West Virginia, United States.

The Lupu Bridge is located in Shanghai, in the south of the city with the aim to ease congestion in the quickly developing areas around the southern side of the river and the city centre. It is a steel box section through tied arch bridge. The central span of the deck is suspended from two sets of 28 double cables, attached to the two inclined arches. The arches were constructed using a cable-stayed cantilever method. Each section of the arch was stayed back to the temporary towers at either side of the arch, after being welded to the previous section. This significantly reduces the bending stresses in the arch during construction and puts the constructed arch section into compression instead, as it would be upon completion.

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[31] Xie B., Yang Z., Liu Z., 2001, New development in Chinese Bridge technique, Proceedings of the Fourth International Conference on Arch Bridge, 19-21 Sept., 2001, Paris, France, pp.815-820

[32] Guiping Y., 2008, *Key technology for design of Lupu bridge,* Proceedings of the First Chinese-Croatian Joint Colloquium, Long arch bridges, July. 10-14 2008, Brijuni Islands, Croatia, pp. 431-438

Feng M., 2010, *Recent development of arch bridges in China,* Proceedings of the 6th International Conference on Arch Bridges, Arch'10, 2010, Fuzhou, China

4. 38 Lupu Bridge, Shanghai, China, 550 m span, 2003

The cables from the temporary towers to the ground are connected at the location of the foundations, that will resist the uplift on completion of the bridge. A mobile carriage was used to lift the arch and brace sections up from the river off the barges they were shipped to site on. The rib section size is not uniform. At the apex of the arch, the depth of the section is smaller than that at the springing points. This increase in depth allows the line of action of some load paths to stay within the arch section, reducing the bending moment induced in the arch itself. [33]

The main bridge of Chongqing, the Chaotianmen Yangtze River Bridge[34] (Fig. 3.39) is a half-through steel tied truss arch, with total a length of 932 m and a span arrangement of 190+552+190 m. Its main span is 2 m longer than the span record of 550 m of any steel arch bridge held by the Lupu Bridge in Shanghai. The Chongqing Chaotianmen Yangtze River Bridge has double decks. The upper deck is 36,5 m wide with six lanes and two sidewalks. The lower one carries two lines of light municipal railways and two other lanes to either side. The steel truss of side span is installed by means of cantilever method with the assistance of provisional supports; the steel truss in the middle span is installed using a sling pylon, by cantilever method, closed at center of the span.
The end span should be installed by cantilever method, on trestles and temporary piers. First of all, two panels of steel truss are installed on the trestles by means of a tower crane beside end pier; next, the erecting gantry is assembled on the upper chord of steel truss; then using this gantry to install the steel trusses in sequence with assistance of temporary piers from the end pier to middle one, using the cantilever method. While installing steel truss, some balanced weight should be used on the end span to make sure in having a stability coefficient.
The steel truss of the middle span will be installed by full cantilever method symmetrically with the assistance of sling pylon, and closed in the middle. The steel truss is installed initially and then the arch rib truss and hangers will be installed one by one until the middle of span is closed.
After the arch truss is closed, the temporary tie should be installed and stressed, and then the sling cables and sling pylon should be removed; erecting the gantry going backwards, the deck crane moves along the upper deck to install ties and upper crossbeams in sequence until the middle span is closed. The upper tie should be closed prior to the lower one; the provisional ties should be removed after a while. Then the deck crane goes backwards from the middle span to install crossbeams, plane bracings, and longitudinal girders of the lower deck, and install the upper and lower steel bridge decks. To eliminate the effect of integral-action of orthotropic steel plate and main truss, some temporary connection between the

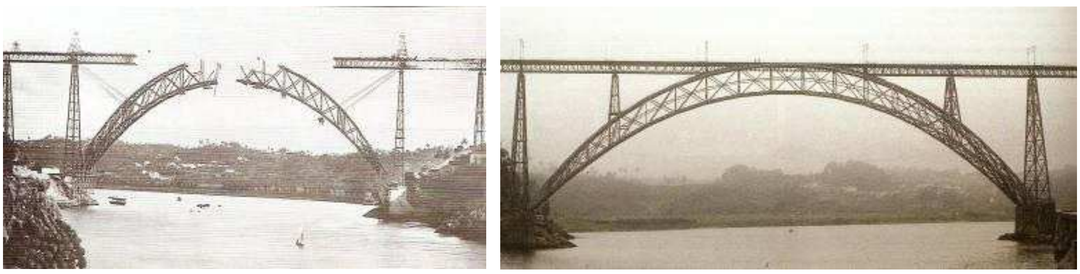
[33] Ellis L. J. H., *Critical analysis of the Lupu Bridge in Shanghai*, Bridge Engineering, 2° Conference, Spring 2007, Department of Architecture and Civil Engineering, University of Bath
Lin Y., Zhang Z., Ma B., Zhou L., 2004, *Lupu arch Bridge, Shanghai*, Structural Engineering International, Feb. 2004, pp. 24-26
[34] Duan X., 2008, *Design of main bridge of Chaotianmen Yangtze River bridge*, Proceedings of the First Chinese-Croatian Joint Colloquium, Long arch bridges, July. 10-14 2008, Brijuni Islands, Croatia
Duan X., Xiao X. and Xu W., 2010, *Design & technology characteristics of main bridge of Chaotianmen Yangtze River Bridge*, ARCH'10 – 6th International Conference on Arch Bridges, pp. 107-112

steel plate and crossbeam should be made; the permanent connection should not be done until all members are installed completely. The assistant cables are installed and stressed after all bridge members are completed. After the bridge is finished and the auxiliary facilities and pavement are completed, the forces in hangers and assistant cables must be adjusted to meet the design requirements.

4. 39 Chaotianmen Bridge, located in Chongqing, 552 m

World

The first utilization of this method can be seen in the construction of steel arch bridges: in fact the same construction procedures were first used in steel bridges and only later on applied to the concrete ones.[35] This is due the fact that, firstly, steel bridges began being built one century earlier than the concrete ones, and secondly, steel bridges are lighter, which makes constructing them easier, leaving more space for innovation. The following two examples are of the free-cantilever construction method designed by Gustave Eiffel (Fig. 4.40 and 4.41).

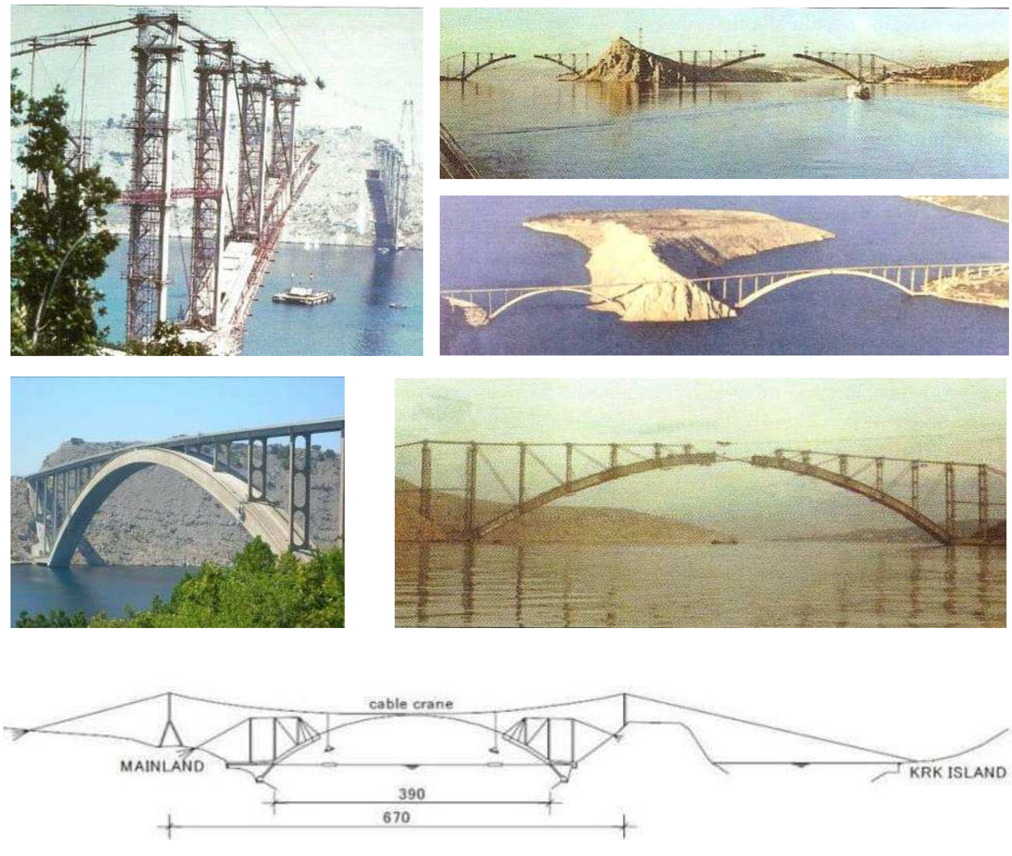


4. 40 Maria Pia Bridge, Duero River, Porto, Portugal, 160 m span, 1877, G. Eiffel

35 Tang M.C., 2007, *Evolution of bridge technology*, Proceedings of IABSE Symposium, Weimar 2007

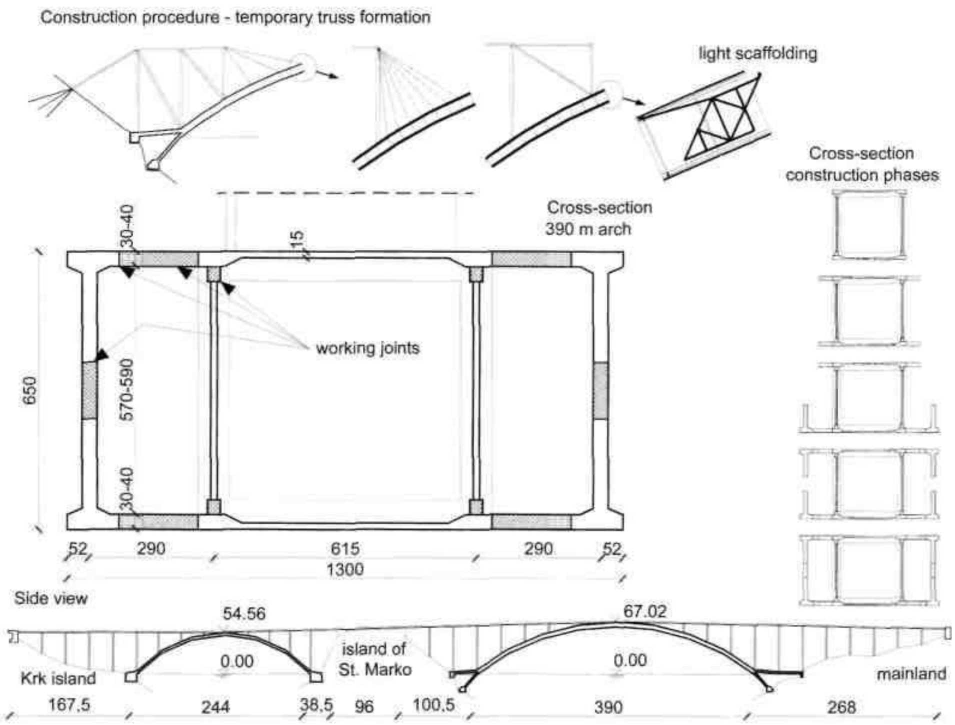
4. 41 Garabit Bridge, Gorge River, France, 166 m span, 1884, G. Eiffel

This method is used in the construction of concrete arch bridges too, and one example it is the Krk Bridge (Fig. 4.42). It is comprised of two reinforced concrete arches, the Krk I (390 m) and Krk II (244 m). The smaller arch is located between two islands – Krk Island and the St. Marc Island across the Windy Channel, while the longer one connects the Mainland to St. Marc Island crossing the Quiet Channel. The rise of Krk II arch is 47,5 m and the rise of the Krk I arch is 60 m. The Krk II arch is fixed to arch abutments on rock, while the Krk I arch is elastically fixed, with both its abutments fixed to the horizontal beams of triangular concrete structures beneath sea level. Both arches are made up of three cell box type cross sections with constant outer dimensions along the entire length of the bridge.



4. 42 Krk Bridge, Croazia, 390 m span, 1979, Eng. Stojadinovic

The shape and size of the arches were determined not only according to structural demands, but also taking into account the construction procedure, economical issues and aesthetics. Building the arches of constant outer dimensions had great advantages regarding prefabrication and assembly of arch elements. More than 60% of the larger arch and 86% of the smaller arch was constructed using precast elements. External webs of the box type cross section were designed as double T-section in order to achieve visual reduction of the arch depth along the whole length from the abutments to the crown.

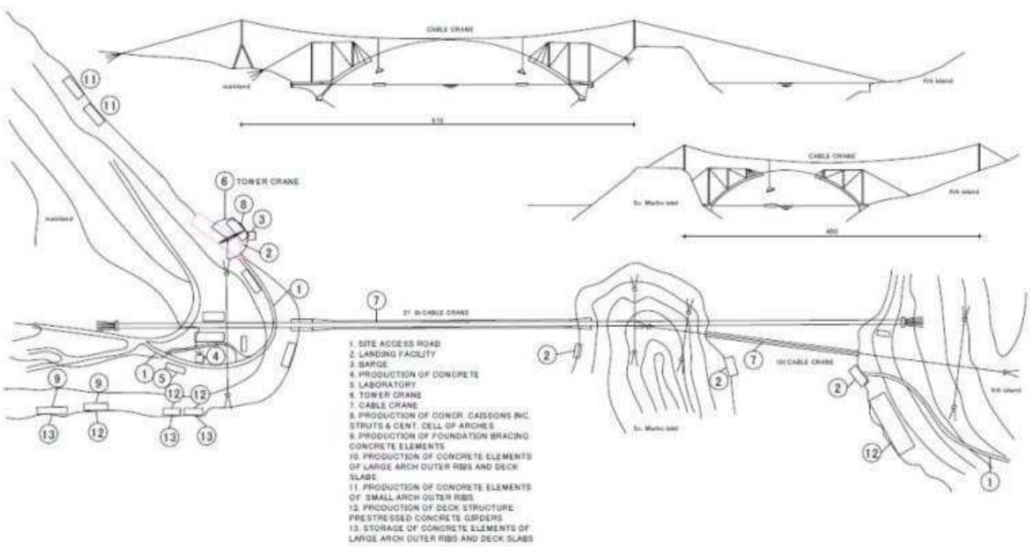


4. 43 Krk Bridge, Croazia, 390 m span, 1979, Eng. Stojadinovic
Construction method drawing of the Krk I bridge

The arches Krk I and Krk II of the bridge were constructed by cantilevering truss method (Fig. 4.43) and arch and spandrel columns above the arch were constructed simultaneously. The central arch part was erected first, after which it served as scaffolding for the subsequently built lateral arch parts.[36]
In the yard there were only two cable-cranes each of a 10 t capacity, available for local transport on site. Arc segments of the bridges were prefabricated on a barge, placed in position by cable-cranes and then assembled *in situ* by concreting “wet” joints.

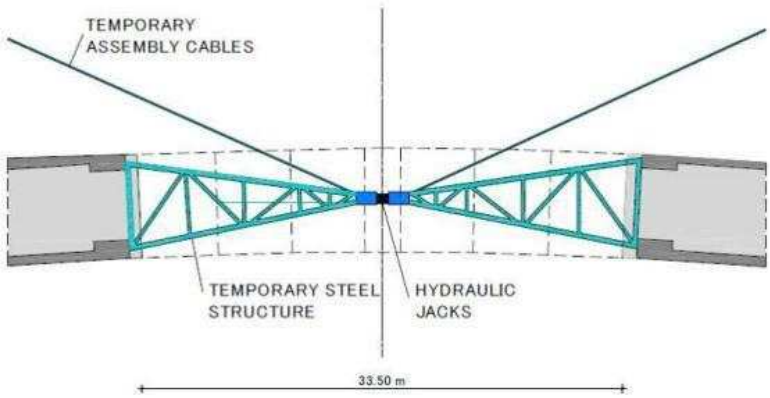
[36] Šavor Z., Šavor M., Srbić M., 2009, *Krk bridge from inception to today*, Proceedings of the Chinese Crotian Joint Colloquium, Construction of arch bridges, Fuzhou, 5-9 October 2009, pp. 377-395

The entire yard site was organized to facilitate the construction, concrete production and its transport, prefabrication, transportation and assembly of concrete elements and finally concreting of joints between precast elements (Fig. 4.44). An effort was made to use specialized equipment, such as cable cranes, barges and tower cranes, simultaneously for all the construction work, not only for the arches.



4. 44 Krk Bridge, Croazia, 390 m span, 1979, Eng. Stojadinovic
Construction site organization

The central cell of the arch was assembled first through cantilevering and when completed, served as load carrying element for suspended scaffolding and formwork for concreting side cells. The side cells were concreted after installation of hydraulic jacks at the crown (Fig. 4.45).

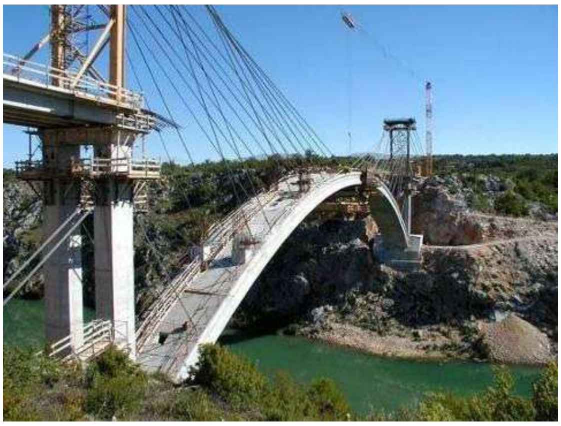


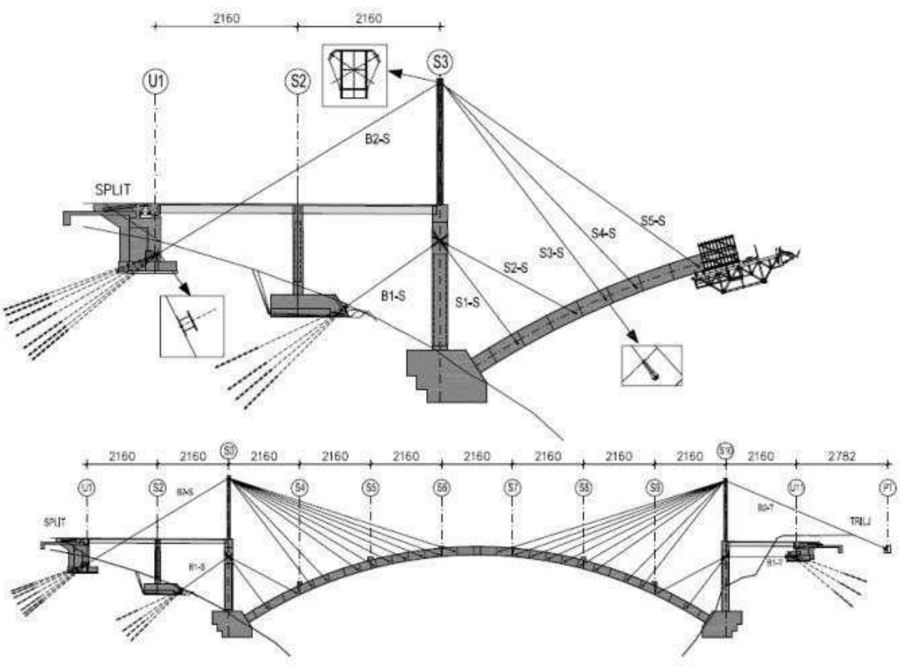
4. 45 Krk Bridge, Croazia, 390 m span, 1979, Eng. Stojadinovic
Steel trusses at arch crown

Elements were concreted on the shore or on large barges in horizontal position, therefore providing a good concrete quality and implementation precision. Precast elements were transported by a barge to a place reachable by cable cranes, which were then used for the erection and assembly of elements on cantilevered truss scaffolding. After positioning, they were fixed to the previous segment. After completion of the first few arch segments, the arch was tied by a diagonal stay to the top of the previous column and the temporary diagonal cables were then dismantled.
Several sections before the closure of the arch, two steel trusses were assembled by cable cranes to provide support for the installation of hydraulic jacks at the crown. Thus, the completion of the arch was speeded up, the mismatch between the two cantilevered ends could be corrected on time and stresses in all elements of the scaffolding, stays and spandrel columns decreased and vertical deflections of cantilevers were significantly reduced. Hence, the utilization of steel trusses significantly lowered construction costs.

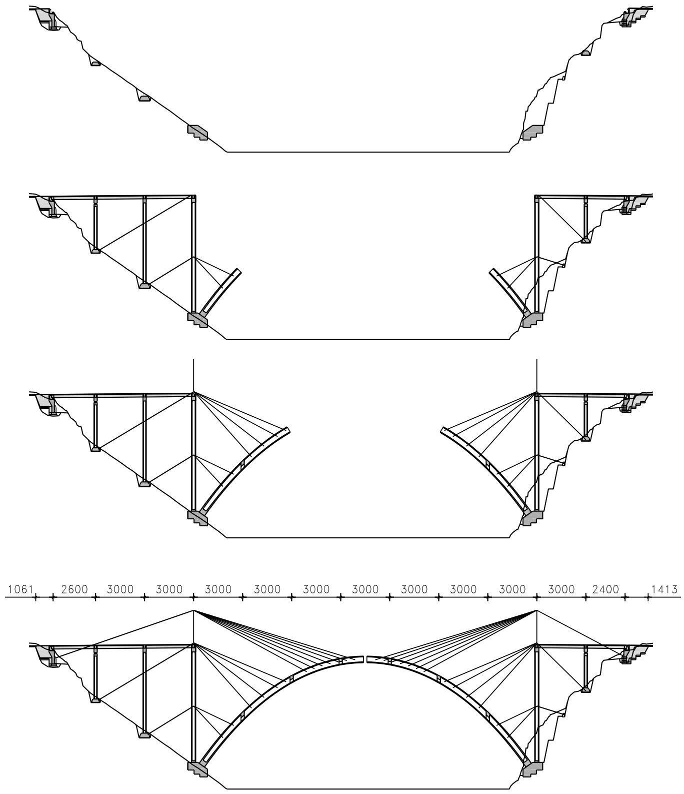
Another example is the Cetina Bridge[37] (Fig. 4.46), built in Croatia in 2007. In the first phase of its construction all foundations, including arch abutments, were completed. The columns on the river banks were constructed next, utilizing climbing formwork in segments 5 m long, followed by the construction of both bridge abutments.
The approach spans were completed by placing precast girders, and on-site concreting of the deck and cross-girders. At the same time the whole cross section of the arch was constructed by free cantilever, on travelling formwork carriages, in segments 5 m long, starting symmetrically from the arch springing. During construction the arch was supported by stays equilibrated by anchor stays, connected to rock anchors (Fig. 4.47). The 18,5 m high auxiliary steel pylons were erected on top of columns at the arch springing to facilitate the arch construction from the 3rd segment. A two-level suspension was used: the lower level stays were anchored into the columns at the arch springing, and the upper level stays were anchored in the cross-girder of the auxiliary steel pylon. The horizontal component of the forces in stays was equilibrated by back-stays connected to rock-anchors through transfer beams.
The construction of spandrel columns and superstructure above followed after the closing of the arch and after the removal of temporary stays and backstays.

[37] Žderić Ž., Runjić A., Hrelja G., 2008, *Design and construction of Cetina arch bridge,* Proceedings of the First Chinese-Croatian Joint Colloquium, Long arch bridges, July. 10-14 2008, Brijuni Islands, Croatia, pp.285-292
Žderić Ž., Runjić A., Hrelja G., 2007, *Design and construction of Cetina River arch bridge,* ARCH'07, 5th International Conference on Arch Bridges 2007, pp.745-750





4. 46 Cetina Bridge, Croatia, 2007, Žderić Ž., Runjić A., Hrelja G., construction phase and state of art



4. 47 Cetina Bridge construction phases

4.5 CFST

The CFST arch bridge can also be erected by the traditional cantilever method with cable crane. By the statistics, 67% of CFST arch bridges were built using this cantilever method and in the eight bridges with a span of no less than 300 m, there are seven of them that used this method.[38] However, with an increase of the span, the segment numbers and weight of the arch rib will increase also, and so too will the cantilever length of the stayed half arch as well as the height of the main cable tower. Ever more CFST arch bridges are being built. Innovation and technological progress in the cantilever erection technology has also developed significantly.

[38] Chen B., 2007, *An overview of concrete and CFST arch bridges in China*, 5th International Conference on Arch Bridges, Arch07, 2007, pp.29-44
Chen B., Wang T., 2009, *Overview of concrete filled steel tube arch bridges in China*, ASCE, May 2009, pp. 70-80

China

The Wuxia Yangtze River Bridge (Fig. 4.48) is a half-through concrete-filled steel tubular arch bridge with a main span of 460 m, which is the longest for this kind of bridge in the world, was completed in 2005.[39]

The main arch was constructed using the cable stayed cantilever method whereby a tower was erected on either side of the gorge and cables temporarily radiate out from it to support individual sections of the arch until the two halves could be joined in the middle. A cable high line was used between the tops of the two towers to move the steel sections into place. Once the arch was closed, concrete was pumped into the 8 main ribs of the arch span, stiffening and strengthening the entire structure.

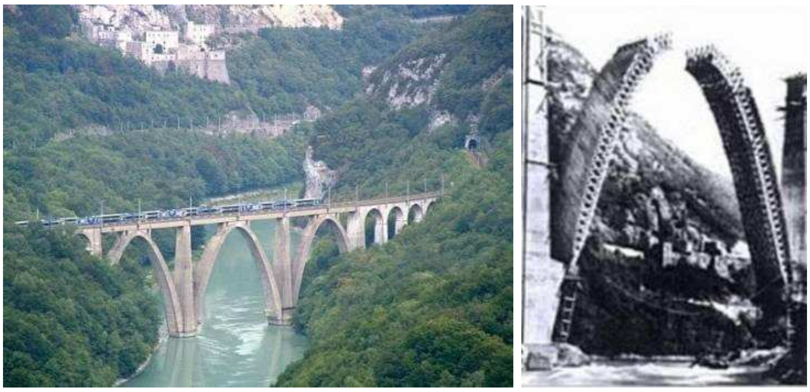
4. 48 Wuxia Yangtze River Bridge in Wushan, China, 460 m span, 2005

[39] Lu W., Sun Y., Zhang Z., Yu Z., He L., Wang M., 2007, *A key technique of construction for Wuxia Yangtze River Bridge*, ARCH'07, 5th International Conference on Arch Bridges, 2007, pp. 839-847

Mu T., Fan B., Zheng X., Zheng Y. and Xie B., 2007, *Wuxia Yangtze River Bridge in Wushan, China*, ARCH'07, 5th International Conference on Arch Bridges, 2007, pp. 911-918

4.6 Swing method

This procedure consists of building two semi-arches in a quasi-vertical position over the abutments and rotating them later on by means of a back stay, until closing them at the keystone. This method was first used in 1943 to build the wooden arches of the centering of the Longeray on the Rhone Viaduct (Fig. 4.49) with three concrete arches of a 69 m span each. It was also used to build the wooden arches of the centering of the Saboya Bridge (Fig. 4.50), also over the Rhone, of an 80 m span, that was built shortly afterwards.



4. 49 Longeray on the Rhone Viaduct, France, 1943, 69 m span, R. Breiffel, Gaston Le Marec, Medotte

4. 50 Centering for Saboya bridge in Bellegarde over the Rhone, 80 m span.

According to the rotation direction, the swing method can be classified into vertical swing method, horizontal swing method, as well as a combination of these two methods.[40]

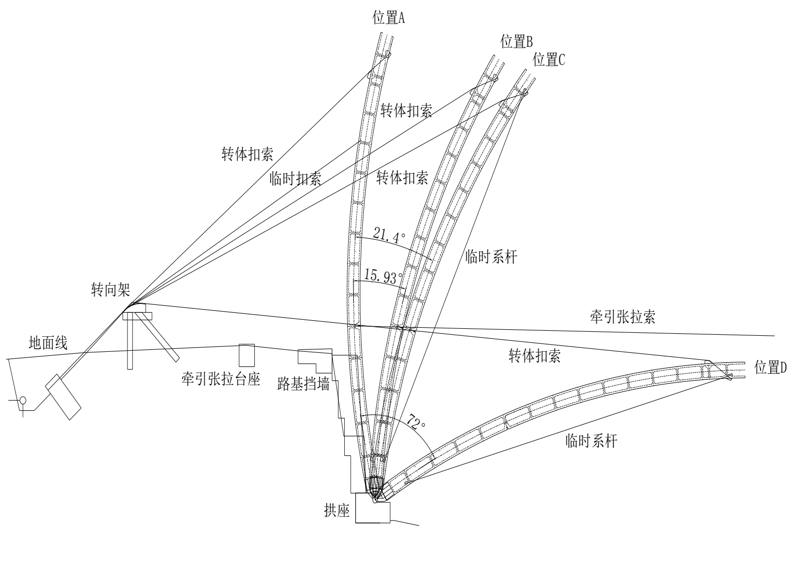
[40] Troyano L.F., 2004, *Procedures for the construction of large concrete arches*. In Arch Bridges IV Proceedings – Advances in Assessment, Structural Design and Construction, Barcelona, CIMNE, 2004, pp. 55-66.

Vertical swing

With this method, each half arch is cast along the arch plane separately, and then the completed halves are swung from the bottom.[41] If the half arches are built vertically on the spring and they are rotated from a high position to a lower position for closure the method is called as *downward vertical swing method*; while if the half arches are built near the spring level as a vertical curved beam and they are then rotated from a low position to a high position for closure the method is called as *lift-up vertical swing method*.

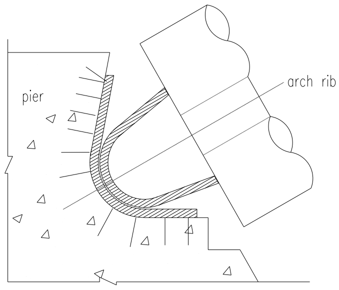
Downward vertical swing method

The semi-arches are built in a quasi vertical position over the abutments by means of a climbing formwork in the same way, just like the piers of a bridge are built (Fig. 4.51). The initial position of the semi-arches must be as vertical as possible in order to make their construction easier. It is convenient, for the stability of the entire structure, that the vertical force of the centre of gravity for both semi-arches remains initially outside the arch span, in order to use the overturning moment to support the semi-arches on the extrados. In order to perform the rotation of the semi-arches, hinges are placed at its base (Fig. 4.52), allowing for the rotation. Since the semi-arches are supported at their base by provisional hinges used to perform the rotation which has to be provisionally blocked in order to assure their stability during construction. Afterwards a hinge has to be placed at the keystone, in order to allow the completion of the initial three-hinged arch.



4. 51 downward vertical swing method

41 Chen B., 2009, *Construction methods of arch bridges in China*, Proceedings of the Second Chinese-Croatian Joint Colloquium, Construction of arch bridges, Oct. 5-9 2009, Fuzhou, China, pp. 1-192



4. 52 Hinge at the abutment

The first problem that could be encountered during the construction phase is the rotation stability, and the second one is that the hinges have to permit for the corrections in the plan and the elevation of the position of the semi-arches once they have to be rotated, in order to make sure the final direction is correct. This is achieved by placing horizontal jacks between the hinges at the base of the arch, and the foundations.

To begin the rotation, the arch has to be launched using jacks, fixed to one end of the already built deck, while on the other side they are attached to the arches. This is because the semi-arches in their initial position are overturned towards the exterior of the arch. These jacks allow for the moving of the semi-arches until they reach the vertical axis of their centre of gravity. In fact this position permits them to be rotated using their own weight while held by the stay.

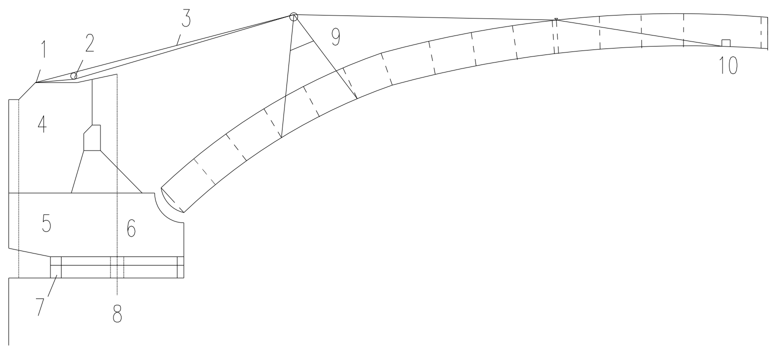
Lift-up vertical swing method

The lift-up vertical swing method is suitable for bridges crossing over smooth, shallow-water rivers or roads. Along the longitudinal direction, the arch is divided into two halves; each one fabricated from the abutment with low scaffold. Once finished, hoisting machines and cables are used to rotate and lift the halves to their designed position.

As the projections of the two halves are longer than the real arch span, this method does ot allow for the lifting of two halves simultaneously, one half is lifted after the other one is in position. The vertical swing system is usually composed of ribs, cable support tower, cables, dragging system and balancing system. For high towers, the lifting angle is relatively small; consequently a smaller lifting force is required. However, a higher tower means a higher slenderness ratio: the stability of the tower is an issue therefore more material should be used. A cable saddle, a working platform, knotted rope, and balancing cables are assembled on the tower. The balancing cables should be prestressed according to the lifting load before the lift-up swing. To make sure the rib can swing around the arch abutment, rotating facilities are necessary at the abutment and at the crown of the arch. Lubricant oil is applied between the two thick parabolic steel plates as to reduce friction. After the ribs are lifted into position, they are then adjusted and welded together.[42]

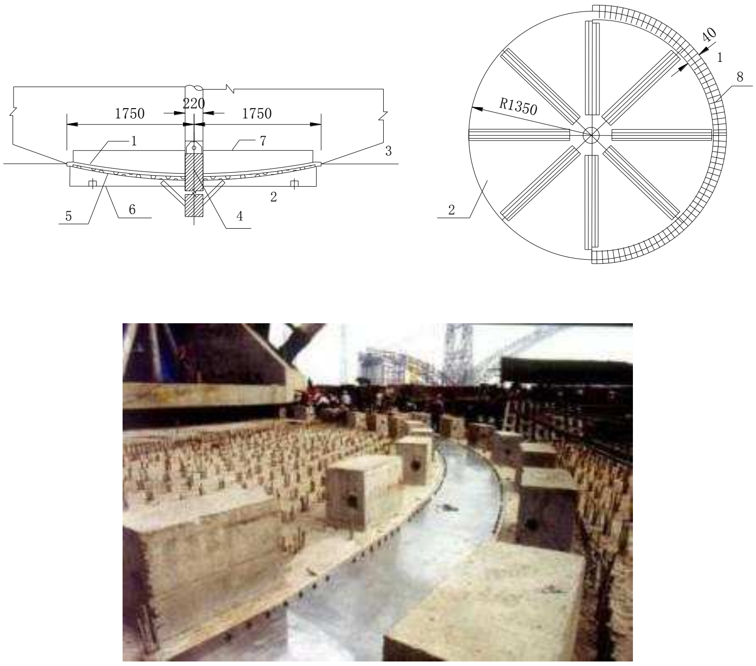
Horizontal swing:
The fabricated semi-arch and the counterweight abutment on the rotation disk are rotated horizontally around a pivot and a preinstalled Teflon ring-like slide until closure position is reached.

Counterweight horizontal swing[43]
The balanced horizontal swing system is composed of a balancing system, a rotating system (axis and rotating pass) and a displacement control system (Fig. 4.53). For the balanced swinging of single span arch bridges, the stay cable is fixed to the abutment; the upper infrastructure has a long lever arm but lower weight while the abutment is the is the other way around.
The rotating system (Fig. 4.54) of the horizontal swing method is mainly composed of rotating support and the rotation dragging system: the rotating support is the critical facility of horizontal swing method. It is composed of an upper turn plate, a lower turn plate and the axis. The upper turn plate supports the rotation of the structure and the lower one is fixed to the basement. The axis is the centre of rotation, directly affecting the stability and the rotation moment, requiring accuracy, high strength and smoothness.
The horizontal swing method uses the relative motion between the upper and the lower turn plates. The support must perform functions such as rotating, load bearing and balancing. According to the balance condition of the horizontal rotation, the rotated structure can be supported by the center of the millstone that supports the entire rotating weight.



1.tail cable; 2.anchor beam; 3.stayed cable; 4.counterweight; 5. upper turn plate; 6.axis; 7.loop road; 8.center support; 9.steel scaffold; 10.anchor slot
4. 53 Counterweight Horizontal swing method

[42] Chen B., 2009
[43] Chen B., 2009

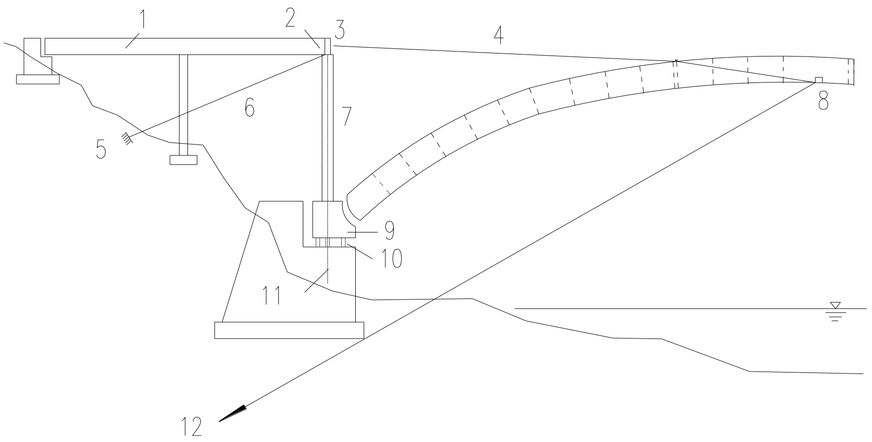


1. spherical hinge face; 2.lower turn plate; 3.lower turn plate surface;
4. rotation center line; 5. Tetraf sheet; 6.stiffener; 7.stiffner rib;
8.uni-distributed 138 of M8 wire hole with 15mm in depth
4. 54 The rotating hinge

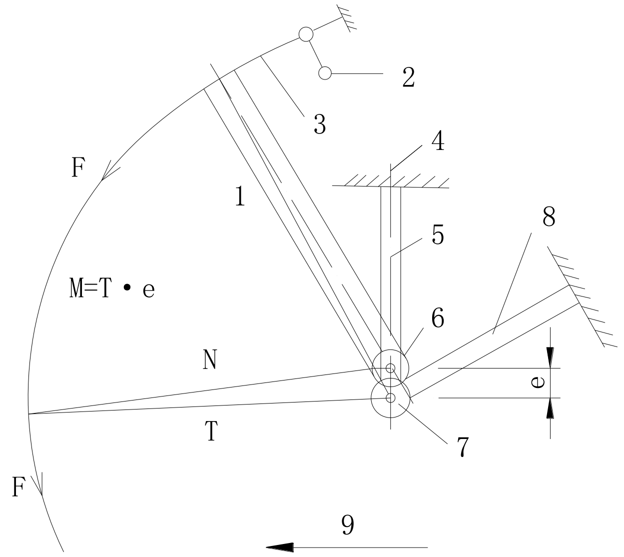
Non-counterweight horizontal swing[44]

The end of the half arch rib is stayed by cable that is anchored to the anchor beams (Fig. 4.55 and 4.56). The anchor beam, with a rotating inner axis, is placed on the abutment or on top of the pier, and anchored to the ground by back cable and supported by reinforced concrete beams at its top. The back cable was usually made of deformed steel bars or high strength wire cables. One end of the back cable is connected to the guy anchor and the other end to the anchor beam via horizontal brace, to pass tensile force. With the rotation of arch rib, the forces in the cables stayed will be adjusted automatically. In order to reduce the rotation weight, the arch rib usually without the upper flange as an open box (U-shape section), is fabricated and rotated. After the two half arches are united at the crown, the upper flange is cast-in-situ to form a closed box section. Finally, the gap between upper and lower turn plates is filled with concrete, and cables stayed are removed. [45]

[44] Chen B., 2009
[45] Zhang L. Y. and Chen J., 2001, *Application and development of the Rotation Construction Method of Arch Bridges in China*, Proceedings of the Fourth International Conference on Arch Bridge, 19-21 Sept., 2001, Paris, France, pp.883-888.
Xie B., Yang Z., Liu Z., 2001, New development in Chinese Bridge technique, Proceedings of the Fourth International Conference on Arch Bridge, 19-21 Sept., 2001, Paris, France, pp.815-820



1.approach girder; 2.anchor beam; 3.upper shaft; 4.stayed cable; 5.anchor; 6.back cable; 7.vertical prop; 8. anchor slot; 9.upper turn plate; 10. loop road; 11. lower shaft; 12.guy cable (traveling rope of arch ring rotation)
4. 55 Non-counterweight horizontal swing method



1. fabricated arch ring; 2.winch; 3.guy rope; 4.bridge axis; 5. horizontal support beam; 6.lower turn plate; 7.upper turn plate; 8.inclined support beam; 9.water flow direction; N axial force of arch rib; T---force of stayed cable; e---eccentricity
4. 56 Plan sketch of non-counterweight horizontal swing system

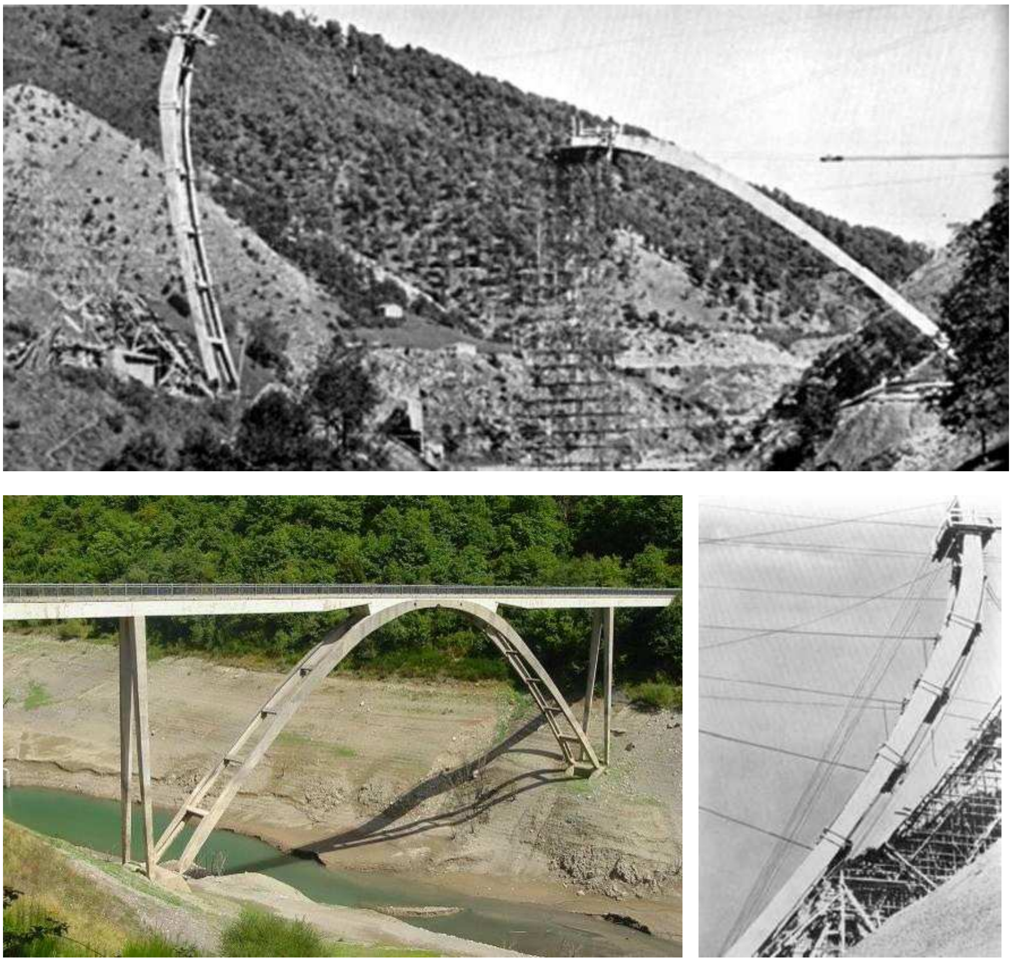
Vertical and horizontal swing

In the hybrid swing method, the semi-arch ribs are firstly fabricated in a low position and then hoisted up to design height and finally rotated horizontally to the bridge axis and interlinked by the crown segment to form an arch.[46]

[46] Chen B., 2009

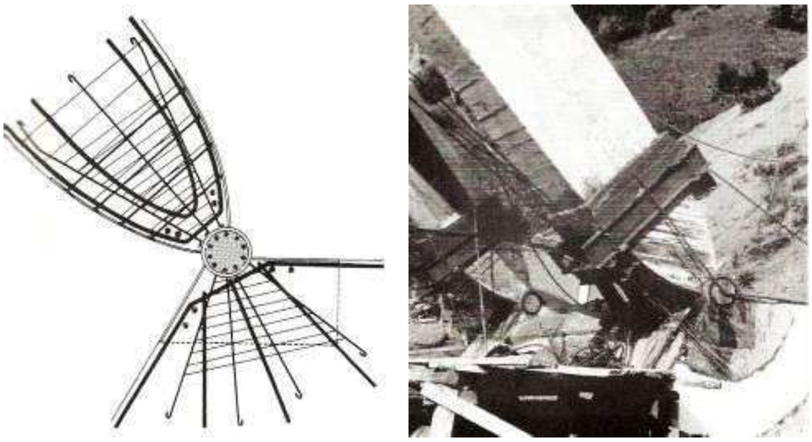
Italy

The first engineer to use a procedure similar to the free rotation of the semi-arches in a concrete bridge, was Riccardo Morandi (1902-1989) on the Torrente Lussia Footbridge[47] in Italy (Fig. 4.57), with a 70 m span, that was completed in 1953. The structure is a three-hinge arch bridge. The construction of an arch centering would have been too expensive in this case due to the characteristics of the location. The semi-arches of the footbridge were built on the riverbank and then they were rotated on two hinges at the abutment until the ribs were supported on a central tower, that was removed once the arch was closed (Fig. 4.58).



4. 57 Lussia Footbridge, Valle di Sotto, Lucca, Italy, 70 m span, 1955, R. Morandi

[47] Imbesi G., *Riccardo Morandi*, Gangemi Editore, Roma, Italy
Masini, L.V., 1974, *Riccardo Morandi*, Roma, Italy
Benvenuto E., Boaga G., Bottero M., Cetica P.A., Gennari M., 1985, *Riccardo Morandi: ingegnere italiano*, Firenze, in *Realizzazioni italiane in cemento armato precompresso*, a cura dell'AITEC, supplemento straordinario al n.5, maggio 1962, de "L'Industria Italiana del Cemento", 1962



4. 58 Lussia footbridge: hinge at the abutment

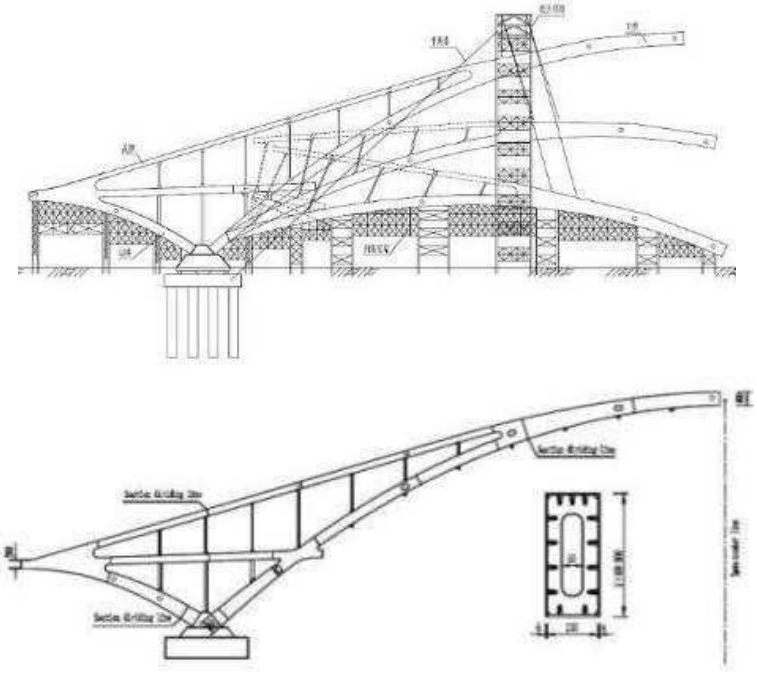
China

There are several concrete arch bridges in China that have recently been constructed using the swing method.

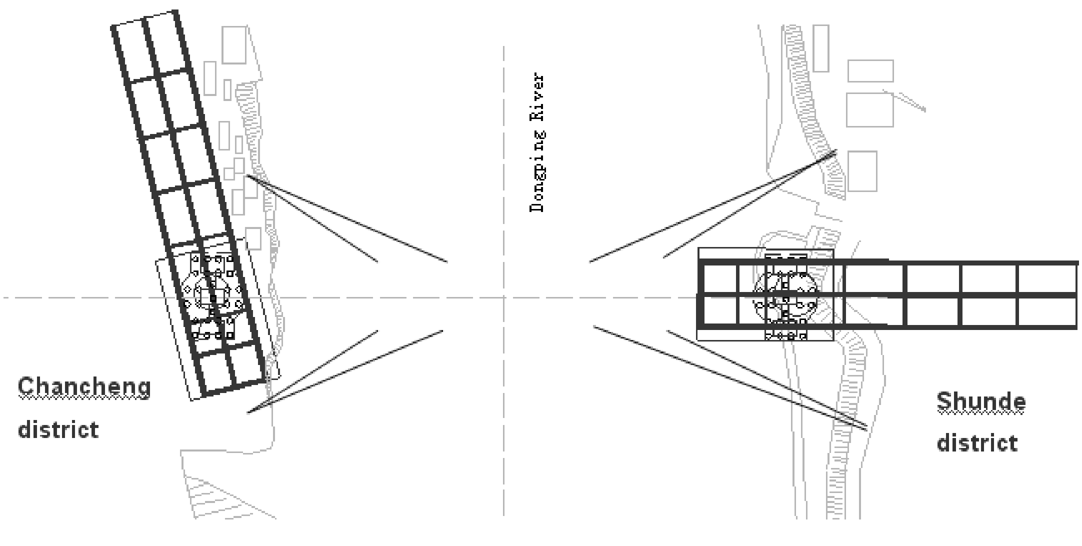
An example of the horizontal rotation construction method is represented by the Dongping Bridge[48]. The total span of the Chinese bridge is 578 m and the main span is 300 m. The main bridge is a cooperative-system steel box tied arch bridge with prestressed concrete continuous beams. The bridge was constructed using the vertical swing rotation method (Fig. 4.59) with subsequent horizontal rotation (Fig. 4.60). The main arch rib consists of a main arch and a sub arch. The sub arch serves as a self-balanced system during the rotation construction. The side span steel structure was assembled on the scaffolding and the half arch, in the central span, was assembled in low scaffolding near the ground as a beam. The assembled half arch rib was lifted to its designed elevation by means of a lifting tower and hydraulic system. Then, the sub arch and tie rod box were closed and the vertical rotation articulation was rigidly fixed. Before horizontal rotation the hoisting tower and balancing cable were taken down. After the central half arch was lifted to the designed elevation, the sub rib and the tied bars, in deck level between the central span and the side span, were connected together. Then the hoisting tower and lifting cables, as well as the backstays, were dismantled. Thus, a horizontal swing unit on each river bank was formed and prepared for the horizontal swing. No

[48] Tian Z., Zhang L., 2008, *Construction and construction monitoring of steel box arch bridges*, Chinese-Croatian Joint Colloquium Long arch bridges, Brijuni Islands, 10-14 July 2008, pp. 455-462
Fan B.,. Mu T, Liang J., 2007, *Researches on key techniques of Dong ping Bridge in Fuoshan City, China*, Proceeding of the conference: Arch'07, 5th International Conference on Arch Bridges, pp. 903-910
Tian Z., Peng T., Ma F., Ding Y., Zhang L., 2007, *Dynamic control technique research of Dongping bridge during the rotation stage,* ARCH'07, 5th International Conference on Arch Bridges, pp.799-805

auxiliary cables nor temporary tower were needed to form a horizontal swing unit, because the sub rib could connect the half arches of the central span and the side span together.



4. 59 Vertical lifting and self counterweight structure



4. 60 Sketch of the horizontal swing phase

The two units were rotated horizontally one by one and the two half arches were united together by the crown segment (Fig. 4.61).

4. 61 Dong ping Bridge, China, 2006, 300 m span, construction phases

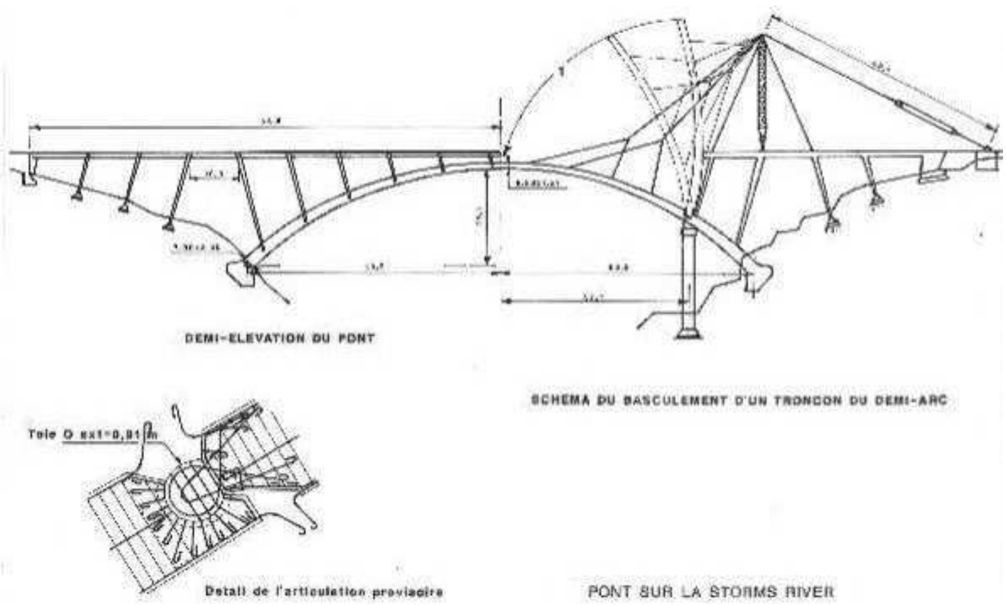
World

In 1954 Riccardo Morandi used the system of rotation until closure at the keystone for another project: the Storm River Bridge in South Africa (Fig. 4.62). This was a 100 m span arch. The semi-arches were built in a quasi vertical position over the abutments and were then rotated simultaneously until they were closed at the keystone without the use of a provisional tower (Fig. 4.63).

The Storm River Bridge is unusual for the fact of having inclined spandrel supports that radiate out from the main arch rib. The approach supports are also inclined in the opposite direction, balancing out the profile of the entire bridge. The use of inclined supports is a typical Morandi trait that is visible in nearly all of his bridges.

In this particular project, Morandi built the two sites of the arch vertically above the foundations with a climbing formwork on either side of the canyon. The two sides were then carefully tilted outward over the gorge until they met at the crown.

4. 62 Storm River, South Africa, 100 m span, 1953 - 1956, R. Morandi



4. 63 Storm River Bridge: construction drawing

The same method is used for the realization of steel arch bridges and an example of this is the Alconetar Bridge (Fig. 4.64), completed in 2006. The entire length of each half span was built vertically above the foundation and then carefully lowered out over the river and finally closed at the crown.

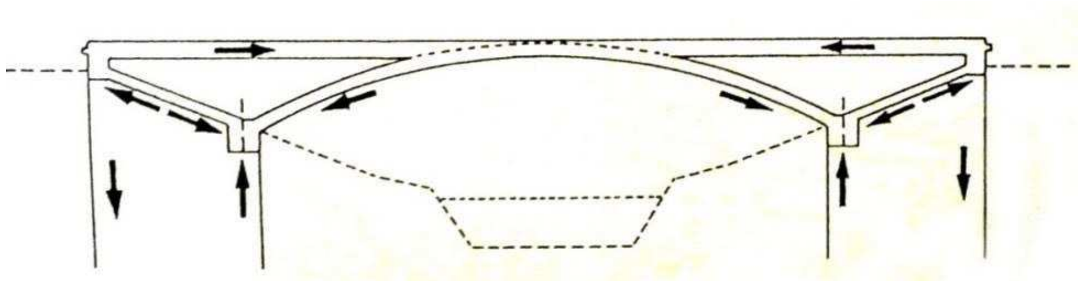
4. 64 Alconetar Viaduct, Spain, 2006, 220 m span, J.A.Llombart, J. Revoltós, S. Couto

4.7 New construction methods for small and medium span bridges

As we have seen, the construction techniques for long spans have already been well developed with procedures that are becoming ever more economical and safe. However the same thing cannot be said for what happens to small and medium-size spans that are generally considered minor works, but do in fact represent the vast majority of new projects.[49] The frequent neglect regarding the arch because of

[49] Siviero E., Cecchi A., 1994, *Un ponte ad arco di moderna concezione*, pp. 177-189, in *Il progetto del ponte*, a.c.d. Siviero E. con Casucci S. e Cecchi A., Architettura e strutture – Collana diretta da E. Siviero, n°6, Ed. Biblioteca di Galileo, 1994
Siviero E., Bullo S., Di Marco R., 2001, *Concezione dei ponti ad arco in calcestruzzo armato e precompresso – the conception of arch bridges in reinforced and prestressed concrete*, Convegno *The World of Brid*ges, aprile 2001, IUAV, Venezia.
Siviero E., Ceriolo L., 1996*, Utilizzazione di calcestruzzi ad alte prestazioni per il progetto di*

construction costs (see Chapter 3 *State of art* in the section dedicated to Italian arch bridges) have seen a new renaissance in recent years thanks to the use of construction methods that allow a quick implementation and permits the project site to acquire its very own identity and value. Therefore, the arch shape can be considered competitive in cost when compared to the beam that must be revisited thanks to the opportunities provided by new high strength materials and prefabrication.
If what happens at every stage of the assembly phase is studied properly and if prestressed materials are used, therefore consenting easier transportation and assembly of the bridges, which from the economic point of view should not be considered excessive in relation to any other type of girder bridge, but at the same time gaining a certain quality of composition at the place of execution.



4. 65 Evolution of Maillart's arch bridge typology, diagram of the flow of the forces

The structural design of the bridge incorporates the idea of Maillart closed bridge, but with a new revaluation in typology: the much shallower arch is structurally integrated to the foundations and the deck, a solution which offers considerable aesthetic and architectural advantage, with its slender elements of concrete and its lower arch creating a particular shapely overall effect (Fig. 4.65). Low arches have the problem of horizontal thrust, which in this case is absorbed by the deck that works as a tie-beam. The action of deck chain is absorbed by foundation system. The structure appears rigid due to the closed system. In this way the centering for the construction of the arch is removed and the elements that constitute the semi-arches are placed at the same time side by side having a static scheme with three hinges and a provisional support in the river. The deck is created with casting concrete above the precast elements and the arch is also empty in the tympanums, creating a light and permeable shape.[50]

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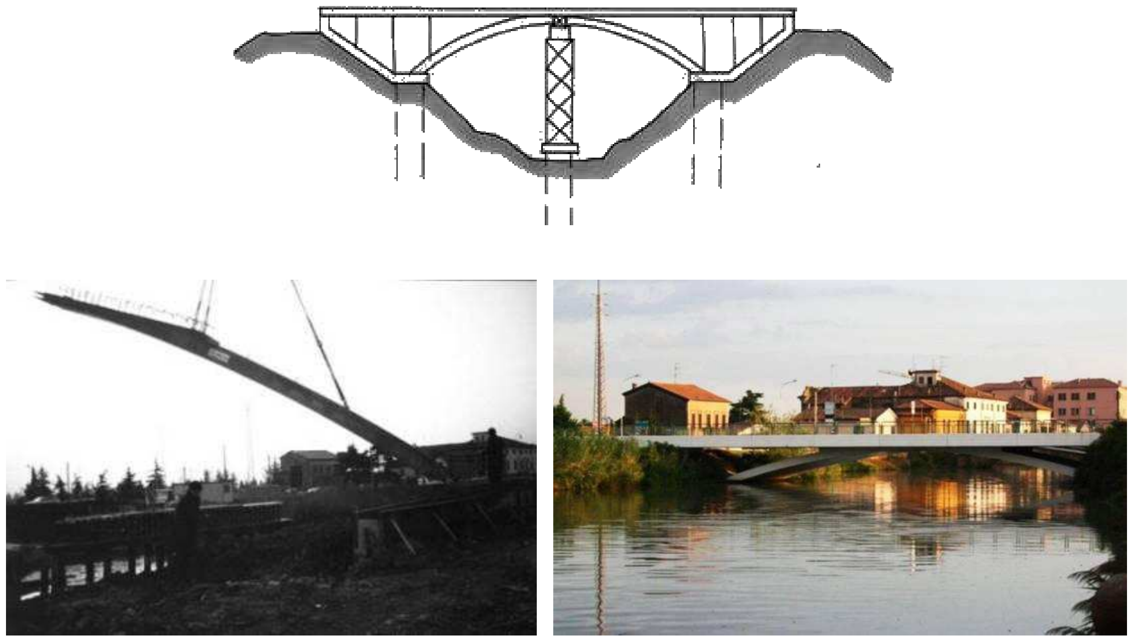
una passerella ad arco, 11° congresso CTE nuova tecnologia edilizia per l'Europa, Napoli 7-8-9 novembre 1996
[50] Bullo S., Di Marco R., Siviero E., Zanchettin A., 2005, *Nuove proposte per la realizzazione di ponti ad arco di piccola e media luce in cemento armato ed a struttura mista*, pp. 71-94, in Arici M., Siviero E., *Nuovi orientamenti per la progettazione di ponti e viadotti*, Dario Flaccovio Editore, Palermo, 2005
Siviero E., Casucci S., 1995, *The evolution of Maillart's arch bridges: a prototype for the*

A valid example of this is the Battaglia Terme Bridge[51] (Padova) built in 1994 and designed by Enzo Siviero (1945). The project, surpassing the Battaglia Channel (Fig. 4.66), on a site of considerable historical and architectural interest, stemming from the need to find an alternative solution to the historical masonry arch bridge which was inadequate to cater for the increasing quantity of traffic, while attempting at the same time leave the outline of the old bridge unchanged, which was used as pedestrian bridge. The new bridge is characterized primarily by a very low arch.



4. 66 Battaglia Terme Bridge, Padova, Italy, 1994, 29,5 m span, E. Siviero

The prefabricated arch has a span of 29,5 m made by 2x6 semi-arches in reinforced concrete, combined and linked together at the crown and at the foundation. For the installation of the semi-arches, a support in the riverbed was used and the angles shaped by the arch were achieved through the mutual slip between elements along the axis of the bridge. The construction took place as follows: 1. positioning of the prefabricated semi-arches over a provisional central pier and during this phase the semi-arches acting as a simply supported beam; 2. dismantling of the provisional pier after the concrete solidification; 3. deck casting; 4. finishing of the bridge: in this latter phase, the bridge assumes the final static scheme, following the removal of all the supports and prestressing bars.

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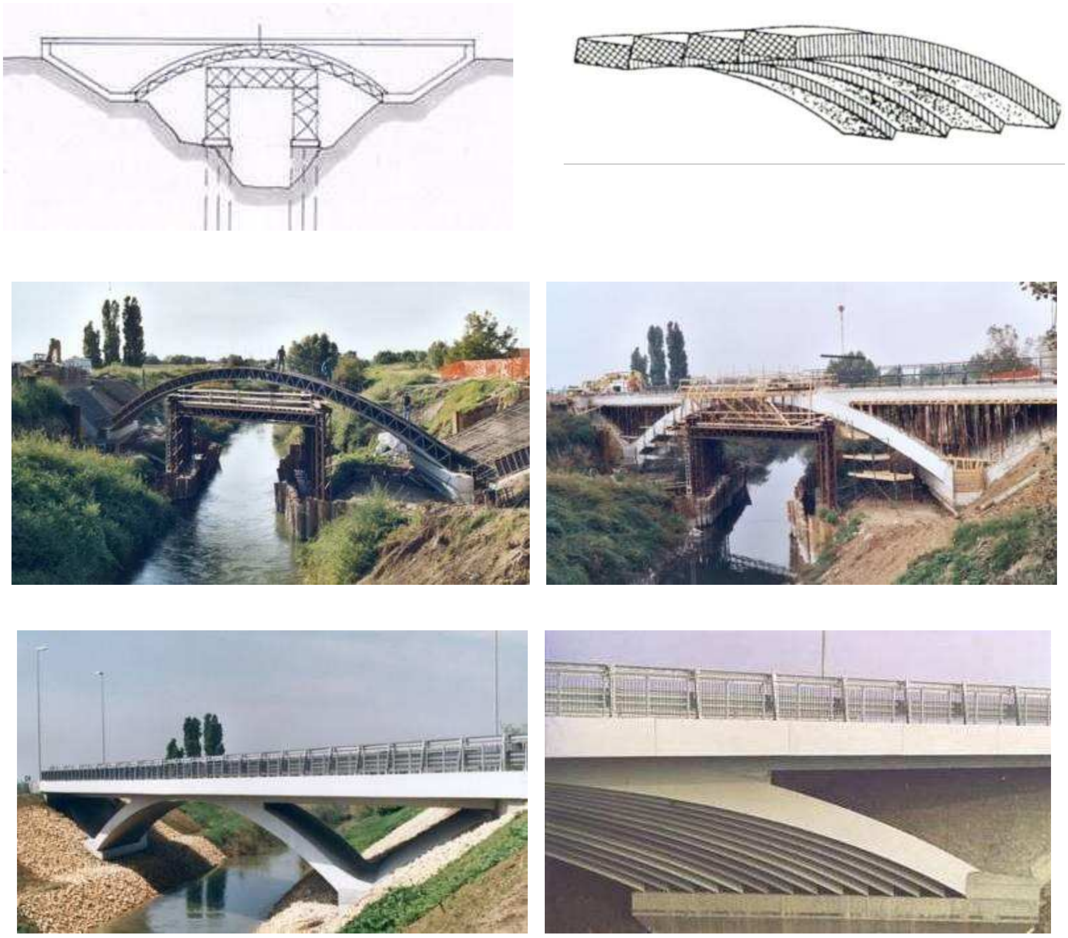
coming years, First International Conference on Arch Bridges, Bolton, U.K., 3-6 September 1995

Culatti M., Attolico L., Danieli N., Garghella P., 2006, *Ponti ad arco in calcestruzzo*, Rivista Strade e Autostrade 2-2006

[51] Siviero E., 2008, *Arch Bridges – Personal Experiences*, in Proceedings of Long Arch Bridges, Chinese-Croatian Joint Colloquium, Brijuni Islands, 10-14 July 2008, pp. 149-162

The St. Urbano Bridge[52] (Fig. 4.67), designed by Enzo Siviero and built in 2001, over the Santa Caterina Drainage Canal, in Padua, is an evolved design of the Battaglia Terme design. In this case there is a marked inclination of the axis of the artifact respect to the perpendicular level of the watercourse. The construction of the arch bridge has proceeded according to a precise procedure, that provides partial phases of construction corresponding to particular static situations. On completion of the foundations the installation of the half metal prefabricated arches followed and later on again the concreting casting.



4. 67 St. Urbano Bridge, Padua, Italy, 2001, 39 m span, E. Siviero

To construct the arch, the designer envisaged 14+14 prefabricated curved elements in reinforced concrete, each one making up half of the arch, arranged transversally

[52] Siviero E., Di Marco R., 2003, *Ponte sul canale Santa Caterina e viabilità connessa Sant'Urbano a Padova*, Rivista Strade e Autostrade, N° 1 – 2003
Bullo S., Di Marco R., Siviero E., Mingarelli P., 1999, *Un ponte ad arco realizzato con elementi prefabbricati: modalità di esecuzione ed effetto delle fasi costruttive sul comportamento strutturale*, Giornate AICAP 1999, Torino 4-6 novembre 1999

end to end, to make a single arch 7 meters wide, but shifted lengthwise in order to follow the strong slope of the arch axis with respect to the impost. During the construction, the half arches were positioned on two intermediate underpinnings. The arch was connected with the foundations and the deck, working jointly to counteract the thrust.
The bridge has a total length of 60.4 m with a central span of 39 m and 4.54 m rise.
The final visual outcome is a subsequent reinterpretation of the arch shape, that follows the inclination of the riverbank respect to the road axial, creating a series of staggered aches, that emphasize the width of the deck and the bridge structure.

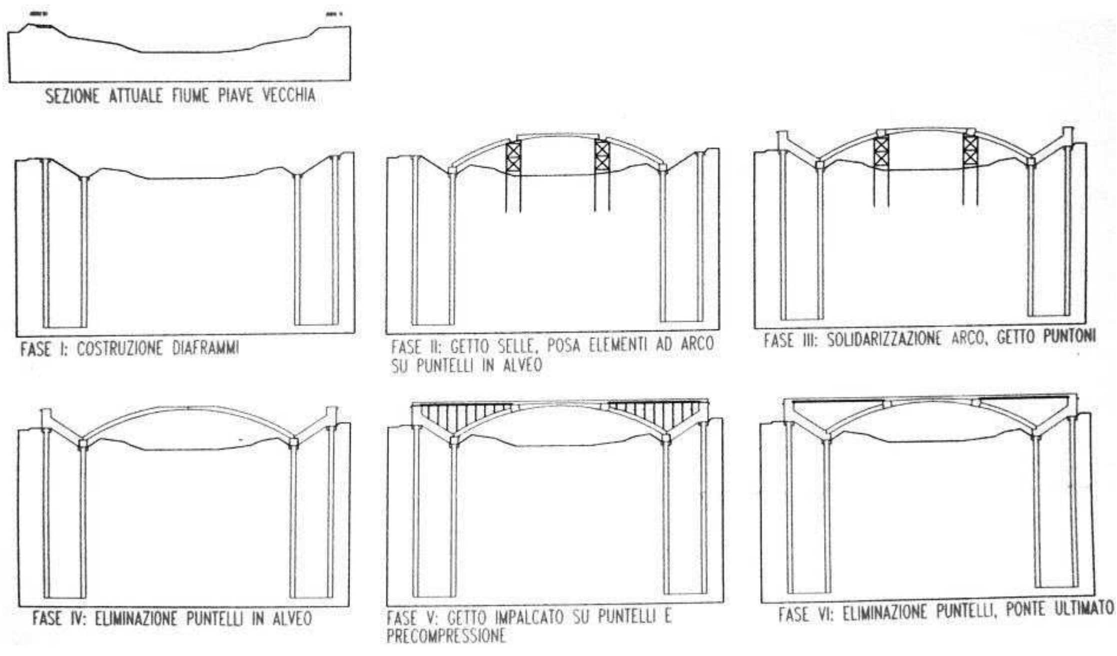
The construction of the bicycle and pedestrian Bridge of San Nicolò over the Bacchiglione River (Fig. 4.68), in Padua, was completed in 1998. This project had also affronted the issue of precast reinforced concrete construction. The arch is 42 m span and it is made up of 14+14 prefabricated semi-arches combined in order to obtain a single arch.

4. 68 Bicycle and Pedestrian Bridge at Ponte San Nicolò, Padua, 1998, E. Siviero

During the transition phase, before the final static arrangement was achieved, a provisional tie-rod system was used to contain the thrust generated by the three-hinged arch. On the completion of the bridge as a whole, and after the curing of

concrete, the cables connecting the springers supporting the arch were cut, thus transferring the load to the upper deck.[53]
The choice of the construction system, focused on the prefabrication of most of the structural elements, made it possible to launch the footbridge relatively quickly without the use of temporary supports in the riverbed.

Another interesting solution is represented by the Bridge over the River Piave Vecchia (Fig. 4.69), near Venice, erected in 2002 with the REP adoption beams. The final project of this bridge, designed by Flavio Zanchettin with the conceptual design of Enzo Siviero, spanning 63 m with an inferior 45 m lower arch, takes advantage of all the prior experiences, like in the Bridge over the Battaglia Channel, but with an innovative aspect consisting in the use of self bearing curved beams, according to the Italian patent REP[54]. These beams have a metallic plate at the bottom which substitutes the formwork for the cast of concrete. The bridge is constituted by 15 curved steel beams subdivided into three parts and sustained with two provisional piers in the river. The deck works as a chain and it is made of prestressed concrete. The use of the REP patent permitted to complete the assembling of the entire bridge in only 45 days.



53 Siviero E., Ceriolo L., Attolico L., 1999, *An arched r.c. Footbridge in the province of Padua*, Atti del 16th BIBM International Congress, Venezia, May 25-28, 1999.
54 Palaoro S., Siviero E., 2008, *Salvatore Leone e il brevetto n°805.383. La trave Rep compie quarant'anni*, Rivista Galileo n°185, maggio 2008, pp. 22-23

4. 69 Piave Vecchia Bridge, San Donà di Piave, Venezia, 2002, 45 m span, F. Zanchettin, E. Siviero

The Sgurgula Bridge[55] (Fig. 4.70), over the Sacco River, is part of the reconfiguration effort for the viability system following the laying down of the high speed railway going from Rome to Naples. The surroundings are particularly charming and is characterized by the presence of an ancient masonry bridge. The new bridge had not only to be functional in sustaining the high traffic levels of the area but also valid concerning its aesthetics and dialogue with its pre-existent. It was built in 2005.

This work, which spans 132 m and has two 56 meters long arches, can be considered a reasonably big span structure, even though it was built with the same easy and efficient techniques which were used successfully for smaller span bridges described above. Of course, this bigger size requires a more careful attention to aspects such as viscosity and high strength materials, but the structural system is basically the same, with the deck acting as a chain with the particular innovation of a tension member at the edge, set to verticalie as much as possible the arch’s thrust.

Each arch is formed by 20 precast elements, 0.50 m wide, set on provisional props and linked together with a finishing concrete cast. The number of provisional props is calculated in order to minimize the cost of erection and transport. At the mid span of each arch, the deck slab is connected directly to the arches or to the ribbed elements of various heights supported by arches. In line with the abutments and the pier, the deck is set on prefabricated upside-down T beams placed side by side. At the abutment ends of the deck, tie-rods are installed to balance the effects of eccentricity between the thrust of the arch and the chain action of the deck. The erection process foresees the use of a provisional chain, when just one of the arches is assembled.

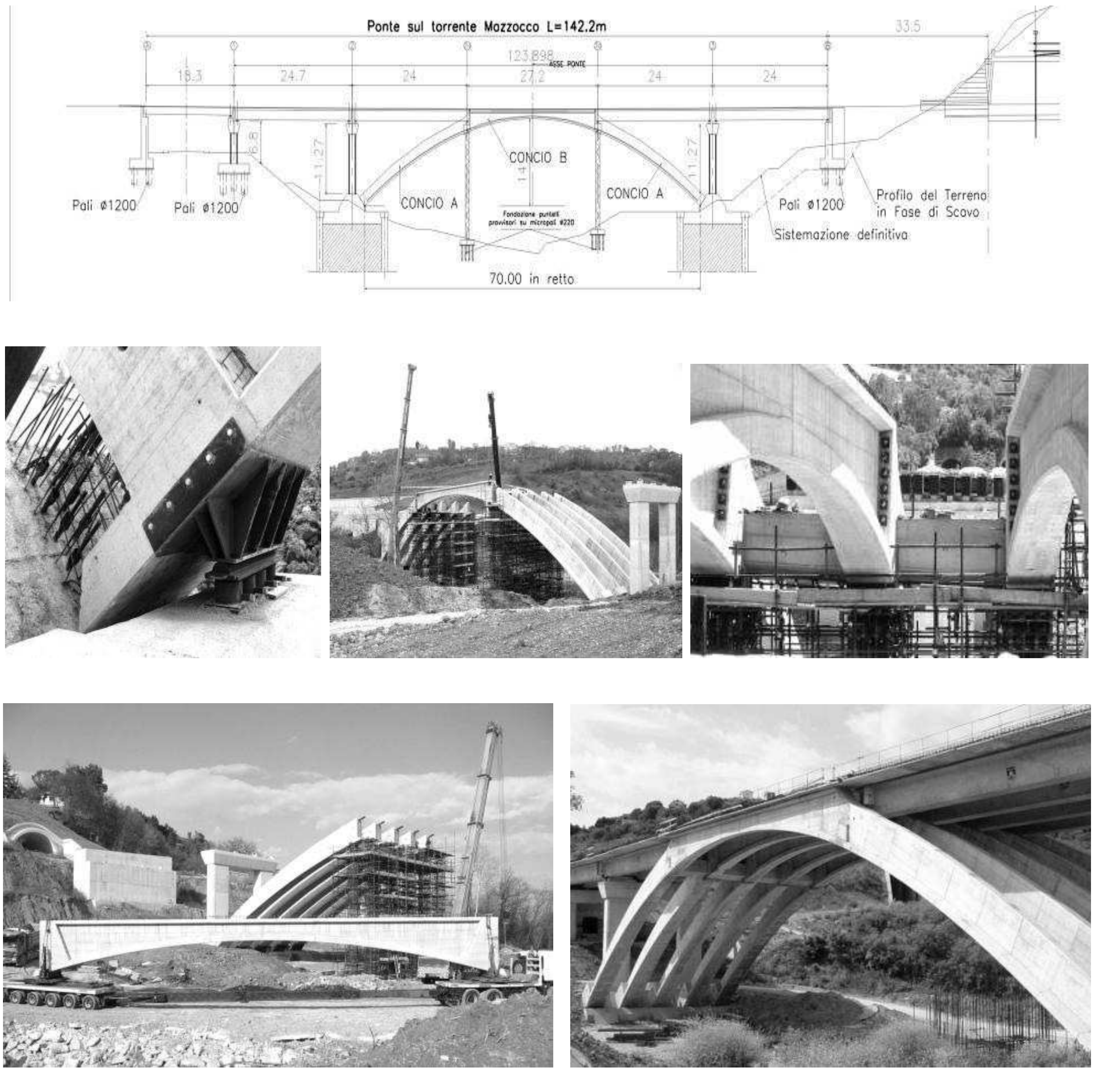
[55] Culatti M., Attolico L., Danieli N., Garghella P., 2006, *Ponti ad arco in calcestruzzo*, seconda parte, Rivista Strade e Autostrade 3-2006



4. 70 Sgurgula Bridge, Rome, 2005, 56 m span, E. Siviero

Another example of a prestressed concrete arch bridge is the Mazzocco Bridge[56] (Fig. 4.71) with a span of 70 m designed by Mario Paolo Petrangeli (1938), realized in 2007. The 15 precast elements, necessary for composing the 5 ribs of the arch, were built in a prefabrication yard, located very close to the bridge site. Wooden formworks placed over a concrete basement were utilized and the central elements have been prestressed before launching them. Two provisional piers were prepared to assemble the precast elements. In the first stage, all the 5+5 lower elements were put into place over the foundations and the provisional piers. The 5 central elements were brought on site at a second stage. In the end, the prestressing bars were inserted. After having completed all the connections, the provisional supports were disengaged by lowering the jack screws and the sand boxes on which the precast element were rested.

[56] Petrangeli M. P., *Prefabrication of medium span arch bridges*, Proceedings of ARCH'07 – 5th International Conference on Arch Bridges, 2007, pp. 759-766



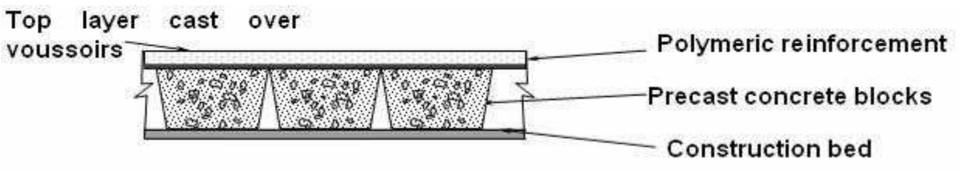
4. 71 Mazzocco Bridge, Pescara, Italy, 2007, 70 m span, M. P. Petrangeli

For more information about Italian arch bridges, please see Chapter 3 *State of art* in the final section dedicated to the ones built in Italy.

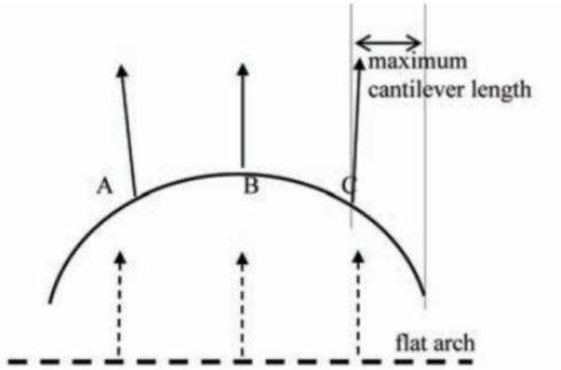
Lastly, speaking about small arch bridges, a recent study called Flexi-Arch expects the construction of arch bridges using individual precast concrete voussoirs that with the correct taper and connected by a polymeric membrane allows them to form an arch, when lifted (Fig. 4.72). The system is easily transported by lorry as a flat-pack to site, where it is then craned into position on precast abutment, forming an arch shape as it is lifted.[57]

[57] Bourke J., Taylor S., Robinson D. and Long A., 2010, *Analysis of a flexible concrete arch*, Proceedings of ARCH'10 – 6th International Conference on Arch Bridges, Fuzhou, China, 2010, pp.133-139

The construction is as follows: a set of concrete voussoirs has been laid contiguously in a horizontal form with the tapered gap at the bottom. A grid of polymeric reinforcement is placed on top and a thin layer of concrete added.



4. 72 Components of Flexi Arch system



4. 73 Lifting procedure for the prototype arch

When lifted into position, concrete cracks allow to rotation to take place and the arch profile is formed from the flat pack (Fig. 4.73).
A prototype arch unit of 5 m internal span, 2 m internal rise and 2,56 m internal radius was created. This study could be a renaissance in building of arches, using unreinforced masonry materials, the system provides a sustainable and efficient arch form for the infrastructure of the future.[58]

The construction technique, based on the assembly of precast elements, constitutes an cost-effective solution for reducing construction times and permits to respond positively to technological, economical, functional and formal issues. In addition, the concrete arch bridge, although being a modern design, fits positively into the environment and proof demonstrates the fact that “modern” may be the natural evolution of “ancient”.[59]

[58] Taylor S., Long A., Robinson D., Rankin B., Gupta A., Kirkpatrick J., Hogg I., 2007, *Development of a flexible concrete arch*, Journal CONCRETE Oct 2007, pp.34-37
[59] Siviero E., Casucci S., 1995, *The evolution of Maillart’s arch bridges: a prototype for the coming years*, First International Conference on Arch Bridges, Bolton, U.K., 3-6 September 1995

4.8 Advantages and disadvantage of the construction methods

"*The first principle of architecture is that the essential lines of a monument be determined by a perfect watching to its destination*", with these words Gustave Eiffel explained the importance of the position where a bridge is situated. The structure must be designed accurately before its realization, so that it can be most suitable as possible for its surroundings and safe for the length of its life service. Starting from the assumption and the certitude that in the bridge's design the formal and architectural expression cannot be separated from its structural function, and before outlining the advantages and the disadvantages of each method and then defining a relationship with other constructive processes, it is helpful to understand the selection criteria of the shape and the construction phases that a designer, architect and engineer, must know before the planning of a new bridge.
There are many factors that have to be considered during the design process which mainly depending on the site where the project will be eventually built with the various obstacles to be overcome, on the structural bridge typology necessary in that precise place, like vehicles, pedestrians or railway bridge, on external agents that must be planned and calculated, to the most convenient material choice to the given situation.

Shape
In the design phase of an arch bridge, the fundamental problems consist in the initial choice of the arch shape, that can never be separated from its structure, as well as the choice of the materials to be used, the amount of spans and lengths, and so on.
When an engineer and an architect decide to built an arch bridge it is clear that they know perfectly well that this kind of structure works due to its shape, as it supports the compression stresses thanks to the curve line that passes down the exertions to the ground. The arch bridge has a shape that directly reflects its structure and this structure has many manufacturing processes for it to be accomplished. The choice of the most convenient construction method to be adopting of any specific case is fundamental for the good realization of the final structure. This is the reason why the architectural design and the structural analysis must not and can never be separated from each other.

Place
From the start, the first principal factor that a designer has to take into consideration is the location, the environment, the surrounding nature, which becomes determinant when choosing the construction process. During the construction phase it could be necessary to be independent on the environment: many valid

examples of this are the bridges on major waterways, rivers or areas prone to recurring floods, therefore with the necessity and the possible advantage to navigate underneath them easily, or to pass over them by motorway, railway lines, etc. In these cases, where there is an obstacle to be overcome, after realizing the foundations, the rest of the work must be done in a suspended manner, without interfering with the underlying assets. This is one of the problems or constraints that may influence and determine the construction of the bridge.

Span

Another element, which undoubtedly influences the shape and structure of the arch, is the scale factor that it must acquire, meaning the span it has to reach in order to overcome the given obstacle. If the environment allows for it, the bridge can separate the entire length creating various spans, but if this is not possible, as in the case of a deep valley, the arch span will be equal to that of the obstacle it has to overcome.

For long bridges, it is necessary, in the design and construction phase, to divide the structure into different parts to make installation as controlled as possible. The bridge will be built in succession of every individual peace, so that each stage of the building construction process has a partial structure capable of withstanding collapse separately and can allow the assembly of the next piece. Another way is obtained by using the auxiliary structures that support the various sections until the final structure is completed with the disassembly of the auxiliary on completion.

Material

The arch represents the only one structural bridge typology that, unlike the others, has had a long application in history and it is the only one that has been using all the possible construction materials such as stone, timber, concrete and steel; that due to this varied possibility materials arch bridge achieved many architectural shapes over time.

Construction equipment can be reduced ensuring that the various constituent parts of the bridge will be as light as possible. Therefore, it is convenient to use materials that are more specific resistance. The specific resistance of steel is higher than that of concrete and thus if we consider two arch bridges of equal span made of these two different materials, the weight of a metal structure will be always lighter than that of a reinforced concrete structure and with the increase in span, this factor becomes ever more decisive and the economical and feasibility aspects must be taken into consideration too. For this reason, the construction of a metal bridge is always cheaper than the equivalent in concrete, so it is probable that the bridge with a longest span will be built in metal. In the small and medium span bridges the cost of concrete, compared with that of steel, can offset the higher cost of construction.

Cost

The construction method is not the only one element to be taken into consideration: in fact all the characteristics during the process are to be considered. However, the construction method will always be a determining factor in the choice of the best and most suitable solution for any particular project and becomes an ever more important issue with increase in span.
The arch constructed by means of cable-stayed span requires the use of temporary braces and generally more reinforcement than would be needed when the bridge is completed. The construction difficulty of this arch bridge, however, does not invalidate this solution rather than the beam one, in fact the construction process, although crucial, is not the only element that determines the economy of the bridge. To calculate the cost of the finished project it is necessary to add the cost of materials and labour as well as all the elements essential for its construction. So the bridge that is built with the most economic building process is not therefore necessarily the most economical one: there may be examples in which the increase of materials and of yard tools needed for the construction work is compensated by the materials economy of the bridge itself, so the total cost may be lower than that of other structures that could be built with cheaper construction processes, but with higher costs for the bridge parts. The arch bridge is the easiest case to understand this concept, because the arch, being a structure that resists due to the shape, cannot function as such until it is completed. For this reason it requires a large amount of resources for its construction, however, the material economy in the arch structure once completed can compensate in many cases to the large amount of auxiliary tools on the yard.

Construction method
The most appropriate construction process applied is the one that requires the least construction tools, or the least amount of additional construction material, to ensure that the partial structures are able to support themselves for the next step. The greatest cost-cutting measures for construction tools is obtained when the partial structures built in succession resemble as much as possible to that of the final structure, requiring minimal contributions, or none at all, of structural material to withstand intermediate states.
The construction phases are closely tied to a logical process of assembly that starts from the base of the bridge and ends with the arch closing at the key. The creation of the foundations is strictly influenced by the type of soil and by the superstructure, which in the case of arches will sustain the strength that it produces. The second phase is devoted to the assembly of the visible parts of the bridge. The choice of materials entails a different manufacturing process: stone must be shaped into blocks according to the required size; for steel structures the different parts (sections and plates) must be united in workshop by welding, so the final structure will consist of prefabricated elements; for concrete the size and the construction of

formwork must be evaluated that will serve as the casting mold for the concrete in its original plastic state until it solidifies acquiring the characteristics of resistance.
An example of manufacturing work is when self-supporting rib are used, which may also be movable to allow the movement of construction machinery. The different bridge parts can also be produced in the workshop, prefabricated and then transported and assembled in place, or made *in situ* in their final position without being further moved. When the project is a big one, with an significant span, the construction is done by means of industrialization phases, bringing precast segments directly from the factory or realizing the ribs directly on the yard site. The assembly phase involves the use of auxiliary structures with the task of supporting themselves and the weight of the next phase of construction, that when building an arch becomes essential in reaching its resistant characteristic only once completed.

What are the auxiliary structures that can be used in the various construction methods?
The scaffolding construction method consists in the use of an auxiliary structure, which becomes an arch with an equal span to the final one. The centering is a lighter structure able to withstand its own weight and that of the final arch bridge. The quantity of materials used and the consistent cost during the construction of the scaffolding becomes it an important reason to take into consideration the choice of this typology.
Melan centering, which is a particular scaffolding type, is used for the realization of a progressive structure that begins with the construction of a light arch with an increasing section till the definitive one. The initial arch has the function of scaffolding, that is later on incorporated into the concrete and to do this the amount of steel required by the initial arch is greater than the reinforcement required by the concrete arch.
The cantilever construction method is used for the construction of a bridge with a long span and requires many different tools on the yard such as provisional towers, cables and the hoisting system needs to be well calculated. Many external factors, like thermal and elastic changes, could influence the cable-stayed during the construction and the weight of the suspended pieces.
The swing method, at least, does not have many applications as the previous one because of its difficult to keep the stability during the rotation process and the use of hinge at the abutment and lifting tower and hydraulic system.

To analyzing more precisely the advantages and disadvantages that each method offers, they have been listed in the box below where the most positive and negative elements to take into consideration in the project phase are inserted, when it is necessary to understand which method would be the best answer for any given bridge construction.

Table of the advantages and disadvantages of the various construction methods

CONSTRUCTION METHODS		ADVANTAGES	DISADVANTAGES
SCAFFOLDING	Centering	- temporary structures are simple both fabrication and erection - easy to be reloaded and removed -can be used repeatedly - reliability of the full span centering and easy to be mastered - suitable for arch bridges with relatively small span and located in places not so height - support the weight of the entire structure and all the tools on the yard - different shape possibilities depending on the environment situation -using a strut-framed centering	- economic problem in large arch bridges, elevated cost of the centering - large assumption of material for the centering - threatened by flood - restricted applications - dismantling of the centering - the construction of the structure could have some problems if loaded in a wrong way
	Melan	- metal scaffolding has double function: scaffolding and reinforcement of the final structure - timber centering for arch construction could be omitted, Melan scaffolding could be built with the centering construction method or the rotation one - high load - carrying capacity - prefabrication increase - free space on the yard - useful in the deep valleys and for long spans	- amount of steel require by the initial arch is greater than the reinforcement required by the concrete arch. - use of some others tools and construction methods to build only the Melan centering

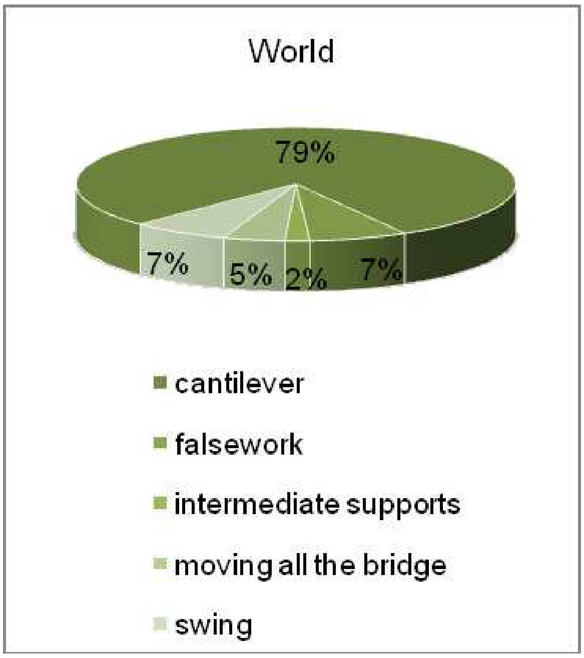
	Intermediate supports	- assembly of prefabricated elements - rapid construction of steel arch bridges	- use of some others tools and construction methods to hang the elements
CANTILEVER	Cable stayed	- simultaneous construction of the semi-arches from the springing to the crown - possibility of cast in situ the elements segment by segment - simultaneous construction of the arch rib and the deck - use of different construction methods in the same time - the cableway crane has the advantage of not burdening the arch with their weight and serve both side for a parallel building - vary elements could be assembly direct on the place hoisting them by the lateral side or from barges below	- necessity of many tools like pylons or towers and cables - hoisting system needs a good calculation - cable-stayed cantilever structure is influenced both thermal and elastic changes and by lengthening of the wires due the continuous increase of load - wind resistance - displacement of the tower top - forces on the main cable - dynamical situation - joints between precast elements
	Free cantilever	- tension forces in the structure above the arch are transmitted to the abutment by means of appropriate temporary elements - inclusion of structural elements above the arch into loading-bearing system during the construction period - easy application in steel	- truss shape - it is not so used in concrete material - sometimes it is necessary the use of cables and tower like the cable-stayed method
SWING	Vertical and horizontal	- construction of the half arch on the lateral site or to lower position without a cantilever	- stability during rotation - hinge at the abutment -use of lifting tower and hydraulic system

From the analysis in the design phase of all the elements that may influence the construction and from a careful choice of the best construction method in any one case, it is emphasized that each method may have a particular applicability to various architectural types of bridges and to materials of which they are made up. With the data available it can be seen, by means of the table below, for which bridge type the construction method is used and in which ones it would preferable to adopt other alternatives.

CONSTRUCTION METHODS		TYPOLOGY					
		Deck		Half-through		Bowstring	
		Concrete	Steel	Concrete	Steel	Concrete	Steel
Scaffolding	Centering	✓		✓	✓	✓	✓
	Melan	✓		✓			
	Intermediate supports	✓	✓		✓		✓
Cantilever	Cable stayed	✓	✓	✓	✓	✓	✓
	Free		✓		✓		
Swing	Vertical	✓	✓		✓		
	Horizontal	✓	✓		✓		
	Vertical-Horizontal	✓			✓		✓

As shown, the cable stayed cantilever method is the only one that is used for all the arch typologies, both in steel and concrete. Instead, the methods using structures that support them from below, like centering, finds a major application in concrete construction rather than in steel, more precisely because the temporary elements are used to support the cast phase, even when the concrete does not possess the resistance characteristics. This logic could be applied for the Melan method too, which for the its scaffolding characteristic is used as reinforcement for concrete. Differently, the free cantilever method is adopted for the construction of trusses, and for the construction of long steel truss bridges.

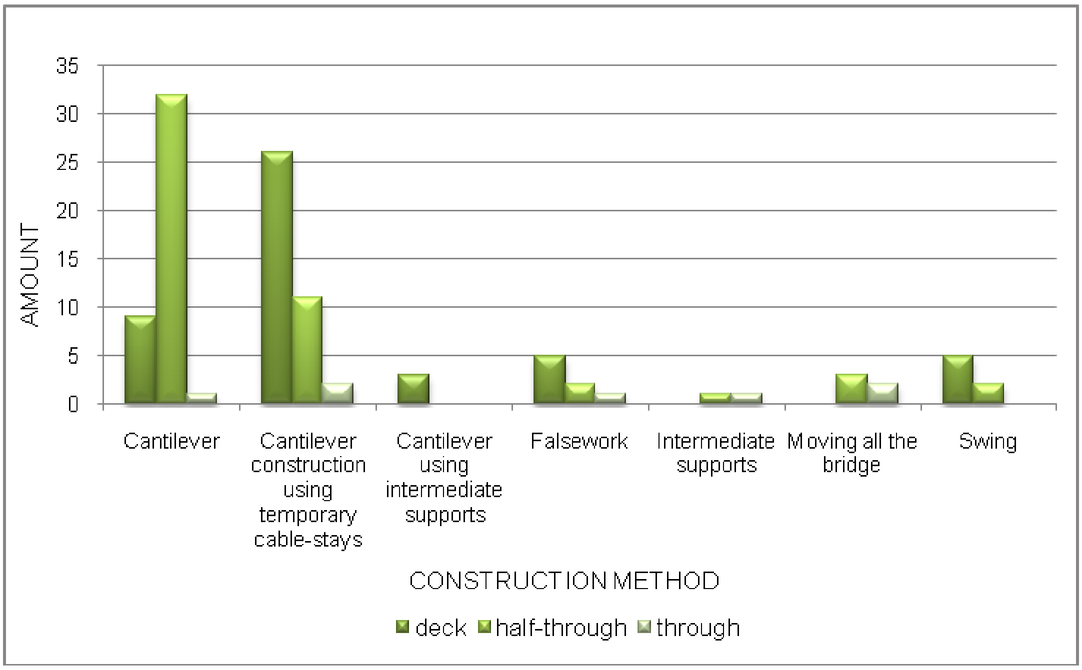
Some 600 examples of arch bridges in the world were taken into account, with the two common characteristics of having been built after the year 1900 and with a span of more than 100 m. From the graph below (Fig. 4.74, as seen in Chapter 3 State of art Fig.3.40) it can be said that the cantilever construction method, although it needs a lot of tools on the yard and a careful analysis of the cables system that support the various parts of the structure, is by far the most employed method in the construction of arch bridges, with appropriate modifications depending on the case examined.



4. 74 Percentage used for every construction method

As mentioned above, each construction method is adapted to the particular case using materials and tools convenient for the project in consideration. This often means that different methods are used simultaneously creating hybrid situations with the use of structures and elements that are characteristic of one or the other, taking all the benefits that each method can offer to the construction phase of the bridge.

With the graph below it is clear how the construction methods are used depending on the type of bridge itself, deck, half-through and through arch bridge. The cantilever method, with the help of cables and towers, is undoubtedly the most used method in construction of deck arch bridges, as in fact it is easy to understand thanks to its characteristic to support the structure from above trough pulled cables.
However other types of cantilever constructions, for example the free cantilever one, are of greater use in the construction of half-through bridges such as truss bridges, because the original contemporary construction of the arch and deck at the spring allows for having a more rigid structure and therefore a shorter free span.
Other considerations relating to the following chart (Fig.4.75) are: that the centering is used more often for the construction of deck bridges just as the swing method is, while on the other hand, the shifting of the entire structure or the utilization of intermediate supports are applied more to the half-through and through arch bridges.



4. 75 Amount of each construction method, subdivided into typologies

From the considerations made before there are examples given, that will clarify what has been said: in the following table, the bridges with the longest spans in the world carried out in different architectural typology, with different materials and different construction methods used during the erection phases are collected.

Record spans in every architectural type and with various construction method:

ARCH BRIDGE TYPOLOGY	MATERIALS	CONSTRUCTION METHODS		
		CENTERING	CANTILEVER	SWING
DECK	steel		**New River Gorge** **518** m, 1978, USA 	**Alconétar** **220** m, 2006. Spain 
	concrete	**Wanxian** **420** m, 1997, China 	**Krk I** **390** m, 1980, Croatia 	**Fuling** **200** m, 1989, China 
HALF-THROUGH	steel	**Juscelino Kubitschek** **240** m, 2002, Brazil 	**Chaotianmen** **552** m, 2008, China 	**Dongping** **300** m, 2006, China 
	concrete	**Yongjiang** **312** m, 1996, China	**Svinesund** **247** m, 2005, Sweden 	

BOWSTRING	steel	**Blennerhassett** **267** m, 2008, Ireland 	**Bircheneoug** **329** m, 1935, Zimbabwe 	
	concrete	**Third Millennium** **216** m, 2008, Spain 	**New Indian River Inlet** **305** m, 2010, USA	

With a careful analysis of all the factors that may influence the design and construction (location, transports on site, costs, type of bridge, weights that burdening on the structure, future maintenance), examined with appropriate methodologies and applications, the choice of architectural type, materials and building processes most suitable for the bridge design can be made with better accuracy and assurance.

The assembly execution provides the choice of a technique and an operative program, which are carefully defined before starting the work. The yard activity is therefore strictly conditioned by the stages that precede it. Safety and success of the work depend primarily on suitability of assembly technique choice, on the consistency with which the study was developed in relation to the executive plan and to the local conditions of the yard, on the adequacy and the organization of the Constructor Company at the work characteristics and at the staff experience, and at equipment availability.

While proposal of the general construction method is formulated by the bridge drawings and by summary information (forecasts of the maximum weight and size of the prefabricated elements, links typology at the springing, access to site and to deposit places, type and capacity of equipment already on site, etc ...), the assembly planning involves the examination of all the final project drawings to provide in detail the most correct and advantage sequence of the various assembly operations for each element.

It must analyze each assembly phase and ensure strength stability of the construction on static schemes ranging generally from phase to phase. Therefore, a technical control plan is needed during the construction process to monitor the relief work in the intermediate stages and its allowable tolerance. Despite the careful analysis of the project and the attention during the installation phases, construction methods may be particularly sensitive to the boundary conditions, such as the unexpected difficulties on the yard, construction defects and the exceptional nature actions.
This leads to the risk analysis with which it seeks to understand and expect the different consequences that may go wrong during the different stages of life work, from the design and construction, but also service time, degradation maintenance and decommissioning.

From this second chapter *Construction methods* some technological characteristics that influence the projects of arch bridges stand out: construction efficiency as well as the construction methods themselves.

CONCLUSION

"A great work of art evolves from an idea in the mind of its creator. It is brought (transcribed by the engineer) on(to) paper, or into more contemplative form, and then changed and remodeled. Not until the plans have passed through changes and corrections, and have been submitted to an almost endless series of finishing touches, does the great work of art attain perfection… A great bridge in a great city, although primarily utilitarian in its purpose, should nevertheless be a work of art which science lends its aid. An elaborate stress sheet, worked out on purely economic and scientific bases, does not make a great bridge. This is only accomplished with a broad sense of beauty and harmony"

Othmar H. Ammann

This doctoral research has considered the aspects of the arch bridge over its entire lifespan, from the design of its shape to its final completion, to the construction phases and to how it relates to its context and to how people live it once completed. This theme is undoubtedly very vast and also examines bridges though history.
The goal of this research is to find out what are the characteristics that designer must take into account when planning an arch bridge that has to meet the needs of the place and of the people who will live it. With this in mind, four areas were analyzed each different from one another, but that at the same time bind together into a very dense network of a relationship: in fact, studied individually, they are each a single aspect of the bridge, but when considered together they represent the entire life of the bridge from start to finish (design, construction and future use). The four topics relating to the subject, which I believe are all fundamental as to understand its features, are:
- architectural design of the arch shape and its historical development,
- perception, studied from two points of view: the first one that takes into account the psychological objective laws that switch the bridge from subject to object, considering man as user of the finished work, and the second one that sees the close relationship between the arch bridges and landscape,
- a careful look has been taken at what has been built and what is under construction as to make a comparison,
- and construction methods used for the realization of the arch bridges.
To summarize what has been analyzed in each individual concept, being spit up separately into singular chapters, are the basic concepts which are defined here:

Chapter 1: design, project, arch shape, journey in the history
The first chapter deals essentially with the arch shape being used in bridge design and how it mutated over history. The text, supported by examples, shows how the increasing knowledge of the resistant structure of the arch and the progress of construction techniques, emphasized by new materials emerging, have helped the evolution of the structural shape with consequent architectural development.
The arch shape is becoming ever thinner and lower: up until the 18th century the arch bridge was built of wood and stone. Romans realized bridges that still stand to this day, generally consisting of a series of small arch span, while Romans used the semicircular shape in the Middle Ages the arch bridge became gradually lower. During the 20th century, concrete is used in the bridge construction and prestressed concrete and steel were introduced, materials that are commonly used today: a great development took place in the last century with the result of some spectacular structures been built, reaching new records in terms of size and therefore offering solutions for new challenges.
Over the centuries, bridges allowed men to relate to each other ensuring the connection among regions, countries, by going beyond political boundaries.

Bridges, and especially arch bridges, have always impressed men thanks to their beauty, elegance, slimness, inspiring many painters so that the bridge not only became an engineering task but also something that was often called “art”.[1] The importance of the arch bridge has turned throughout history and especially in recent years in its meaning and value. Arch bridge construction today is a conscious choice, because the bridge is not only synonymous of passage, but has become a place to be lived and an important imprint in the landscape. Even today, as in the past, the bridge represents a path, a resting place and a landmark and the new realizations lead in modern reading key what it was in the past: you should take a look at the past to realize how the planning phase is closely linked to that executive on the yard.

From this first analysis, essentially historical, we infer some specific characteristics of the arch bridge that affect the architectural design:

span, rise, rise/span ratio, deck position

These design characteristics denote the arch geometry and the proportion that it has in the project.

Chapter 2: human and landscape perception

In this chapter we attempt to investigate how the finished bridge is lived by man, and overall what is its impact on the environment and what is indispensable in the user’s life, these points are certainly very valuable to know during the design phase. Then again bridges acquire much more importance than their fundamental function as a passage way for people and goods: they also have a social, visual and symbolical function and are significant elements for the place they are built and for the community. Every project is different from the other and each one will have its own characteristics which will make it unique. However, the various typologies will be joined together by some similarities in landscape, that the designer can take into account in the architectural design of the arch bridge. Through these measures, the designer may contribute and ensure the realization of good projects that will be part of people who will live them, making them somewhat proud of its presence.[2]

Besides man, in this section a lot of attention is paid to the environment, and to the changes it undergoes from before and after the installation of a bridge. Landscape becomes a crucial point in the design and it must have conformity with the characteristics of the surrounding environment. In fact, landscape greatly affects the appearance of a bridge: the examples of arch bridges that are positioned near

[1] Artamonov A., Bendel C., Blueckert C., Landrin H., Spencer M., Wallace P., Wassmer L., Wannick H., 2008, *Bridges – Construction, Insurance and Risk Management*, IMIA Conference Gleneagles, 2008, pp.1-44

[2] *Bridge aesthetics sourcebook, Practical Ideas for Short- and Medium-Span Bridges*, September 2010, AASHTO American Association of State Highway and Transportation Officials Draft, September 2010, www.bridgeaesthetics.org

rivers are generally appreciated more than those which are partially hidden by adjacent objects. The bridge structure must be in harmony with its context and must not seem as an intrusion. To ensure this harmony, the general structural lines must blend in with those of its belonging environment. The bridge is viewed from different angles and every point of view will produce its own individual feel.[3]
From this study the characteristics of perception are defined in the following way:
efficiency of architectural design, landscape perception

Chapter 3: State of art in the world and in Italy
Looking closely to what has been carried out in the last century, makes it possible to get the latest arch bridge realizations as note examples from which to start future projects. This section establishes which were the most commonly materials used, spans reached and construction method adopted. Learning from many examples around the world, and particularly the ones on Italian territory, it is definitely the first step in achieving a more conscious design. From the history of bridges can be witnessed the progress of constructive techniques analyzing the transformation in design that became ever more daring. For centuries, bridges were much more than a common structure, becoming a symbol of communication, a connection between people separated by an obstacle, and during the last decade engineers have shown a renewed interest in aesthetic and, combining in a conscious way, the need to relate their structure to the local environment. [4]
The structural type of a bridge defines its formal character and through the last century we have passed from elegant architectural solutions to structures apparently only functional. Many of these projects, which had a considerable technical level, now represent the union between an formal and a technical concept, pointing out a new link between architecture and engineering, a connection that allows for the creation of bridges that are not only pleasant but above all stable. Hence comes the idea of Structural Architecture.

Key features for the analysis of complex arch bridge structures is therefore the place and location of construction: this means analyze the topography of the place and the obstacles to be overcome.
Another distinctive character that emphasizes the functional importance of a bridge in a particular environment is the traffic condition; as a result to economic growth, a huge increase of freight and passenger transport has been seen: an obvious consequence of this development is the growing need of modernization and expansion of the existing infrastructures and the construction of new ones. Each

[3] Troitsky M. S., 1994, *Planning and Design of bridges*, Edited by John Wiley & Sons Inc., USA, p.167
[4] *The aesthetics of concrete bridges: report of a task group*, 2000,Crowthorne: Concrete bridge development.

project of transport infrastructures, roads, motorways, railways, includes a large number of bridges of all types and lengths.
The construction of arch bridges in cities and in urban regions influences the natural landscape or changes the general character of the city. When planning modern urban bridges, the designer should be guided by the transport problem (vehicular and pedestrian transition, that may have to cross the river in an urban environment), by technical problems (determination of the geometry, choice of the structural system and deck position, to determine the optimal length, with particular attention to the details) and by architectural requirements (satisfying the high standards of artistic aspect).[5]
As we have seen, in recent time arch bridges have reacquired a new life, but on the contrary to the use that they had in the past, where this architectural shape was preferred for its structural characteristics, in many cases today they are chosen for their aesthetic merits, without giving great attention to the relationship between their form and structural efficiency. The choice of a curved shape can sometimes be a disadvantage, but despite this, the number of bridges with this kind of feature is already great and ever increasing in recent years.
From this study we define the following characteristics:
place, obstacle

Chapter 4: Construction methods
The fourth chapter tackles the last of the four issues considered, will be a technological investigation that focuses on the methods used most in the construction of arch bridges and to the tools used on yard site. The construction of the bridge, using the most appropriate method, is certainly an important part of the whole project, not only taking into account the analytical and technical terms but, seeing it becomes essential even in the architectural thinking of the new bridge, its shape and its aesthetic appearance. And as Hugo Corres Peiretti says: "*Arch bridges are one of the types of bridges that have been taken up again due to the new possibilities created by the construction methods now available.*" [6]
The starting point in the construction of arch bridges has been building the vault roofs and as the structural shape of the arch almost entirely prevent the tensile strength; solid building materials such as stone proved suitable in providing high resistance to compressive stress: the constructive technique of arch bridges has been used for centuries by replacing other kinds of materials.

[5] Troitsky M. S., 1994, *Planning and Design of bridges*, Edited by John Wiley & Sons Inc., USA, p.45
[6] Peiretti H. C., *Conceptual Design: an engineering approach to get morphologically interesting solutions* in *Tendencias en el Diseno de Puentes/ Trends in Bridge Design*, 2000, Edited by Dolores M., Pulido G., Sobrino J. A., Romo J., Spanish Group of IABSE, pp.147-165

So, how does the arch work? All loads, horizontal and vertical, are drawn down by the structure and absorbed by the abutments and foundations. Sometimes, however, the deck is able to incorporate the horizontal tensions of the arch allowing it to have easier foundations and providing the basis for other forms of arch bridges.
Arch bridges are mostly built on rivers or over deep valleys, even where the installation of any supports would be impossible without using the cantilever method. In fact centering is built with a modular system using reusable components, a system that becomes an integral part of the project having regard to its mounting difficulties. Other methods today are used to overcome difficult local conditions and specially regarding the protection of the landscape, for example by means of the construction of two semi-arches rotated until their closure at the key.[7] The need of large-scale bridges enable a considerable progress in building techniques. In the case of small bridges, the designer generally used typical construction method, which however represents an exception in the case of greater spans.[8]
During the project phase of an arch bridge, the design and the analysis of the construction steps are closely related, in fact there is not one design that should not consider the constructive method, chosen according to the need of each single example. Therefore when discussing arch bridge design, the utility and the consequent suitability of the bridge to the pedestrian, vehicle, train passage should be considered first and foremost and then that of the structure, to guarantee its durability and allowing an adequate lifespan and finally a design that responds to the architectural and aesthetic requirements. The difficult role of the designer is to find the most suitable solution to the problem, considering all the factors upstream of the project. [9]
The analysis of advantages and disadvantages for each method permits us to understand when and how various constructive technologies can be used and which architectural forms will follow. And as Julio Martinez Calzon[10] says: "*The construction factor is one of the most important and it needs to be established from the first moment of the project's conception since it could easily determine important aspects of the design. In general terms, a study or an approximation to an analysis of the construction process and the interaction between the materials that these produce, could lead to the definition of lines of creativity and design which,*

[7] Artamonov A., Bendel C., Blueckert C., Landrin H., Spencer M., Wallace P., Wassmer L., Wannick H., 2008, *Bridges – Construction, Insurance and Risk Management*, IMIA Conference Gleneagles, 2008, pp.1-44
[8] *The aesthetics of concrete bridges : report of a task group*, 2000,Crowthorne: Concrete bridge development.
[9] Artamonov A., Bendel C., Blueckert C., Landrin H., Spencer M., Wallace P., Wassmer L., Wannick H., 2008, *Bridges – Construction, Insurance and Risk Management*, IMIA Conference Gleneagles, 2008, pp.1-44
[10] Calzon J. M., *Innovation on bridge construction. A general contribution about new erection methods in steel and concrete composite bridges* in *Tendencias en el Diseno de Puentes/ Trends in Bridge Design*, 2000, Edited by Dolores M., Pulido G., Sobrino J. A., Romo J., Spanish Group of IABSE, pp.167-185

integrated into the usual overall plans, could actually modify them and even form the basis for new plans for the project". For this reason, in this concluding part, we consider the topic of Chapter 4 *Construction* as a basis for study and report all the derived elements.
From this consideration the following characteristics are defined:
structure, construction methods

Conclusions

The realization of an arch bridge, as an engineering and architectural work, is the result of a long and complex interdisciplinary design process. Synthetically we can affirm that the conception of a new arch bridge derives primarily from the function it will ensure, underlined by the intended use of the object, by the site that it will be erected on, by current laws, by architectural and structural choices, by the materials and by environmental protection requirements.
In the final phase the four topics, that were analyzed separately, are united here:

DESIGN: span, rise, rise/span ratio, deck position
PERCEPTION: landscape perception
STATE OF ART: place, obstacle
CONSTRUCTION: arch structure typology, construction method

In the initial design phase these characteristics and the relationships existing among them must be taken into account: these elements, in fact, are useful to understand the relationships between architecture and engineering and what are the connections between object and environment. Whereas every structural decision is at the same time also an aesthetic decision the construction method is considered as individual feature for each subject. All the purely geometric characteristics of the structure, which will denote architectural and aesthetic features, are closely related to the structural functionality of the bridge: the implication is that somehow every architectural form is attributable to a structural choice that is summarized here and simplified in the construction method most suited for the work in question. On the other hand, if the formal characteristics are related to structural ones, the size, shape, colour choice will be a direct consequence of the feeling people will have towards the bridge.
Consequently, the four main construction methods used in building the arch bridge, analyzed in Chapter 4 *Construction,* are classified by an alphabetical code (Table 1), and through the analysis proposed in Chapter 3 *State of art*, case studies of

concrete arch bridges made since 1900 are used to define numerically how the use of construction methods were subdivided in proportion to the characteristics resulting from the various issues considered.

Construction method	Construction Code
Cantilever	A
Falsework	B
Melan	C
Swing	D

Table 1 Construction code

The beginning of a new project is based on a number of factors that will influence the final design of the bridge. The first step is to list all the plausible options, taking into consideration the intent of the project, the various possible materials, dimension and shape of the elements, the buildability factor and appearance. The solutions, that will emerge, which will be most appropriate to the site, will be those that will be efficient in terms of structure and form. How people react to a new bridge depends on what they see and above all in the way they see it. This means that the part of the bridge consisting of abutments, arch, piers and deck is that which will give the greatest visual impact. The visual character is influenced by the structure type and on its size. In the case of a bridge built in a rural site with few other important structures, a bridge should not dominate the existing landscape through a strong impact but rather have its elements built as thin as possible to minimize its silhouette and to become as transparent as possible to reduce the visual impact of the project. In the case of a bridge with a considerable span there is a structural need to have a superior part of considerable size, consequently acquiring a greater visual impact. Simplicity, good proportion, thinness, clear demonstration of how the structure works and good placement within the landscape are the key characteristics of a good arch bridge.[11] In the initial phase of DESIGN the main features that the structure will have are defined according to its functionality and to the needs of the area.
Therefore, the type of obstacle initially defines the formal characteristics of the future arch, dictating in general its principal proportions, length and height, and what architectural type is more suited to the environment in consideration. Proportion means the relationships between the parts, creating a sense of order.
In addition to the numerical size of the individual components a comparison is also made between the relationships between solids and voids, lights and shadows. On

[11] *Bridge aesthetics sourcebook, Practical Ideas for Short and Medium Span Bridges*, September 2010, AASHTO American Association of State Highway and Transportation Officials Draft, September 2010, www.bridgeaesthetics.org

the other hand, the scale ratio of the structure refers to the relationships between size with the context and there is a strong connection also between man and project. Using statistical data, from the database, the constructive methods most adopted for each single characteristic are showed in percentage (Table 2). By way of explanation we can see for example that the majority of all the concrete arch bridges built with a span between 100 and 200 m, have been built using cantilever construction method, followed then by centering, swing and Melan. This data does not intend to give a universal criteria of design but merely some advice based on what has been done to affront and simplify the initial design phase and constructive choices, though without defining any fixed principles.

DESIGN						
span				**deck position**		
100-200 (76% of all concrete arch bridges)	201-300 (20%)	301-400 (6%)	401-500 (1%)	Deck (75%)	half-through (20%)	Through (5%)
A-60%	A-69%	A-68%	C-100%	A-65%	B-67%	A-60%
B-28%	B-24%	B-C-16%	/	B-24%	A-C-16%	B-D-20%
D-8%	C-7%	/	/	C-7%	/	/
C-4%	/	/	/	D-4%	/	/

DESIGN					
obstacle			**rise span ratio**		
Valley (39%)	River (54%)	Street (7%)	0,50 < f/L < 0,35 (10%)	0,35 < f/L < 0,15 (59%)	0,15 < f/L < 0,10 (31%)
A-60%	A-62%	A-67%	A-71%	A-63%	A-52%
B-25%	B-29%	B-33%	B-29%	B-23%	B-36%
C-10%	C-7%	/	/	C-10%	C-8%
D-5%	D-2%	/	/	D-4%	D-4%

Table 2 Design factors in relation to the construction methods

Before starting a new project the designer must understand that in addition to responding to the needs of structural functionality and transport requirements, consideration must be given also to the social, visual, symbolic system, the community life and the environment. Thanks to size, shape and position, bridges

are often considered to be structures that define a community, a focal point around which people gather. The designer must have a very clear idea of all the criteria that the arch bridge must meet.
The discussion related to the PERCEPTION is probably more complex because it is difficult to state a correlation between construction method and how man lives the object once finished, but I think that both are fundamental elements to be considered during the design phase.
Through the analysis of landscape perception, carried out in Chapter 2, the issue of how arch bridges fit into the natural and anthropic environment has been tackled. In the examples of concrete arch bridges with a positive landscape perception, it can be clearly seen that the construction methods mostly used on them are equally cantilever and centering (Table 3).

perception
landscape perception
A-B-50%
/
/
/

Table 3 Perception in relation to the construction methods

Likewise, for the CONSTRUCTION phase, the construction method most adopted according to the place of realization and how the choice of structural arch bridge typology is a feature closely connected to the construction system, was considered (Table 4).

CONSTRUCTION						
construction efficiency				**structure typology**		
Mountain (34%)	Hill (34%)	Flat (16%)	City (7%)	Fixed (96%)	two-hinged (2%)	three-hinged (2%)
A-72%	A-68%	B-50%	B-50%	A-60%	A-100%	/
B-13%	B-26%	A-39%	A-C-25%	B-29%	/	/
C-9%	C-6%	C-D-5%	/	C-8%	/	/
D-6%	/	/	/	D-3%	/	/

Table 4 Construction factors in relation to the construction methods

The construction site is one of the major factors that influence the configuration and thus the bridge architecture: if the work is designed in a complementary way respect to the site it will respond to the functionally and aesthetic requirements. For example, if the possibility to realize a new arch bridge in a deep gorge was taken into account, the project would require a structural typology that might be unsuitable in the case of a bridge in the city. In fact, in an urban environment there are different requirements to consider: if a new bridge were needed in an industrial area, it would justify a different level of architecture opposed to a pedestrian bridge. The existing architecture, such as buildings or special structures, should somehow dictate the architectural features to be incorporated in the new design.

For the design of a new arch bridge the designer should consider, already in the initial project phase, some architectural features of the object resulting from the construction place and from its constraints. The tables given above, and graphs of the thesis, dictated from past experiences, are intended to lay down a starting point in defining what are the factors to be considered for the realization of an arch bridge that should be structurally efficient, pleasant to observe and functional in terms of human.

The analysis expressed in the individual chapters and especially in Chapter 3 *State of art* and the considerations about construction methods, collected in Chapter 4 *Construction*, were carried out using the database of the arch bridges, carefully collected and cataloged over the three years of my PhD.

As we have seen many times over, many factors were considered, in particular the construction method and the construction site which greatly influence the design of the arch bridge. For this reason these two elements were used for final tables: the methods, that have been used mostly in the construction of the arch bridges over the last century, are the cantilever and centering ones, which reflect the close relationship between construction and the project site.

The most important characteristics found in the course of the thesis by analyzing a large number of arch bridges are summarized here:

It can be seen that most of the bridges, 67% of them (see graph 3.4 Chapter 3 *State of art*) have a length between 100 and 200 m, this means that recent erection methods permit the construction of more elegant arch bridges with longer spans but only a few reach spans of more than 400 m. This data underlines the daily demand of human scale projects, bridges that can overcome small and medium traffic problems.

However, graph 3.3 shows that the majority of arch bridges, 56% in all, were made in steel, while 35% in concrete, the use of concrete in the construction of arch bridges has lead to the achievement of reaching ever greater lengths (see trend lines in 3.9). A further investigation of the materials was carried out, given the data

available, concrete was taken into account: of all concrete bridges found and considered 76% of them all have a span between 100-200m. As seen 75% of these structures correspond to deck arch bridges and 96% are fixed at the abutments.
With regard to the relationship that exists between span and rise, we have seen that most bridges, 59%, have a ratio of 0,35 < f/L < 0,15 (1/3 < f/L <1/6), followed by low arches 0,15 < f/L < 0,10 (1/6 < f/L <1/11) with 31%. Regarding the place of insertion, we can see that the largest number of this type were built in mountainous and hilly landscapes, respectively 34% and 43% (Fig. 3.22) as to overcome deep valleys and rivers, 39% and 54% (Fig. 3.23).

The database provides many ideas for future topics on the evolution of arch bridges and this doctoral research is merely a starting point. The purpose of this PhD thesis is to give a preliminary discussion on some topics that become part of the life of an arch bridge, right from its initial design phase.
In particular, I think it is appropriate to continue the research on arch bridges in Italy, because as we have seen historical memory is of fundamental importance for the future design and the arch bridge, thanks to its unique architectural features is an something that fits in very well into the landscape. In a country, like ours, dotted with countless bridges that mainly pursued the economy, standardization, and construction speed, I think that arch bridges can be a good design inspiration from both an architectural and structural point of view.

Final considerations

The main purpose of any structural design is to serve society with economy, durability, environmental respect and good aesthetic quality. It is definitely the function that should rule the beginning of each project, and the functionality of a work is dictated by the simplicity of its design, and simplicity is synonymous of beauty. A good bridge design must be timeless and, as shown, there are many historical examples that clarify this concept very well and their engineers could be defined as “master builder” of their time. From the second half of last century the cost of construction took precedence over creativity, producing bridges that appeared into the territory, sometimes altering it. In recent years, a certain architectural quality of structures is expected, thanks to the current educational trends at the universities that teach a new design method that combines a correct structural quality and an appropriate aesthetical one. Even in projects where the structure is dominant and where technical and structural issues are employed to check the design, the architectural aspects are also considered by designers as an issue just as important as the first two. Even though we can measure the length of a bridge and evaluate its technical characteristics, but can we measure its beauty?

Beauty is a value and it does not correspond only to an understanding of a given fact, but it becomes an emotion, a condition of our willingness to appreciate something. The perception of beauty is the perception of a positive value. Once the structural issues are resolved, the formal research should be considered as the first target to be achieved. The creativity is an unexplored area that goes beyond the safe and analytical structure. Each construction involves substantial changes to the environment, therefore an unfortunate design decision can dramatically deface it rather than improve it and with it our quality of life. A capable designer should be able to take full advantage of the structural constraints and of the project site. The right choice of the constructive method and useful equipments on the yard is a fundamental component for the success of the work and a practical support to the pursuit of a good architectural shape. On the contrary, if the project has a good formal design, a poor construction phase may damage the final result; hence it is underlined yet again the importance of the construction process, of the planning of the individual work on the yard and how the relationship between architecture and construction is strongly linked because the design influences the construction method but on the other hand the latter can seriously affect the success of the work.
In recent years, we have witnessed a revival of formal concepts thanks to several designers, whose works have been collected in this thesis and that represent concrete examples of their contemporary colleagues and to the new generations of designers. Without abandoning structural features and economy, bridge designers have begun to integrate their projects with cultural values, as well as paying attention to society and the environment. These contemporary examples reflect a sustained effort, from the earliest stages of design, to obtain a developed and balanced relation with the surrounding environment.

The current processing capacities and modern technologies have led to realize great constructions both in terms of technique and architecture. Bridge design represents a union between architecture and engineering knowledge where the final result reflects the designer’s competence in both areas. Therefore, the success of a bridge is shown in the bridge that blends structure, form and functionality together. Bridges reach high architectural quality and social value when they are integrated into their surroundings. The bridge shape of excellent is defined by the arch structure.

This doctoral thesis has considered many issues regarding arch bridges in its entire lifespan, from the conceptual design and construction to its use in everyday life. These issues call for further research in each of their individual parts. This thesis is the result of a significant unit work, that has resulted in an holistic approach to the world of arch bridge building that has yet to be studied.

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