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STONE ARCH BRIDGE
-
A NEW RENAISSANCE?

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Preface

This bridge engineering master thesis is carried out under the framework of the master program for road, railway and transport at the Norwegian University of Science and Technology in Trondheim, Norway (NTNU).

The Norwegian Public Road Administration (SVV) and the Nordic Road Forum (NVF) has supported this study project.

As a bridge engineer at the SVV my interest in stone arch bridges is inspired from colleges and from our old and beautiful stone arch bridges we are assessing. We do take care of the existing ones, but we do not build any new.

In these times with the global focus on sustainability and the common challenge on reducing greenhouse gas emission from our industries, I was trigged to learn more about the old technology of stone arch bridges to challenge if this concept could be a part of the future solution for a more sustainable and environmentally friendly bridge industry.

Many people provided support and encouragement during my work with this thesis.

I thank Professor Jan Arve Øverli at the faculty of structural engineering and the department of structural engineering at NTNU who has been guiding me through the work and for always being available for frequent meetings and discussions.

I also thank mining engineer Helene Nesheim at Lund AS, Professor Santiago Huerta at the Polytechnique University of Madrid, Professor Adrienn Tomor at the Bartlett School of Sustainable Construction in London, bridge asset engineer Callum Gillett at Essex Highways in Cambridge and bridge engineer and software developer Hamish Harvey in Bill Harvey Associates Limited in Cardiff who all have generously hosted my visits and shared their knowledge and experience on stone arch bridges with me.

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July 2024

Abstract

Should we build stone arch bridges again?

This is the main question this thesis is discussing and trying to give an answer to.

The topic selected is inspired by one of the most serious global challenges we have today according to the United Nations. The emissions of green-house gas from human activity causes severe threat to the world's climate. The effect of the observed rise of temperature is disturbing the equilibrium on earth and the UN urge to put high pressure on our activities to change course and reduce the green-house gas emissions. "Business as usual" might be a risky way to go.

Except for the material of wood, all the competitive materials to stone as construction material are extracted from a stone. Cement, aggregate in the concrete, steel and aluminum are all hyper processed stone. The stone used in stone arch bridges is not a processed material, only cut and shaped out from natural rock and delivered for use in its natural composition.

The production of cement and steel consumes a huge part of the world's fossil energy every year and leaves a massive carbon footprint in the atmosphere. The global contribution only from the cement industry is in 2020 8 % of the total CO^2 emission from human activity. The steel industry is at the same level. Together these two materials represent an anthropogenic CO^2 emission og 5.6 giga tons (Gt) in 2022 out of a total of 35 Gt. If the steel and cement industry was regarded as one country alone this cement-steel nation would be the third largest country after China and USA with regards to the contribution of CO^2 emission from human activity.

Today sustainability and holistic thinking is urged for in most aspects. When investing in infrastructure the life circle impact of carbon footprint, energy consumption, maintenance scope and longevity have become major factors when decision-makers are to select the future bridge concepts. The UN goals for sustainable development is now a gamechanger.

From the literature research, interviews of stakeholders, structural analysis, and life cycle assessment carried out in this thesis the following statements forms the conclusion of the work:

- The stone arch bridge requires less energy to build and will leave a smaller carbon footprint than the competitive concepts.
- With quality maintenance the longevity of stone is unbeatable. The low maintenance efforts required should make this concept interesting for all asset managers.
- The stone offers the required strength and resilience, proven by the history of the existing constructions and confirmed with structural analysis.
- The stone arch bridge concept is a low stress structure obtained with a brittle material placed in a system offering ductility.
- The material stone should be a concept of interest and be evaluated together with the alternatives. Today this is not the case. The stone is ignored.
- There are limitations for the stone arch bridge with regards to span and the concept can not be an alternative for all future bridge projects.

Sammendrag

Skal vi bygge steinhvelsbruer igjen? Dette er spørsmålet denne masteroppgaven prøver å svare på.

Temaet er inspirert av en av de største globale utfordringer vi har i dag i følge FN. Utslipp av drivhusgasser fra menneskelig aktivitet er en trussel mot et bærekraftig klima. Effekten av observert temperaturøkninger er en trussel mot den globale likevekten og FN oppfordrer alle å finne løsninger for å skifte kurs og redusere nivået av utslipp. Gjør vi ingenting vil dette kunne koste oss dyrt.

Bortsett fra materialet tre er alle materialene som konkurrerer med stein hentet ut ifra stein. Sement, aggregat i betong, stål og aluminium er alle ultraprosessert stein.

Stein benyttet i en steinhvelvbru er ikke prosessert, bare tatt ut og formet fra naturlig fjell og deretter benyttet i sin naturlige komposisjon.

Produksjon av sement og stål krever store mengder med energi og bidrar med store utslipp av drivhusgasser. Bare sementproduksjonene alene bidrar med 8 % av de totale CO^2-utslippene i verden. Produksjonen av stål bidrar på samme nivå. Til sammen representerte utslippet fra produksjonen av disse to materialene et CO^2 – utslipp på hele 5.6 giga ton (Gt) i 2022 ut av en total på 35 Gt. Hvis utslippene fra produksjonene av sement og stål skulle representere et land ville dette landet være det tredje største landet for utslipp i verden etter Kina og USA.

I dag er bærekraft og helhetlig strategier etterspurt i alle sammenhenger. Når det investeres i infrastruktur er fotavtrykk fra hele livssyklusen som utslipp av klimagasser, energiforbruk, omfang av vedlikehold og forventet levetid sentrale faktorer for beslutningstakere når det skal velges framtidige brukonsepter.

FN's mål for bærekraftig utvikling er nå blitt et vendepunkt.

Litteraturundersøkelser, intervjuer av aktuelle interessenter, strukturanalyser og energi- og utslipps-analyser utført har bidratt til følgende konklusjoner i denne rapporten:

- En steinhvelvbru vil ha mindre behov for energi og vil bidra med mindre utslipp av drivhusgasser enn sine konkurrerende materialer.
- Med kvalitet i vedlikeholdsarbeid vil levetiden for en steinhvelvsbru være uovervinnelig. Det lave omfanget av nødvendig vedlikehold burde gjøre enhver brueier interessert i dette konseptet.
- Stein som material tilbyr nødvendig styrke og robusthet. Dette er underbygget av historien til eksisterende broer og konstruksjonsanalyser.
- En steinhvelvsbro er en konstruksjon med lave spenninger muliggjort av et sprøtt materiale satt i et system som tilbyr duktilitet.
- Stein er et alternativ som bør vurderes ved et konseptvalg av bru. Stein er i dag ignorert.
- En steinhvelvsbru er et konsept med begrensinger for lengder på spenn og kan være uegnet gitt stedsavhengige forhold.

Content

LISTE OF TABLES

LISTE OF FIGURES

1 Introduction

1.1 Background

Why don't we build stone arch bridges anymore? Should we? This is the questions this thesis is trying to give an answer to.

The existing stone arch bridges are all around. We look at them as remains from the past and find them often beautiful. They have been around for more than 2000 years and attract tourists due to their impressive aesthetics expression and endurance. Some are still in operating condition.

Figure 1-1: Viaduc de Cize-Bolozon - France

When planning for new bridge constructions today the stone as a material is not at all in consideration. The standard materials are mainly concrete and steel. Timber, aluminum and modern composite materials are sometimes chosen, but stone not at all.

Except for the material of wood, all the competitive materials to stone as construction material are extracted from a stone. Cement, aggregate in the concrete, steel and aluminum are all hyper processed stone.

The stone used in stone arch bridges is not a processed material, only cut and shaped out from natural rock and delivered for use in its natural composition.

The most serious global challenges we have today according to the United Nations is the emissions of green-house gasses from human activity causing severe treat to our climate. The effect of the observed rise of temperature is a treat to the equilibrium on earth and the UN urge to put high pressure on our activities to change course and reduce the green-house gas emissions. Business as usual can be a risky path to follow.

The production of cement and steel is a major contribution to the consummation of fossil energy and the emission of green-house gasses. The global contribution only from the cement industry is in 2020 8 % of the total CO^2 emission from human activity. The steel industry is at the same level. Together these two materials represent an CO^2 emission og 5.6 giga tons (10^9 tons) in 2022. If the steel and cement industry was regarded as one country alone this cement-steel nation would be the third largest country after China and USA with regards to the contribution of CO^2 emission from human activity.

Today sustainability and holistic thinking is urged for in most aspect. When investing in infrastructure the life circle impact of carbon footprint, energy consumption, maintenance scope and longevity has become major factors when decision-makers are to select the future concepts.

The UN goals for sustainable development and the request for a more environmentally friendly governance is now a gamechanger in many industries.

Is this a change giving reasons for a new "stone age"? Nostalgy and old technology describes the "status quo" for the stone arch bridge concept. It is not obvious to return to past solutions to solve the challenges of tomorrow. It is anyhow important to strive for new ideas when imposed changes arises in the horizon. To adapt for a new reality and prepare for a changed perspective of the future urge for turning of stones. To learn from the past is one of the stones worth turning. For the bridge industry the concept of the stone arch bridge from the past combined with the logistics and tools of today can be a contribution towards a more sustainable solution.

1.2 Purpose

There is a growing interest for using stone in the building industry. The architects see the potential in the stone material for façades, paving, landscaping and even as structural load carrying elements.

Figure 1-2: Padre Pio church – Renzo Piano -Italy

The stone arises as a low-carbon material and the durability is remarkable. The availability is ubiquitous and the aesthetics in harmony with the surroundings.

This master thesis main purpose is to search into the history of the stone arch bridges, investigate the strengths and weaknesses of the concept, find the opinions among stakeholders (Asset owners, engineers, entrepreneurs, researchers) and get a view of the life cycle perspective to prepare for a better discussion weather the stone arch bridge concept can be a part of the sustainable future we are striving for.

1.3 Method description

The work on this thesis has been a journey into the technology of the stone arch bridges.

The history, elements and terms of the concept, the theoretical basis of design and construction methods has been studied.

It has also been a journey into subjects as green-house gasses, climate change, the UN's targets for sustainability and the holistic views of life circle assessment.

The understanding of the strategy behind decision-making and experienced maintenance management of bridges has been important factors to reveal.

I brought with me into this work 32 year of experience within engineering and construction of steel offshore construction and 5 years of bridge inspections and maintenance.

The preface to the master thesis is built on a bachelor's degree from 1986 in civil engineering and recently 8 courses at the NTNU university with the subjects offered for the bridge engineering specialization under the program for road and railway. These courses have been concentrated technically on subject as geotechnics, concrete material technology, bridge design and analysis.

The stone arch bridge as a topic has not been in the focus when building up the foundations of the researcher.

Still, this foundation gives a reasonable basis for learning and understanding this old technology and enables a possible interpretation to find some answers on the main objectives.

The method used for the work is selected from the necessity coming out from the above-described background.

Literature research has been necessary to gain knowledge about:

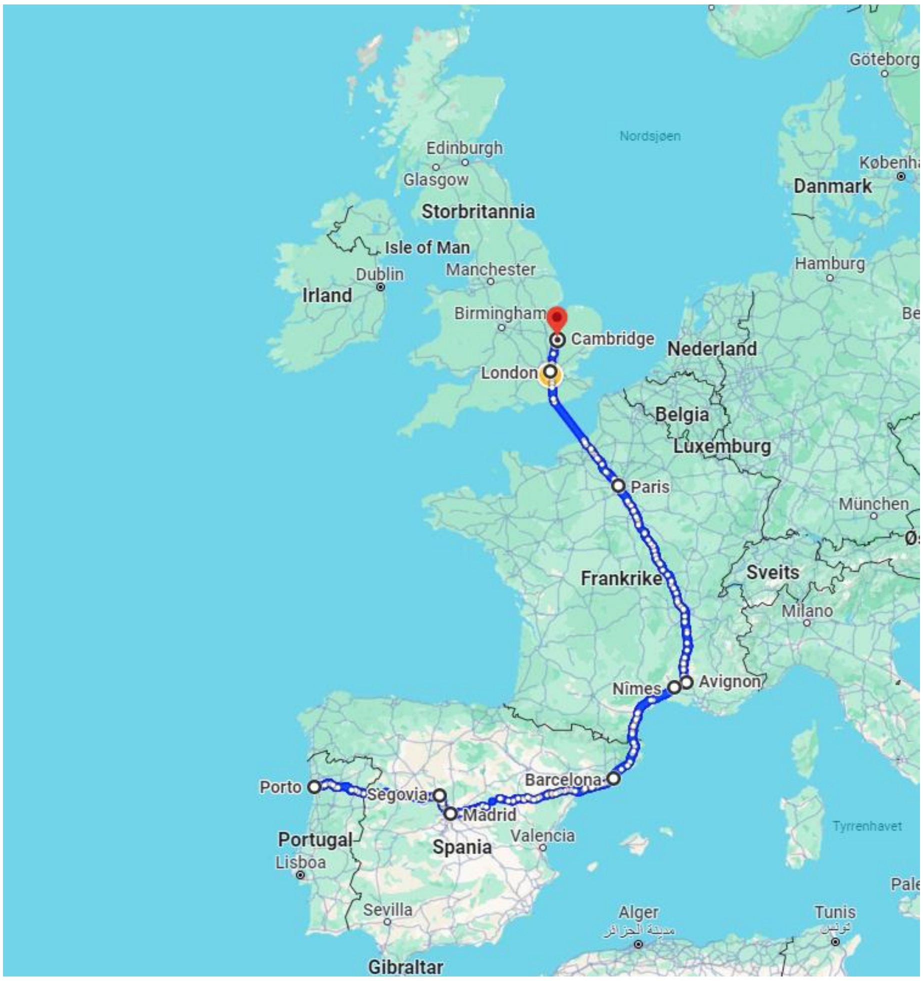
- The history of stone arch bridges.
- The technology of stone arch bridges.
- The green-house gasses emissions and the UN's goals for sustainable development.
- The live circle assessment.

Interviews of stakeholders in the bridge industry is carried out with a basis in questions and subjects relevant for the purpose. The mixture of interview objects represents a wide range of stakeholders representing asset managers, design engineers, authorities for guidelines, environmental engineers, professors in academia, architects, road engineers, project managers for new constructions and entrepreneurs both in the bridge building industry and in the stone quarry industry.

To understand the limits with regard to strength and status of design guidelines an analysis of an existing stone arch bridge in Norway has been carried out. For this work two different approaches are carried out to compare the limit states used in Norway and UK. The programs StaadPro and Archie-M program are used in the analysis.

A site visit to Lund AS in Larvik, Norway was carried out in January 2024 to learn about the logistics in a modern quarry and their knowledge on possibilities and challenges.

Finally, a 3-week educational tour has been carried out meeting with persons of knowledge and visiting sites of relevant structures and quarries in Portugal, Spain, France and UK (see chapter 6).



Tabell 1–1 Study tour itinerary

2 The stone arch bridge

This chapiter presents the stone arch bridge concept.

The terminology, the components, the history and the theoretical science behind are described to determine the state of the art.

2.1 The terms and major components

The stone arch bridge technology developed through times has an established terminology. The following figures presents the major components and terms.

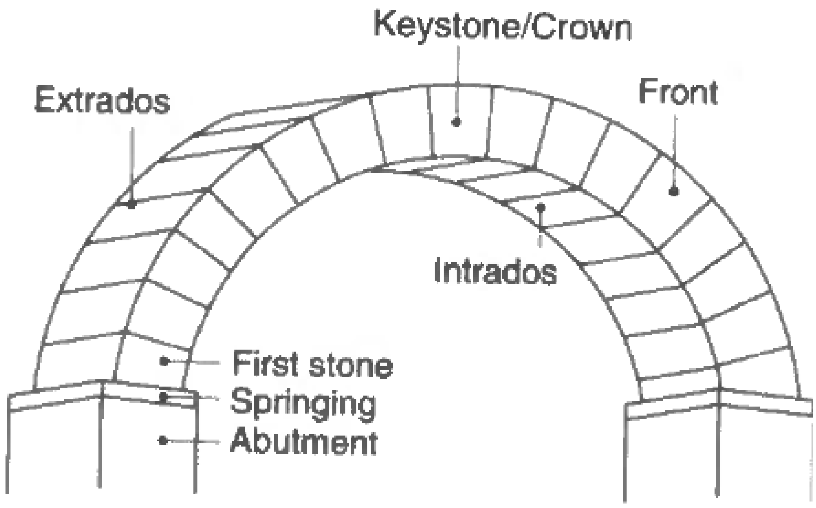


Figure 2-1: Stone arch – components (ref. /9/)

- The arch
  The arch itself is a part of the bridge which carries all the loads above the arch and the self-weight to the foundations. The inner side of the arch is the intrados. The outer side is the extrados.
- The voussoirs
  The voussoirs are the wedge-shaped stones of the arch and the voussoir at the top of the arch is the keystone or the crown.
- The springing (Kemper in Norway and Germany)
  The springing is where the arch meat the topmost part of the abutments and is the point from where the span of the arch is defined.
- The abutment
  The abutment is the construction at each end of the arch transferring horizontal and vertical loads from the arch to the foundations below and behind.
- Spandrel wall
  Spandrel wall is the masonry walls at each side of the bridge above the arch supporting both the backfill and parapets of the bridge.
- The mortar between the voussoirs (if used)

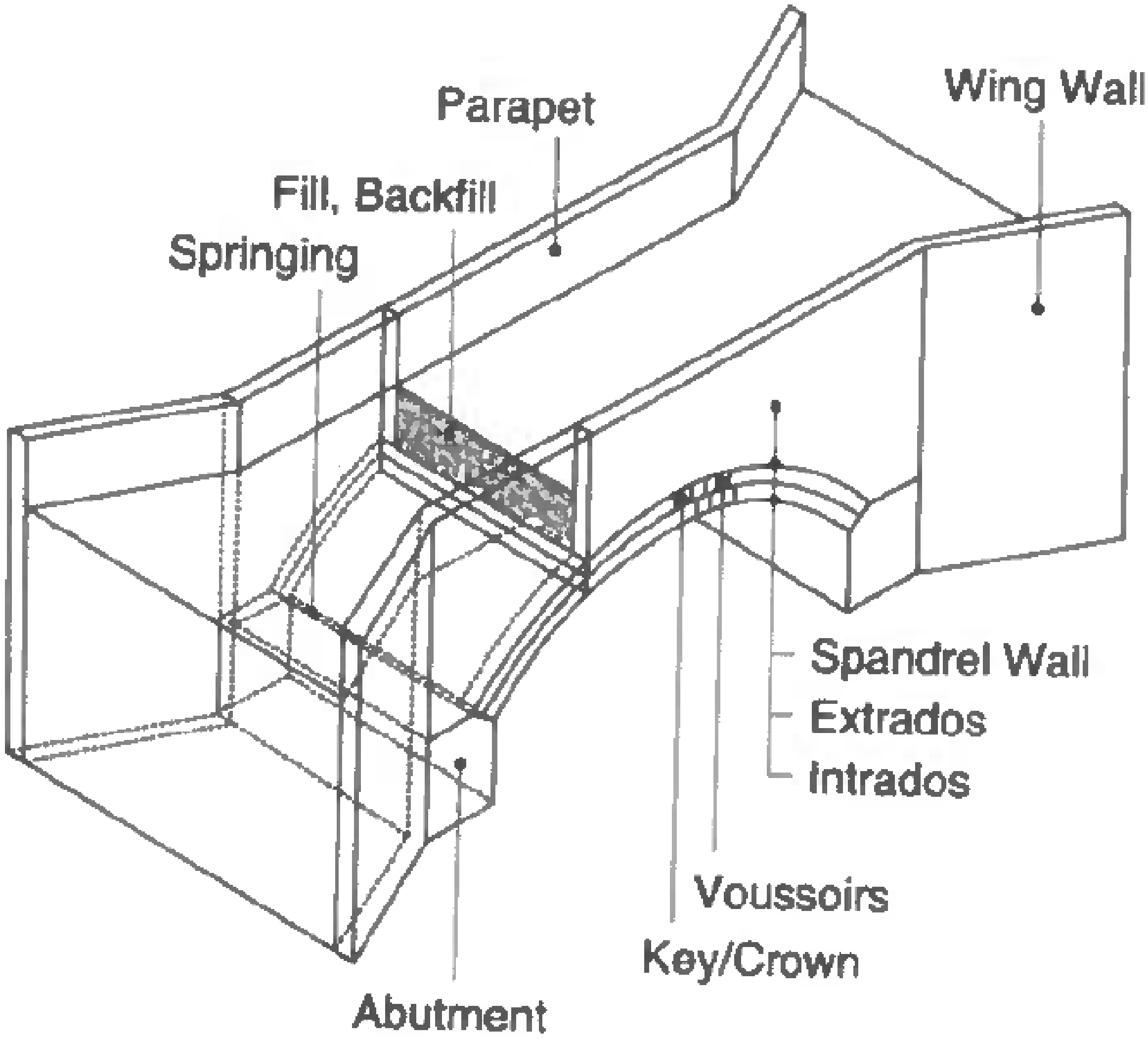


Figure 2-2: Stone arch bridge – components (ref. /9/)

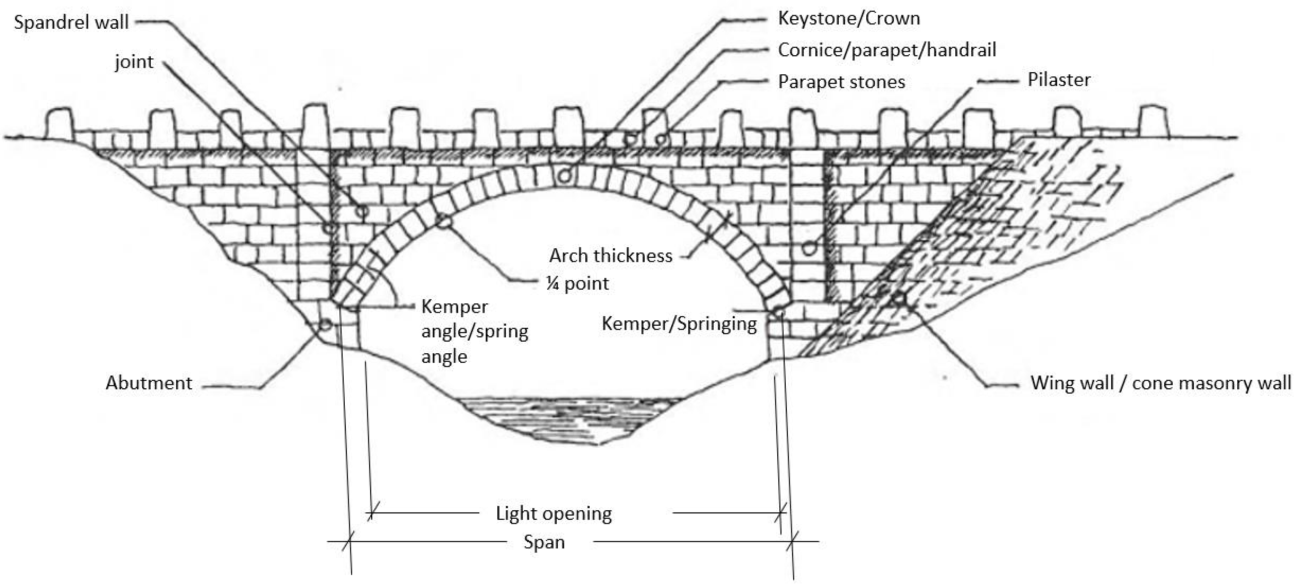


Figure 2-3: Stone arch bridge – components (ref. /1/)

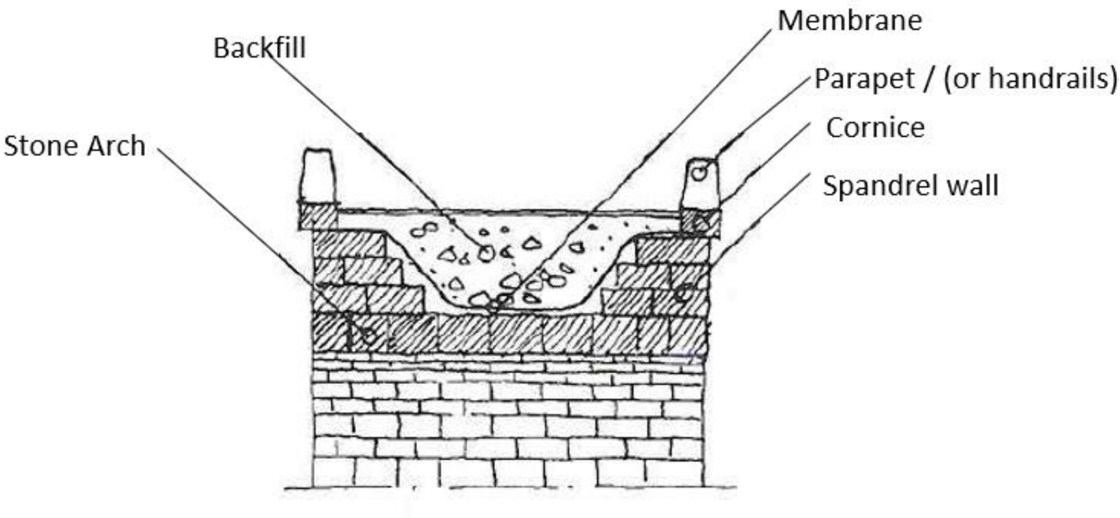


Figure 2-4: Stone arch bridge – components (ref. /1/)

2.2 The history

2.2.1 The start and the early development

Through history stone arch bridges has been a helpful invention for the humans need for mobility and transport. The discovery of the wheel as a tool for transport and the use of bulls and horses to improve the driving force provoked the need of roads. With the building of roads came the construction of bridges and stone arch bridges became a part of the solution.

This period represents only approximately 5-6000 years in the human history. As we have been around for 300 000 year it took us some time to get there.

When considering the existing natural shapes one can imagine where the idea came from. In the Arches national park in Moab (Utah, USA) and the Great Ocean Road (Victoria, Australia) the nature itself speaks to us and points to the idea of a stone arch bridge. After years of erosion and wear the remains of the formations is a natural made stone arch.

(copy right: T.A.Hagstrøm)

Figure 2-5: The arches national park - Moab, USA

Figure 2-6: The arches national park - Moab, USA

Figure 2-7: Great Ocean Road - Victoria, Australia

Archeological discoveries of stone arch constructions dates back 5000 years and are found in Mesopotamic and Egyptian burial chambers. The old Greek and the Etruscans contributed a wide use of stone arch construction. The idea was extended for use in buildings like amphitheaters, city portals and bridges.

A further step of development came with the Romans. Marcus Vitruvius Pollio (engineer and architect) writes to us from the century before year 0 and tells us that buildings should meet 3 requirements – utilitas- firmitas-venustas (useful-lasting-beautiful). A stone arc bridge fulfils his requirements with grate ease and the Romans built many.

In the time of the Roman Empire approximately 80 000 km of roads was constructed. Around year 100 A.D the road system of the Italian provinces of the empire was represented by road system of 16000 km for 8 million people (ref./9/). The Romans understood the power of trade and transport. The investment in transport infrastructure was of high priority. The road network made it easier to govern and explore the resources as the empire expanded.

The extend of the road infrastructure at that time is reflected in the figure 2-8 below. This is an illustration based on The Antonine Itinerary from the time of emperor Antonine Pius in the second century (ref. /38/).

Figure 2-8: The Roman Road map based on The Antonine Itinerary (ref. /47/)

From a global perspective at this time the concept of stone arch bridges also had started in China. As the Romans and the Chinees was two separate cultures it is interesting to observe the independent evolution of ideas.

Despite of a decline after the Roman Empire the development of stone arch bridges got a new boost from the 11th century as the population, number of towns and economy in Europe developed.

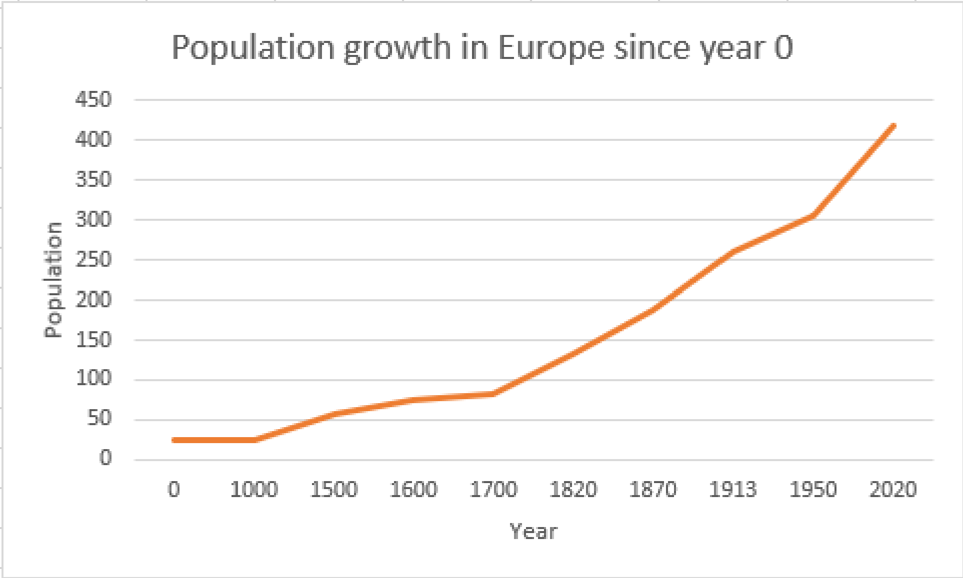


Figure 2-9: Demographics of Europe 0-2020 (in millions)

As the understanding of structural theory evolved and the complexity of the science increased it was necessary to separate the versatile architect-engineer type of expertise into more specialized disciplines. The design of bridge structures grew in complexity as the limits of spans and slenderness was stretched. It became obvious that an engineer or an architect needed to specialize.

As a result of this realization the academical institutions in Europe expanded. The "Ecole des Pont et Chaussée" was founded in Paris in 1747 as the first academy for bridges. Jean-Rudolph Perronet (1708-1794) was the head of this school for the first 47 years. From his long list of bridge constructions one of his masterpieces was the design of the bridge Neuilly built between 1768-1774. In his book "Description des projects et de la construction des pont De Neuilly, de Mantes , d'Orleans" (ref/39/) the construction of the Neuilly bridge is illustrated and described.

His most impressive design is the still standing, the Concorde Bridge in Paris opened in 1794. This was his final contribution. In the National Library of France many of his papers is well preserved.

It is interesting to notice that in the time of Perronet, the horse was still alone on the market giving horsepower to vehicles and he did not experience the first wagon on rails pushed by horses. Still his slender Concorde bridge is carrying the live loads of today.

Perronet made huge influence on later grate engineers like Thomas Tellford (1757-1854) and Paul Séjourné (1851-1939). In the library of the Institute of Civil Engineering (ICE) in London Thomas Tellford's own book from Perronet (ref. /39/) can be studied.

2.2.2 The peak of the construction period

The peak of stone arch bridge construction came after the invention and extended use of trains in the 19th century.

The industrial revolution started in the late 18th century with the discovery of new energy sources, materials, machine tools and mass-production. This is considered as the most important step in human history since the domestication of the animals and plants.

The production of coal, iron, chemicals, tools and textiles grew rapidly. The expansion in population and production volume increased the need for transport.

The requirement for roads and the general mobility of the society demanded new solutions and the possibility of forming the landscape and straighten the road line became easier with the new tools and more power resources.

The slow horse wagon could follow the old tracks in their slow passing but new vehicles with higher speed and heavier load needed straighter roads.

More roads required more river and valley crossings and hence increased the number of bridges.

Up to this time the power of transport was the horse. Even at the early age of the railway the horse was the main source of power.

In 1805 the reduction of friction from a normal road to a railed distance was demonstrated outside London. One horse was expected to move about 1 ton on a normal road.

An iron-plated wooden railway was tested with 36 tons from 12 coupled wagons using the same horse. After 2 hours the horse and the 36 tons have all moved 10 km (ref. /38/).

The 19th century became the time of "Rail-mania" and peaked the construction of stone arch bridges.

The opening of the Göltzsch viaduct in 1851 is one example of the success for the stone masonry bridge industry in this period.

Figure 2-10: The Göltzsch viaduct in Germany - 1851

The bridge engineer Paul Séjourné was born this year (1851) and still he experienced a hole professional career building stone arch bridges till his death in 1939. The Pont Adolphe (Luxembourg -1904), Pont Fontpédrouse (France – 1908) and the Viaduct de Scarassoi (France – 1925) was some among several bridges he designed and constructed.

Figure 2-11: Pont de Paul Sejourne -Viaduc de Fontpedrouse- France

The number of stone arch bridges built in this period is large. Not only in Europe but in every corner of the world where the railway progressed the number of stone arch bridges increased. The bridge industry grew and then also the numbers of qualified engineers and entrepreneurs. Séjourné was one among many experts.

In Norway there is today approximately 650 stone arch bridges in the road and railway system all together. All was constructed before the second world war. Many are still in service. There is one exception. The Åros stone arch bridge was constructed in 1999 but for very particular aesthetic reasons in a small historic village (span 25 m). In comparison the number of road and railway bridges in service is approximately 23 000.

The Orkla railway bridge was built between 1911 and 1916. It is the longest span built in Norway for a stone arch bridge. The stones were extracted in local quarries and for the transport horses was used. This is a three centered symmetrical shaped bridge and the design is based on stress limitations using elastic theory. It is still in service, and the Norwegian Railways authorities states that there has been no major maintenance investments on the main structure so far. Calculations, drawings and descriptions for this bridge is well preserved and gives an important possibility for transfer of experience (ref. /32/ and /33/).

Figure 2-12: Orkla railway bridge - 1916

Globally many have tried to estimate the numbers of stone valve bridges after the "golden age" but it seems like a difficult task where different sources gives a wide range of answers.

The International Union of Railways made a systematic analysis of the arch/vault bridge stock in 2005. Thirteen railway organizations contributed and reported a number of 200 000 railway arch bridges. The report concluded that up to 60% of the stock was stone arch bridges (ref. /9/)

2.2.3 The decline of the concept

Up to 1860 the stone arche bridge was almost alone on the market and specially for railways. The only alternative was wooden bridges. The wood as material was not allowed to use for the railways in Germany from 1865, but new materials was to become competitive.

With the new energy sources came the mining of iron and the further processing of steel materials. The first cast iron road bridge was built over the Severn Coalbrookdale in England in 1779. The improvement from cast to wrought iron increased the possible spans. The refinement to steel improved the concept further. Gustav Eiffel (1832-1923) is one of the pioneers well known for his tower but more important was his contribution in building steel bridges.

In the very late 19th century and in the beginning of the 20th century the first concrete bridges were constructed. Another competitive material made possible due to the new energy supply from coal mining and fossil fuel. At this time in Germany almost 50 % of the new railway bridges was built of steel. The decline of the stone arch bridge had started.

In figure 2.13 and 2.14 the decline is clearly illustrated (ref./9/ and /48/).

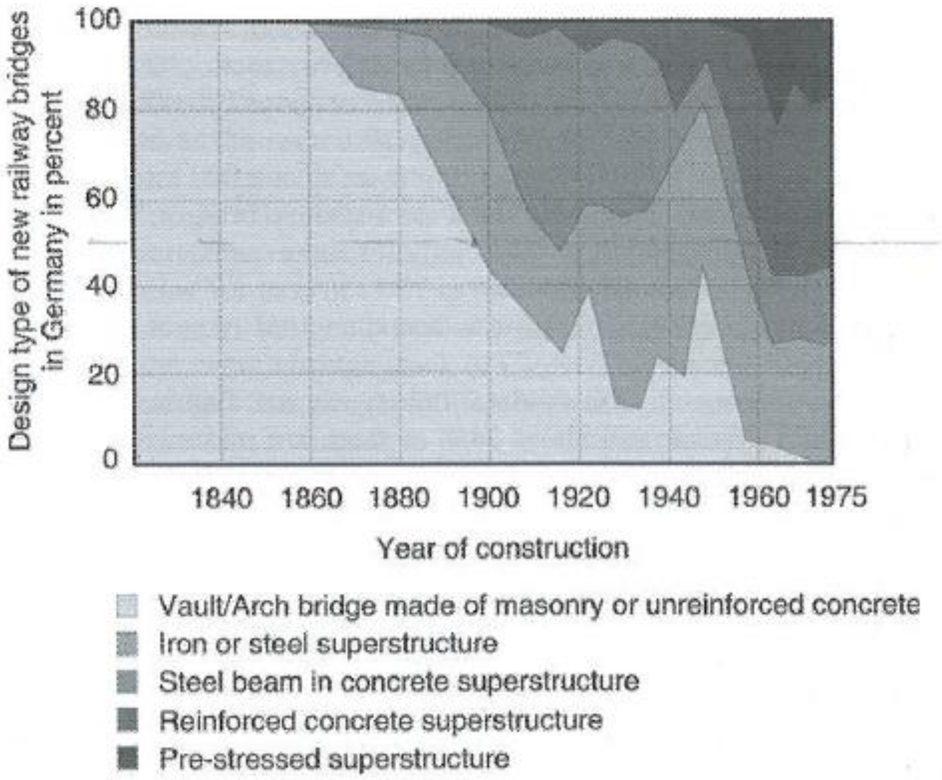


Figure 2-13: Design-type railway bridge in Germany

Similar development is found for the masonry bridge construction in the US. The drop is sudden and the concept fades out after the second world war.

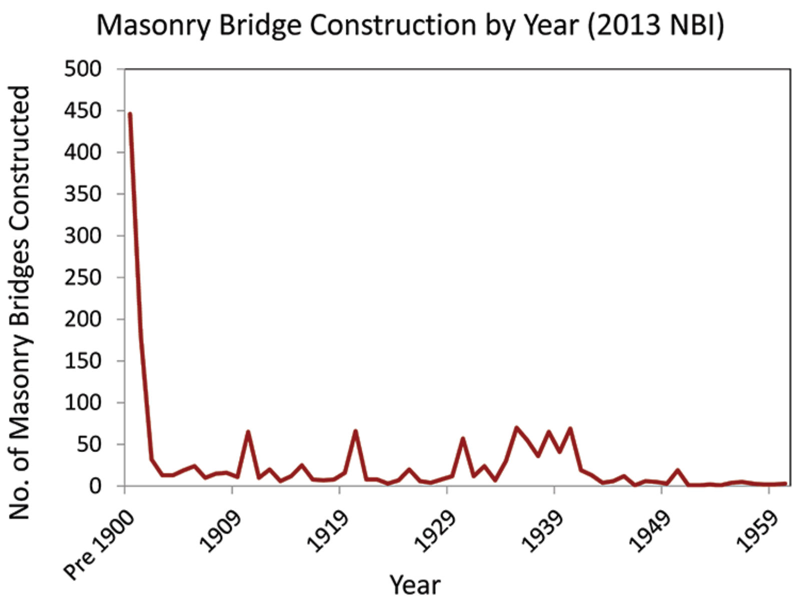


Figure 2-14: Masonry bridge construction over time in the U.S

In this historic perspective, what seems to be the major reasons for this decline which roughly made an end to the use of the stone material for bridges in the middle of the 20th century? Why did we stop making them, the stone arch bridges?

As everything is connected reasoning must consider the dramatic number of individual changes. The expanding population, the academic progress, the technology development, the invention of new tools, the access to new and powerful sources of energy, the invention of new vehicles, the increase level of live loads and the increased production of goods and service are all connected to the industrial revolution.

The new available energy sourced from coal and fossil fuel facilitated the competitive materials. The steel and concrete materials allowed for optimized logistics for the use of labor, reduced the material weighs and allowed for longer and more slender constructions.

The tools for a competitive stone arch bridge productions were not an issue as the alternatives from the high energy intensive materials reduced the time consumption, labor consumption and the costs.

Among all these factors there is also the economy were profits and competition are pushing the direction of development.

The grow rate for both the population and the production of goods increased dramatically. The economical fortunes earlier mostly defined by agriculture found new areas as factories, energy sources, tools and minerals. In the beginning of the 18th century the agricultural property represented 70 % of the total capital in both UK and France. Today this has decreased to 2 % (ref /37/). What we value is not static and the transfer to the modern world have been dramatically the last two centuries. These factors had all an influence on the development of transport infrastructure.

If we should construct a new bridge today, all the materials can be designed to meet the functional requirements. For the large spans and most spectacular bridge constructions the choice becomes more limited. To build a bigger stone arch bridge than the Dahne bridge (China -2001) with one single span of 146 m would be a challenging project. But for smaller spans, which represents most of the constructions, the stone, the steel and the concrete is feasible materials.

Figure 2-15: Dahne bridge – 4 lane motorway – 2001 - China

Most of the old stone arch bridges is out of service because of the change of requirement for width. Many is also standing unused and is worn down by time and weather, abandoned aside of a more updated road.

Lately the value and cost of carbon footprint, energy consumption, water consumption, pollution and loss of nature has entered the scene and appears in this analysis when we are investing in new projects.

The historical perspective show that a change in values and governance strategies has provoked major changes for industries in the past and it is possible that this can happen again.

The list of compound and complex factors behind the decline of the stone arch bridge will today reappear in a new holistic setting and the conclusions of yesterday might not be the answers for tomorrow.

In this context a renaissance for the stone arch bridge might arise.

2.3 The physical understanding and theoretical principles

To understand the structural behavior, the strength and the weaknesses of a stone arch bridge is essential if the concept should in anyway become a preferred concept among competitive concepts and materials.

The stone arch bridge is a concept of low stress utilization. Finding the correct equilibrium and balance between the structure itself, the foundations and the wanted functionality enables a robust construction with it's distinctive ways of offering ductility and safety even if the stone being a brittle material.

Leonardo da Vinci (1452-1519) observed that "an arch is a strength formed by two weaknesses". He considered the arch as two weak parts leaning on each other giving strength.

Robert Hooke (1635-1703) is best remembered for his law of elasticity, but his description of the arch geometry is also a major historic contribution. One of his quotations was published in a series of anagrams in 1675 and included in his book on helioscopes and other instruments (ref /26/). "ut pendet continuum flexile, sic stabit contiguum regidum inversum". As hangs the flexible line, so but inverted stands the rigid arch.

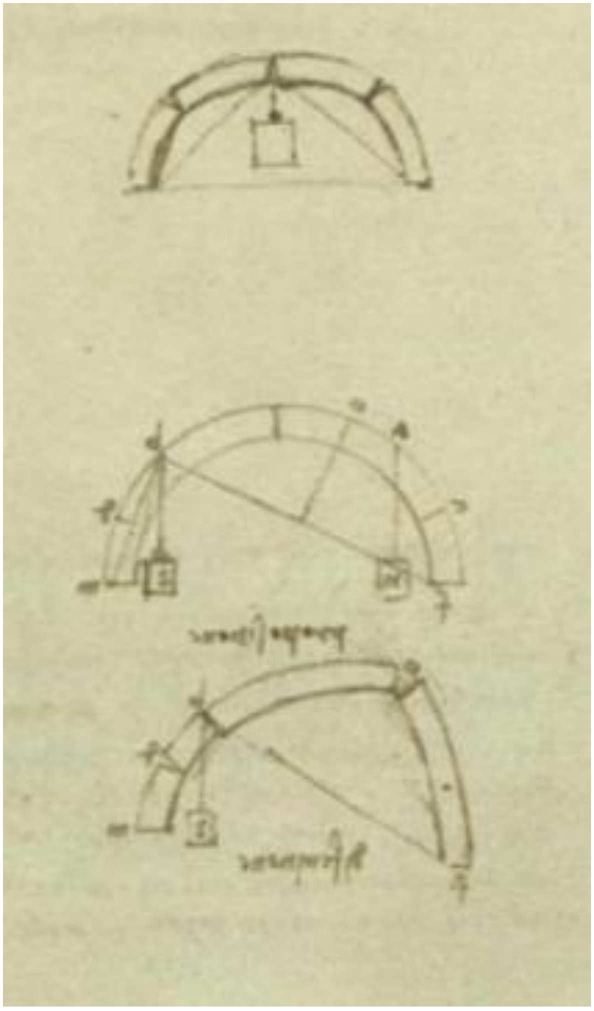


Figure 2-16: Leonardo da Vinci - Codex Madrid

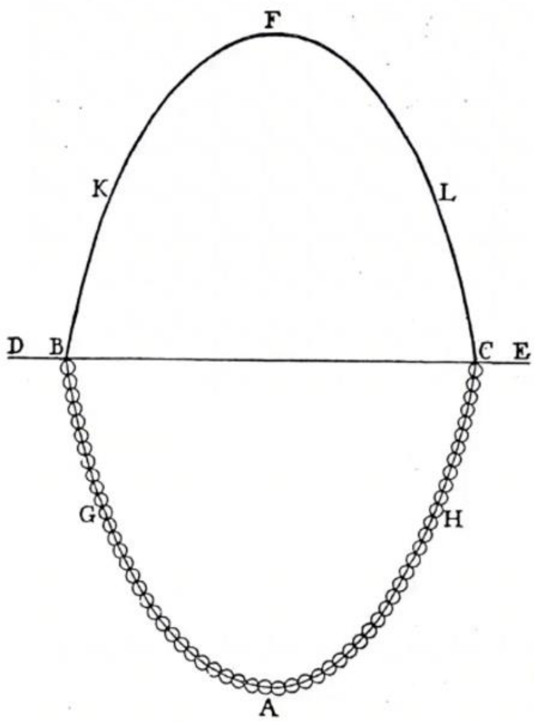


Figure 2-17: Hanging chain - A rigid arch - Robert Hooke

Both these statements reflect upon the physical understanding of an arch. The stone arch is standing due to the equilibrium within the geometrical shape. The gravity of the masses, the strength of the material and the resistance of the abutments contributes to the standing arch.

The vertical load from the weights of each stone is carried in compression to each end of the span. At the springing there is a trust consisting of both a downward vertical and outward horizontal force component. Both are to be resisted of the abutments and the underlaying foundations.

As for the hanging chain pulling the ends horizontally inwards the inverted arch generates a similar pressure on the abutments outwards.

The line of resistance or line of thrust within the arch is defined by the fact that the compressive thrust is passed from stone to stone by contact pressure at each joint. One possible variation of the line of trust is visualized in the figure 2-18. Optional lines of thrust are many.

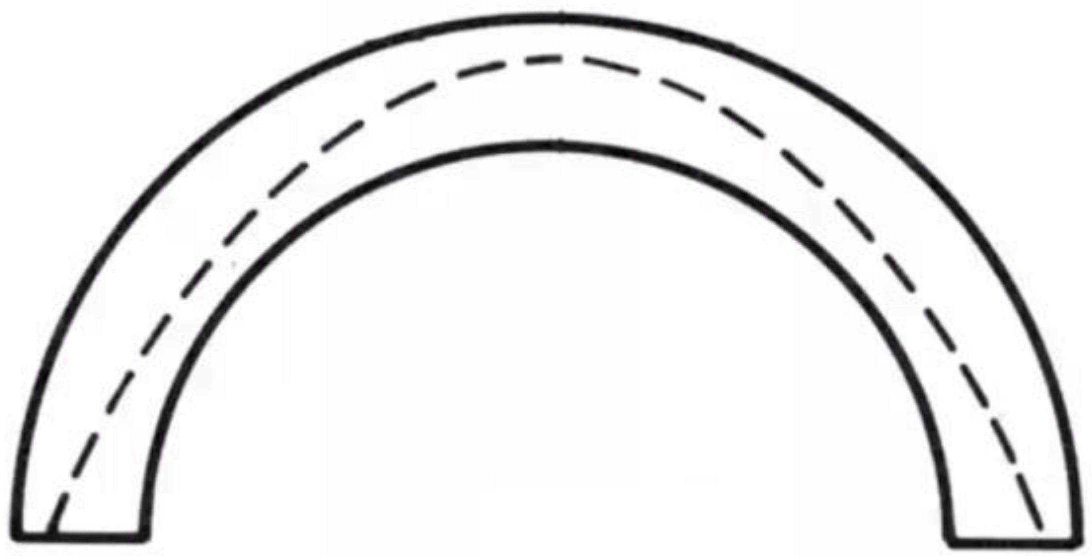


Figure 2-18: The line of thrust within an arch (ref. /27/)

Any changes to the geometry will cause the line of trust to adjust. If the abutments due to outward pressure moves away mobilizing some passive pressure in the fillings/soil, the line of trust becomes as shown in figure 2-19. The indicated gaps/cracks might be very small and even not visible for the eye, but it is obvious that the line of trust at these locations must pass through the contact surface indicated as hinges as there is no tension capacity considered in the cross section of the joints.

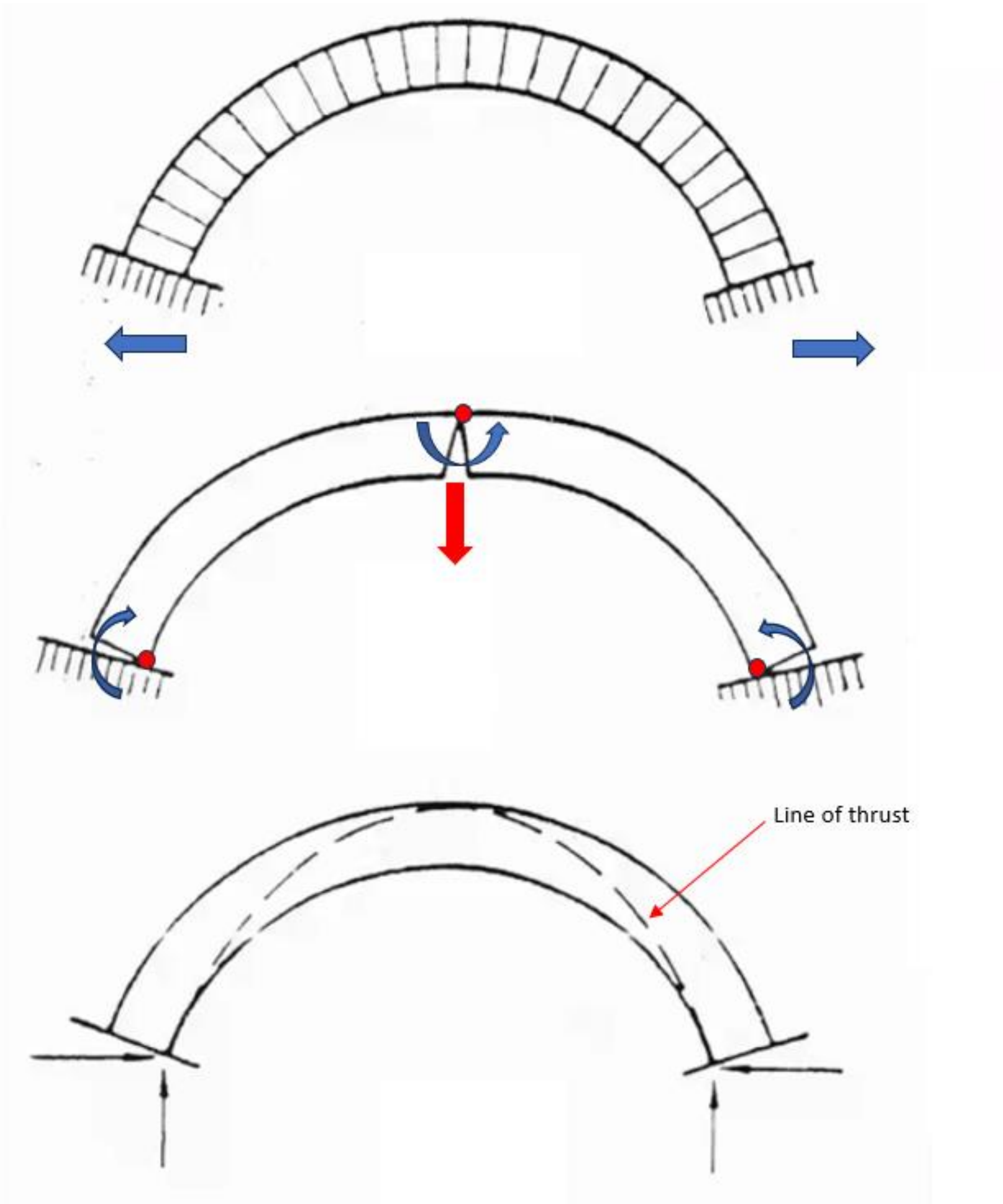


Figure 2-19: The line of thrust – outwards displacements (ref. /27/)

Opposite if active soil pressure generates inward displacement of the abutments the line of thrust moves as shown in figure 2-20.

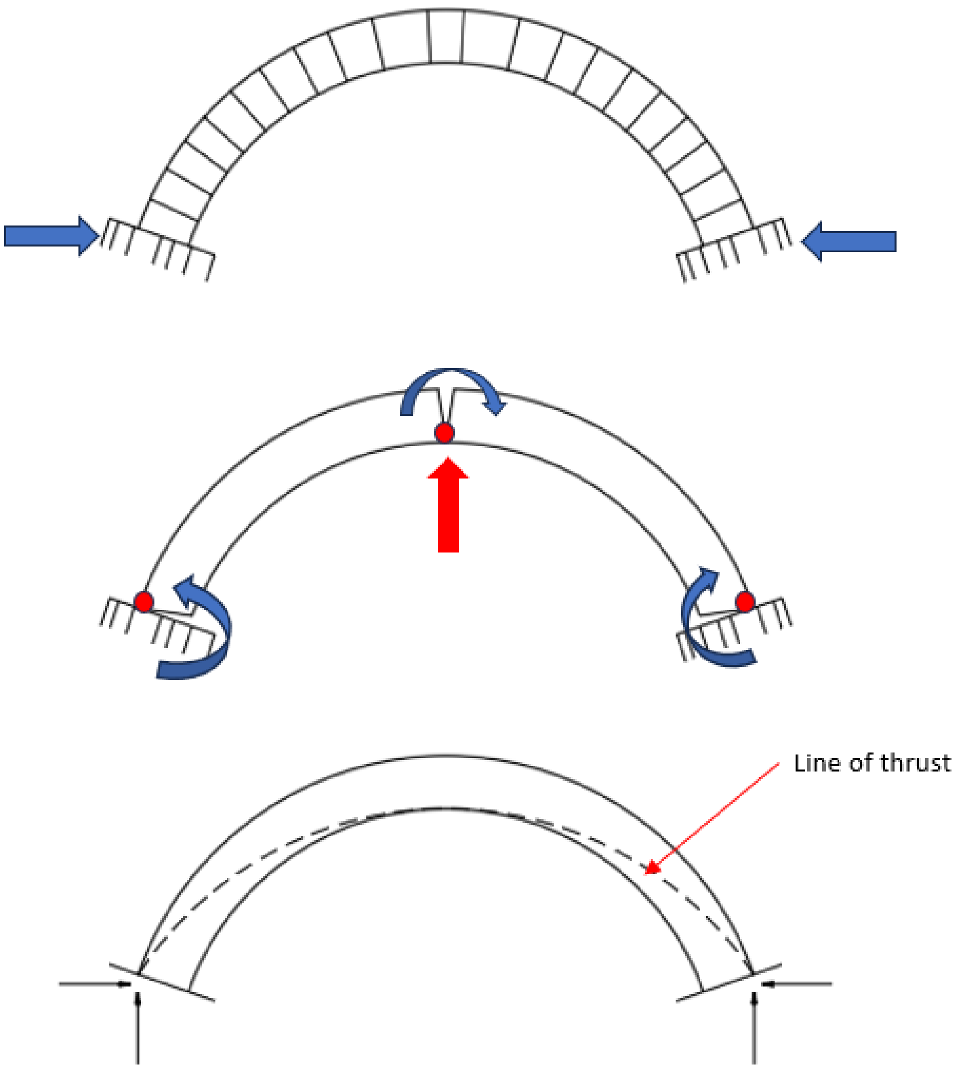


Figure 2-20: The line of thrust – inwards displacements (ref. /27/)

W.H. Barlow demonstrated a visualization with his model at the ICE (Institute of Civil Engineering) in London (1846) of some the possible variations of the line of thrust. He used pieces of wood between the voussoirs and for each line of trust he removed the wooden pieces outside of that specific line of thrust.

In figure 2-21 is the original sketch of the demonstration. In figure 2-22 the visualization is shown using colors. He left only the wooden pieces of the same color to demonstrate each line of thrust.

The blue trust line is where the axial load decrease to a minimum as the abutments move out and the crown is moving downwards.

The green trust line is where the axial load increases to a maximum as the abutments move in and the crown is moving upwards (ref. /17/).

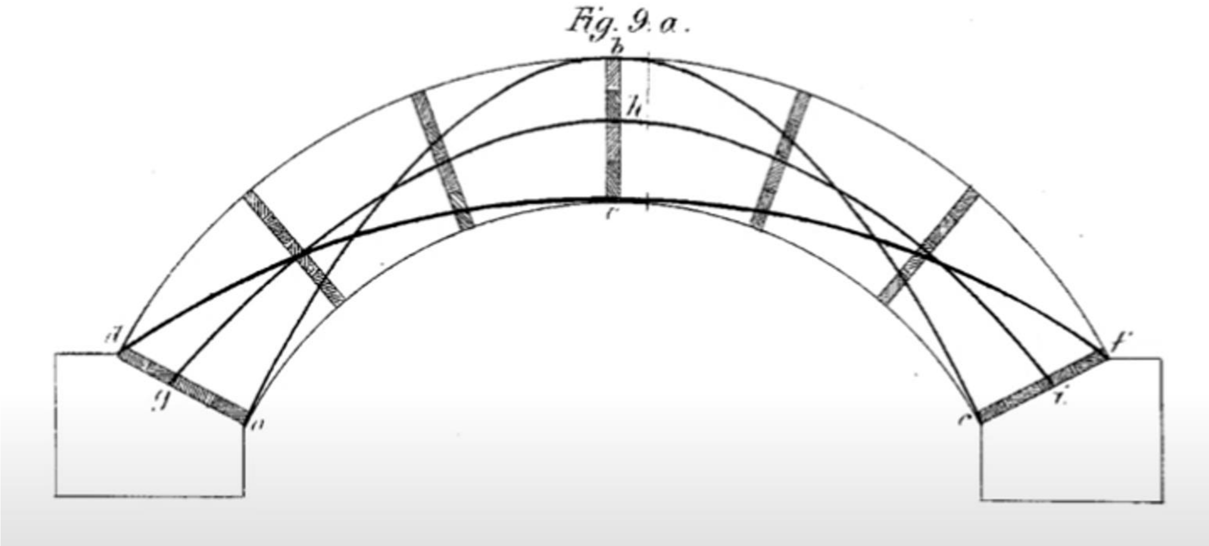


Figure 2-21: The line of thrust demonstrated by Barlow – 1 (ref. /26/)

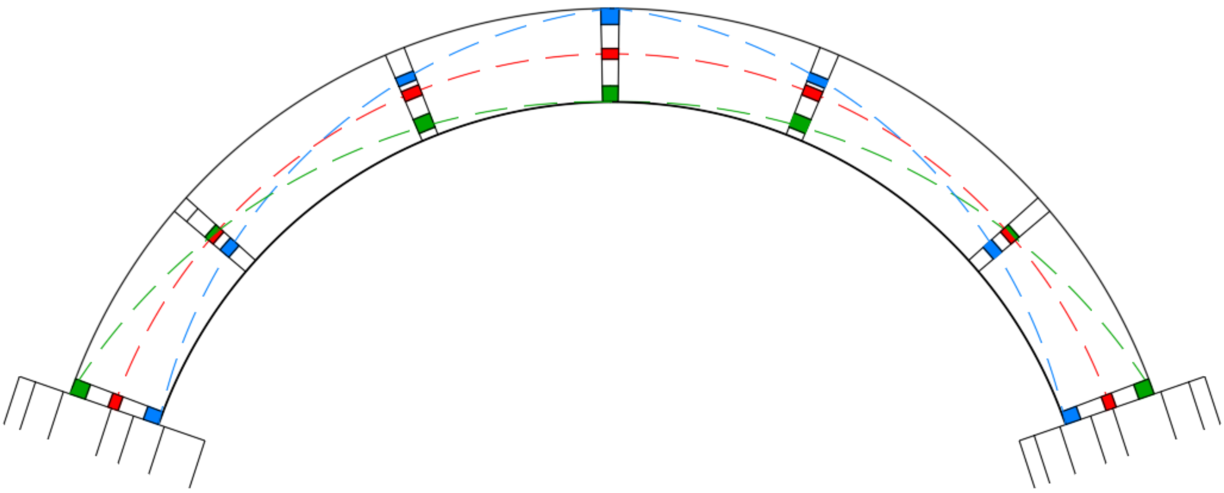


Figure 2-22: The line of thrust demonstrated by Barlow – 2

The two models of figure 2-23 and 2-24 (the blue and the green thrust line) with the defined hinges are statically determinate.

Fx+Rx =0 → Fx=-Rx

W+Ry =0 → W=-Ry

Fx*a+W*b =0 → Fx=-W*b/a

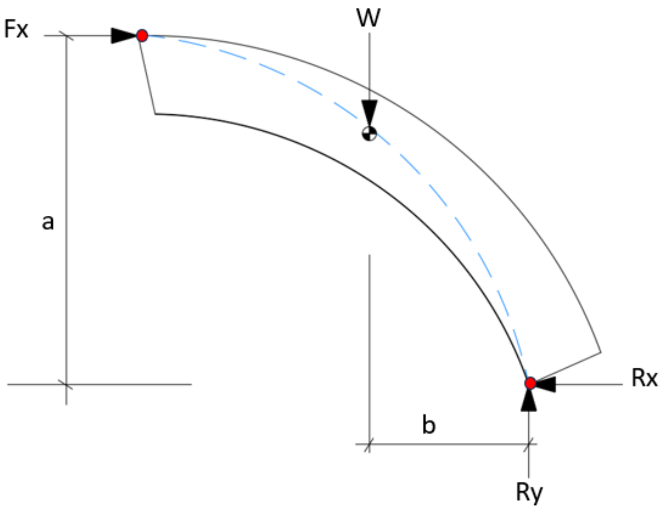


Figure 2-23: Statically determinate model – minimum axial thrust

Fx+Rx =0 → Fx=-Rx

W+Ry =0 → W=-Ry

Fx*a+W*b =0 → Fx=-W*b/a

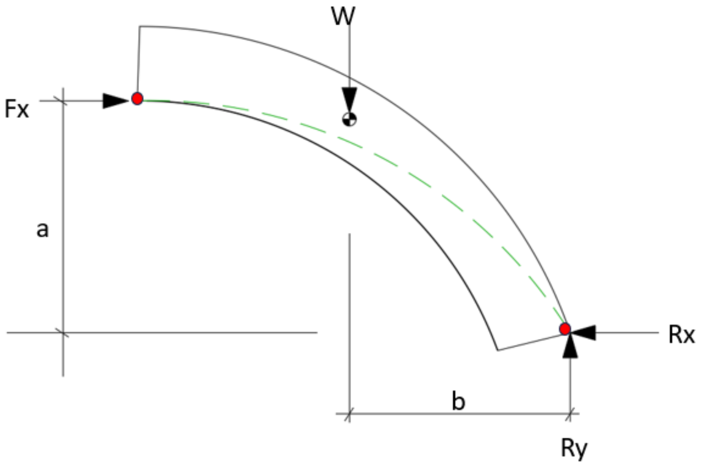
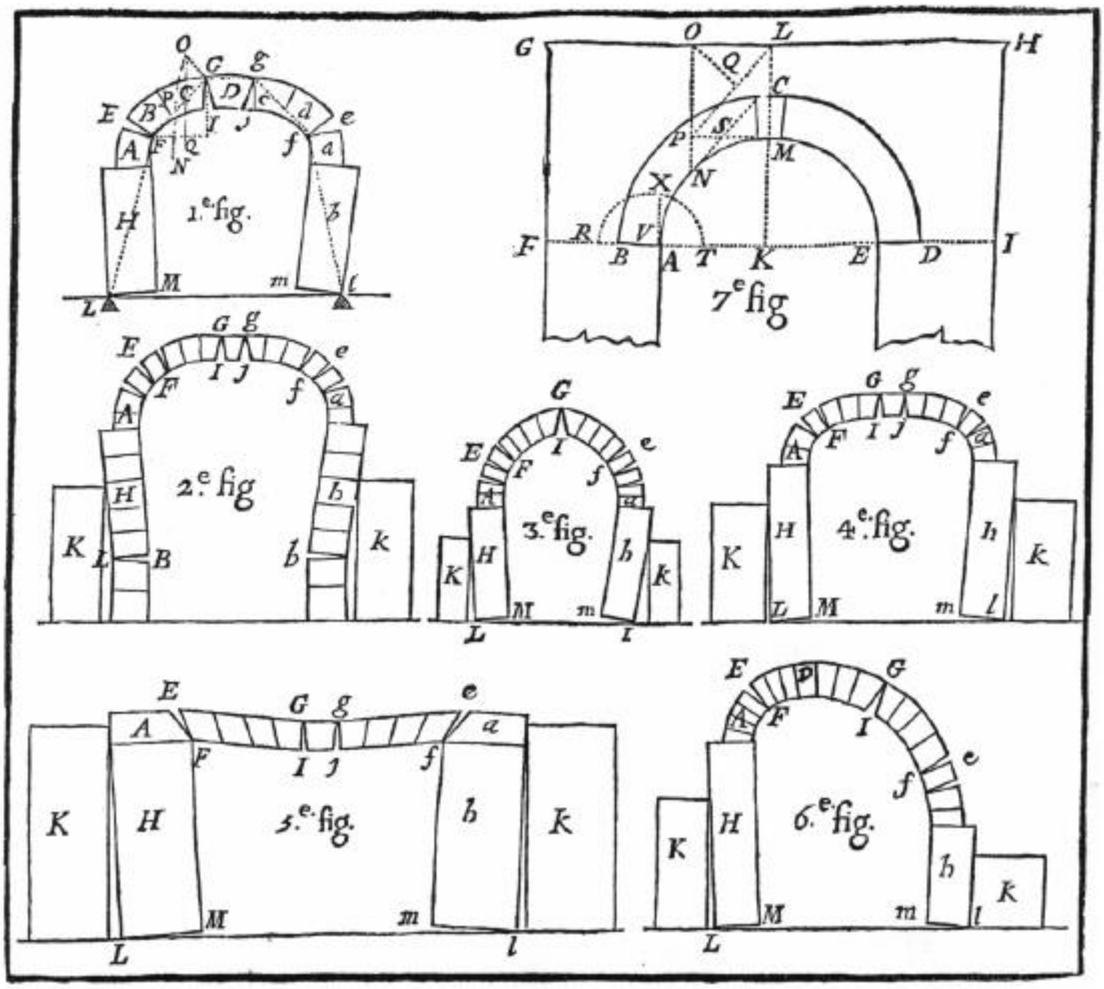


Figure 2-24: Statically determinate model – maximum axial thrust

The various lines of thrust between these two extremities are not known and the model becomes statically indeterminate without selected points of hinges. One can select a given geometry among many possibilities to enable the above definition of theoretical forces.

David Gregory, who in 1697 completed the mathematics for Hook's inverted arch issued the statement that if any thrust line can be found lying within the masonry, the arch will stand (ref 26/).

The arch way of giving ductility and redundance is the many ways within the construction it finds possible displacement configurations where hinges can form (cracks in the joints). 3 hinges are a stable and statically determinate situation. Forming a 4th hinged and the mechanism provokes a collapse. In figure 2-12 presents possible developments of hinges towards a collapse for various masonry structures is presented by Danyzy (ref. /26/).



Figur 2-25: Collapse of masonry structures - Danyzy (1732)

In the design and assessment of the stone arch bridge the compression strength of the arch stones is a major limitation as the stresses should be kept at a low level compared to the ultimate strength of the material. It is the level of axial thrust in the arch that gives the structure it's strength (up to a certain level)

Considering the behavior of the arch and how the hinges might establish is essential to enable the definition of equations of equilibrium and hence enable the calculation of the forces and stress levels.

There are 3 assumptions within the theory (ref. /27/):

1. Masonry has no tensile stress.
2. Stresses are so low that masonry has effectively an unlimited compressive strength.
3. Sliding failure does not occur.

The first assumption is conservative. The stones can have some level of tension capacity. But for the joint and when using mortar this assumption is close to correct.

The second assumption is a statement linked to the fact that a conservative design of an arch bridge should lead to low average compression stresses in the stones. The development of hinges can develop local crushing, splitting or surface spalling. Such local distress will not lead to collapse of the structure but provoke settlement, adjusted line of thrust and a new stable status of equilibrium.

A stone arch bridge should be designed to a low stress utilization rate but one must bear in mind that it is the axial compression loads which give the strength and stability to resist both the deadload and the live load. A typical value of 5-6 MPa in compressive stress is often a selected limitation. The capacity of quality stone in Norway is in the range of 50-200 MPa in compressive strength.

The Orkla bridge in Norway was constructed from 1912-1915 with a span of 60 m.
A statically determinate method was used to define the forces and moments in the structure. Geometrical method using force polygons enabled the calculations. The details of the force polygon and the funicular polygon will not be discussed in this thesis but is well presented by J. Hayman (ref./28/)

Using elasticity theory, the stress levels was calculated in 4 positions of the cross section at 5 positions of the arch. The limiting compression stress allowed was set to 50 kg/m^2 (4.9 MPa). The compressive strength of the stones ranged from 147-187 MPa.

They allowed a limiting tension stress level at the springing due to temperature effects of 0.6 MPa.

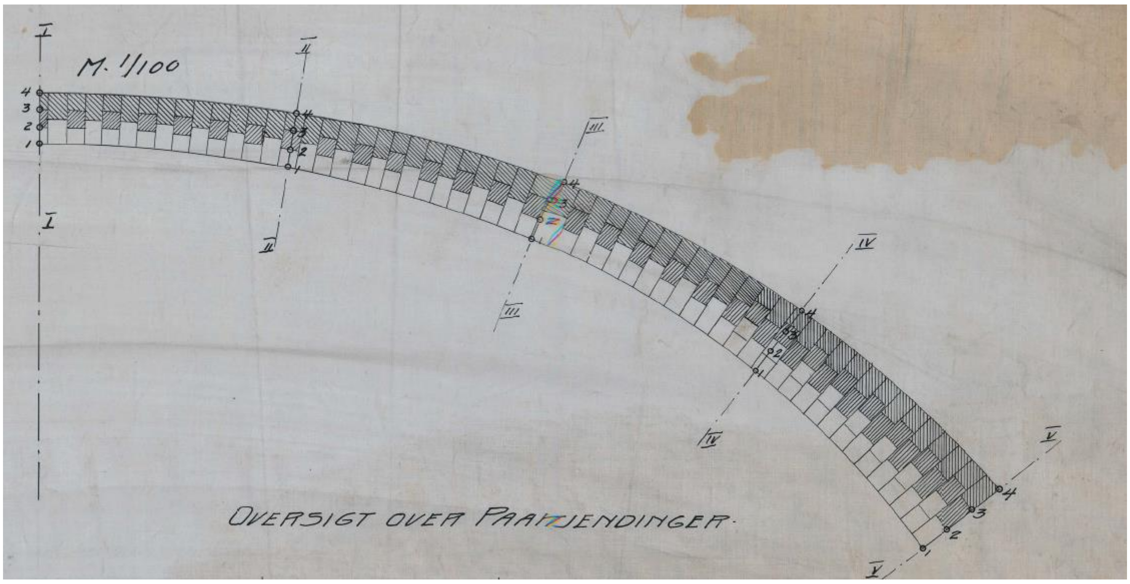


Figure 2-26: Orkla bridge – positions of stress verification

Below is the drawing presenting the elastic calculations performed dated 31.05.1911.

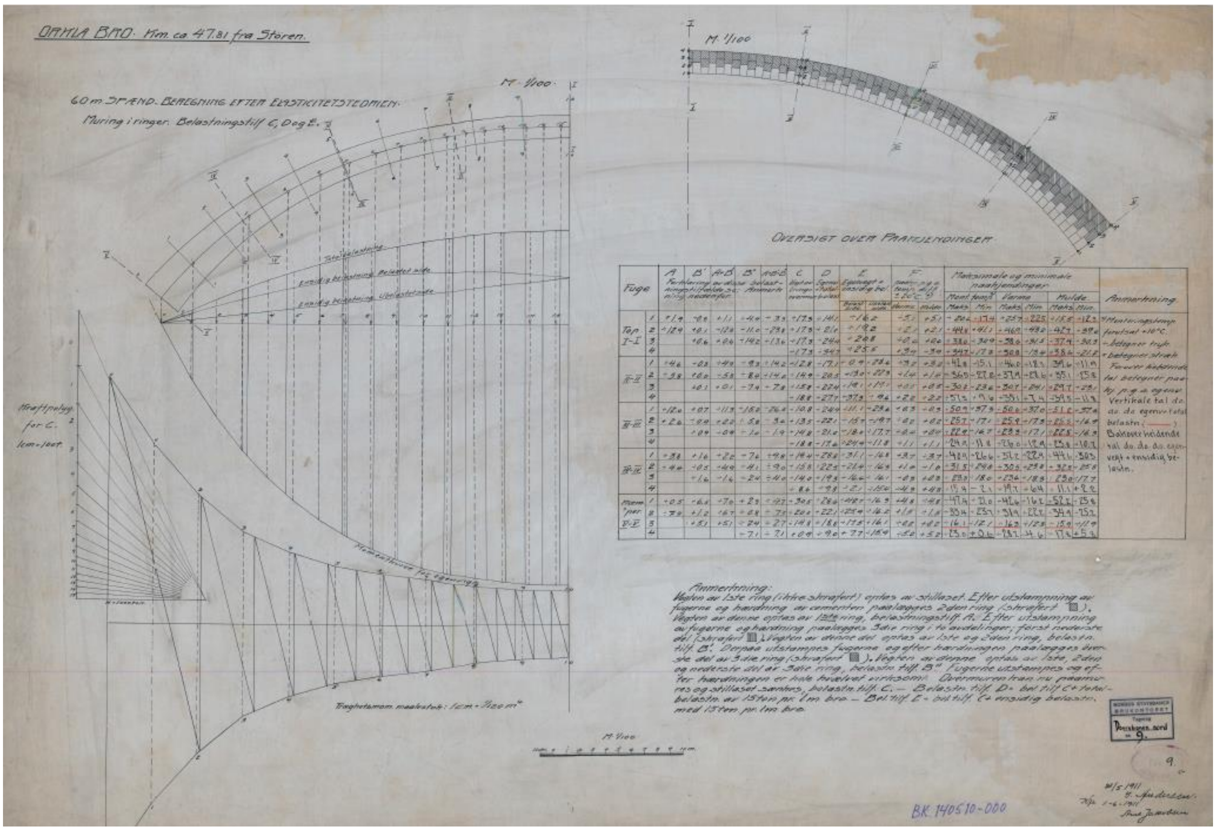


Figure 2-27: Orkla bridge - elastic theory calculations

The Norwegian guidelines of today allows for the use of both statically determinate models and statically indeterminate models or a combination of the two. Hinged models can be used for the dead load if the construction method reflect this, while for the live loads the model can be considered fixed. This because the hinges used during the construction phase often is filled with mortar when completing the bridge and the hinges becomes fixed.

In analytical models using programs for beam elements or solid elements, the elements are considered elastic and tension capacity in cross sections is used.

It is the combination of axial force and moment in a cross section that defines the line of trust. The moment is resisted by considered eccentricity of the axial force. This is one way of accepting the extend of possible cracking in a cross section but at the same time controlling the ratio between the axial trust and the moment.

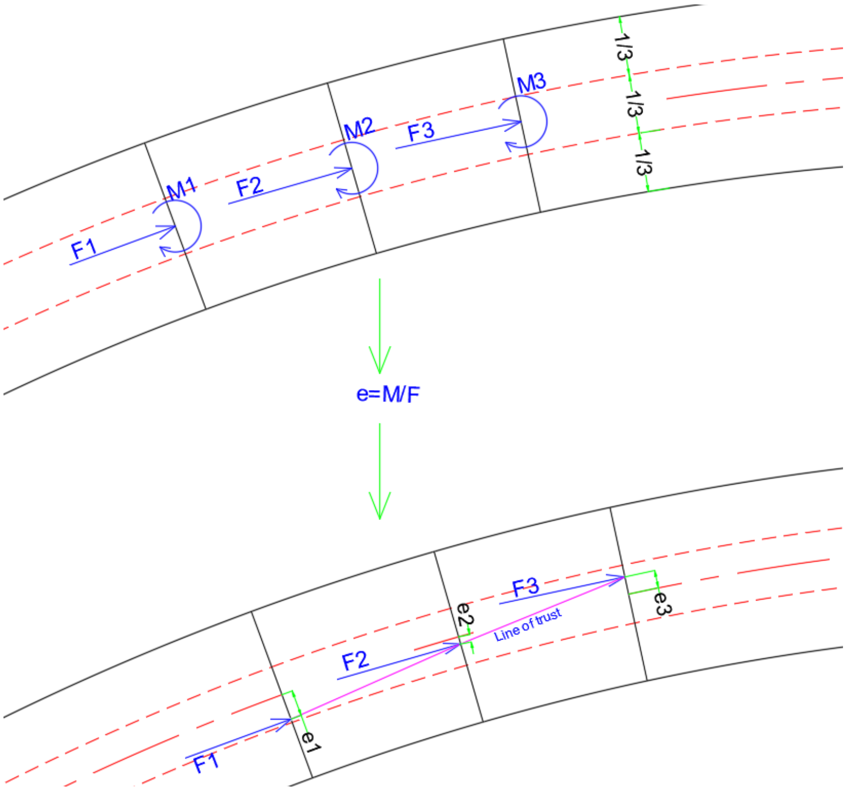


Figure 2-28: Definition of line of thrust in an element model

The limitations in the Norwegian guidelines are intended for the design of new bridges. The limitation for safety is set by the requirement that the line of thrust should be kept within the central 1/3 of the cross section (The middle third rule). This is a very conservative requirement, and it is often found that this limitation must be stretch when assessing older constructions.

The today limitation for compression stress is set to 6 MPa using elastic theory.

Numerous methods of analysis can be used for stone arch bridges. There are simple nomographs and more advanced analytical methods. They are listed below. In reference /11/ by Kristoffer Holmstrøm the methods are further presented.

List of methods:

- The MEXE nomogram (UK)
- The Norwegian nomogram (see appendix A)
- Thrust line analysis
- Thrust zone analysis
- Mechanism method
- Finite Element Methods
- Discrete Element Method

To demonstrate the strength and the way of safe assessment for a stone arch bridge an analysis is carried out in detail in Appendix C.

The analysis carried out use:

- FEM method using the FEM program StaadPro with beam elements.
- Thrust zone method and statically determinate hinged models using the Archie-M program (often used in bridge assessment in the UK)
- The Norwegian nomogram

This presentation of the physical understanding and theoretical principles for a stone arch bridge is an introduction to the science founded by our ancestors. For further details for the wide range of research on arches see reference document /38/ - "The history of the theory of structures" and the literature of Jaques Heyman reference documents /26-29/.

The historic developed methods and modern tools for analysis is a strong foundation for future design. The modern engineer has a solid heritage of methods and tools.

Now is the question whether the modern engineer only will be occupied assessing old structures or if he will get the opportunity to design and build new ones?

3 The interviews

It is today in Europe almost 100 years since we had an industry for making stone arch bridges.

If you stop an industry for 1 year you might have the possibility to restart without losing the knowhow. If you stop for 10 years all the individual experts are absorbed elsewhere and the knowledge and the team logistics for this industry is lost. After 100 year you will have a problem finding anyone who have any experience and the only reference is what remains in the archives, maintenance experience and what the existing stone arch bridge can tell us.

In an ongoing industry you just press the buttons and things happens. When there are no buttons to press you must restart almost from the beginning.

If now suddenly we should start to build stone arch bridges the asset manager, the engineer, the architect, the entrepreneurs, research and academia would have to come together and get the understanding that this is reasonable. Nostalgy or aesthetical reasons is not enough and should not be. There must be a genuine reason for the better.

The interviews are carried out with the intention to test the temperature on a variation of stakeholder in the bridge industry on the objective of this thesis. Should we again start to use the stone in arch bridges and realize a renaissance for this concept?

3.1 The questions and the basis for discussions

The intension with the built up of questions has been to expose and challenge the idea of building stone arch bridges. Expectations for both positive and negative feedback was a major factor when selecting contributors and questions.

It was hence necessary to have a wide and dynamic approach. The background and professional position of the participance are various, hence not every question was relevant in all the interviews. The intension was anyhow to use the questionary throughout all the sessions to encourage and allow for a wider reflection for each participant, also outside their own domain.

The following category of questions was used:

- Strategy and organization
- Economy
- Carbon footprint
- Random questions
- Closing questions for the future

The participants represent the following professions or positions:

- Division director for the road Administration – Operation and maintenance
- Bridge asset managers in Norway and UK
- Structural design engineers in Norway and UK
- Environmental engineers

- Authorities for rules and regulations
- Professors and researchers in universities in Norway, Spain, Portugal and UK
- Bridge and stone quarry entrepreneurs in Norway and UK

A list of the interview objects and informants is attached in Appendix A.

3.2 Interview facilitation

Most of the interviews was carried out using on-line meeting facilities, but there has also been carried out several physical meetings in Norway, Spain and UK.

The interviews have been ongoing throughout the hole period of the work with this thesis (October 2023-May 2024). As knowledge has been collected along the path the questions and the issues have developed throughout the process.

Most of the interviews has been carried out with meeting lasting around 45 minutes. Ohers is carried out over several meetings and even hole working days. Some of the informant's contributions have been limited to telephone conversations.

In appendix B the procedure and questions for the interviews are attached.

3.3 Lessoned learned from the interviews

The lessons learned from the interviews is summarized in this chapter. The knowledge, answers, comments and opinions shared are presented for each question category of questions. The aim of the summary is not to directly quote the single questions or the single answers but rather describe the topic discussed and the overall lesson learned.

The interviews have been an interesting travel among a wide spread of experts and the interest for the main objectives has been surprisingly positive. Everyone has a personal relation to stone arch bridges and the reason seems to be their natural aesthetical exterior, their long presents in history and the fact that there is always one around in the neighborhood.

If I should highlight some quotes, I pick some which all influenced the discussions, increased the motivation and inspired for further effort.

"Why did we stop building them?? " (Bridge asset manager)

"In my long career as a bridge engineer I have always been asking myself why we don't build stone arch bridges" (Bridge engineer 1)

"We used almost a billion NOK on a feasibility study for a big bridge which never will be built, why shouldn't we afford the risk building small stone arch bridges?" (Bridge engineer 2)

"Unfortunately, we do not build our bridges with stone nowadays" (Railway bridge engineer)

"Nothing beats the aesthetics" (Bridge engineer 3)

Figure 3-1: Skodje bridge - Norway – 1922 - arch span 57 m

3.3.1 Summary interview - Strategy and organization

From the input from the interviews the understanding on how the strategy and organization for bridge concepts selection is today is the essential lesson learned in this session.

The way a bridge concept is selected in Norway is depending on the size of the project and the stakeholders involved. The bridges of the main roads are owned by a public administration (State, counties or local communities).

The status for ownership of bridges in the Norwegian register for road bridges (Brutus) is presented in the table below.

(Norwegian Public Road Administration – in Norwegian – Statens Vegvesen -SVV)

Asset owner – road bridges	No. of constructions
Norwegian Public Road Administration (SVV)	5680
SVV and Nye Veier	147
Counties administration	11794
Local communities	2232
Railway	63
Privat	261
Total	**20177**

Table 3–1 Road bridges in Norway (Brutus)

PS: In addition, 2577 bridges are in service on the Norwegian railways (register Maksimo and Proark)

The strategy and organization of the Norwegian Public Road Administrations (SVV) is the most interesting administration as the SVV historically have been the major asset manager for the bridges in Norway. SVV was up to 2020 the operating asset manager for bridges both for national main roads and the main roads of the counties covering more than 17 000 bridges of the total of 20177.

In the period of 2000-2020 a number of 3103 new bridges was constructed and opened for traffic. The length of the bridges constructed in this period is presented in the table below.

Bridges constructed in the period 2000-2020	No. of constructions
Span 2.5 – 20 m	1638
Span 20 – 50 m	735
Span 50 – 100 m	442
Span 100– 150 m	124
Span >150m	164
Total	**3103**

Table 3–2 New bridges – 2000-2020 (Brutus)

The following materials was used for these constructions:

Material use for bridges constructed in the period 2000-2020	No. of constructions
Concrete	2631
Steel	281
Wood	135
Plastic	25
Other or not registered	30
Stone	1
Total	**3103**

Table 3–3 Material in new bridges – 2000-2020 (Brutus)

In the SVV the process for selection of bridge concept is rooted in the quality system.

For megaprojects above 1 billion NOK the selection of concept requires a wide investigation with involvement from internal and external consultants to assure the quality of concept. These huge projects need in addition political approval in two separate decision gates before an investment decision is concluded.

For smaller projects, as will be the case for most possible stone arch bridges, the strategi for selection of concepts is defined in the quality system owned by the section for operation and maintenance in SVV.

The relevant processes in the QA-system.

- Planning for bridges
- Planning for bridges in a municipal subdivision plan
- Planning for bridges in a regulation plan
- Investigate and consider bridge concepts
- Decide bridge concepts
- Further development of bridge concepts

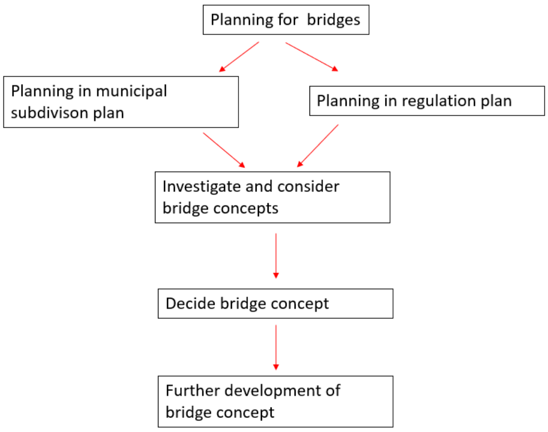


Figure 3-2: Hierarchy in the QA system

The stakeholders involved are:

- Project sponsor – Purchaser of road project
- Bridge asset manager
- Overall project planner and planners for related disciplines
- Bridge planner
- Section manager bridge department
- Discipline coordinator bridge department

The owner of the process in the QA-system is the division director for SVV – Operation and maintenance.

For the process of investigate, considering or further development the bridge discipline coordinator with his bridge engineers gives the major input based on the functional requirements defined. Input from other disciplines as road engineers, geotechnical engineers, landscape and aesthetic architects are implemented.

For the process of decision the only stakeholder listed is the project sponsor. This position will be the local asset manager of the area or the division director for operation and maintenance. With support from the stakeholders involved the preferred concepts will be selected. In this process also external stakeholders can be invited as the concepts can be governed also by national interests as safety and preparedness, environmental issues or other external factors.

A new bridge is mostly linked to a new road project with the possibility of several bridge crossings within the project, but also single bridge replacement projects are common.

From the point of view of a project sponsor the functional requirement is the major requirement. The choice of material is not a major issue but rather the functionality, robustness, resilience, redundance, longevity and low maintenance requirements.

A bridge engineer can be surprised seeing his favorite concepts being overrun by requirements from national interests as safety and preparedness, environmental issues or other external factors.

Authorities for rules and regulations can also influence the selection of concept as they give the final authorizations and approval.

It seems that the "copy-paste" method is well present and for a good reason. What worked in the previous project is a very efficient and low risk selection. To invent new concepts involves always more work and risk.

It seems that for some projects industrial and political interest can influence a concept selection. The concept of wooden bridges is of some stakeholders experienced as a "fashion" for various reasons in a period.

Wooden bridges – construction year	No. of constructions
1950-1990	32
1990-2020	189
Total in period	**221**

Table 3–4 Wooden bridges– 1950-2020 (Brutus)

Industries for competitive material as aluminum and composite have an interest to enter the scene of bridge constructions but up today these materials represent only a handful on Norwegian roads.

SVV has a guideline V420 for the development of bridge aesthetics with the goal of forming the bridges in harmony with the landscape. A major target for this guideline is to satisfy not only technology and economy but also culture, identity and aesthetics to obtain beautiful roads and bridges. From the experience of a landscape architects these guidelines are not always respected. This leads to unconscious harmonization with the landscape and a lack of visual expression. This is most common for smaller bridges.

As seen from table 3-3 above the dominating material are concrete, steel and wood. Stone as a building material is almost totally absent. The stone material is not even in the discussion. This is confirmed in all interviews. The only stone arch bridge constructed for traffic in Norway after the second world war was constructed in 1999 in the little village Sogndalstrand. For this bridge, the Åros bridge, the values of culture, identity and aesthetics was decisive.

Risk, knowledge among entrepreneurs and governing rules for design is stated as major factors for the absent of stone as a construction material. This is a reasonable reservation.

Taking the risk on untraditional selection of concept where design rules are insufficient, experience among entrepreneurs are limited and where the details required for construction process definitions are absent might be a tough call. To rely only on reference projects from ancient times is not a comfortable foundation.

In the design guidelines for design of bridges a new paragraph was introduce in 2024 (SVV- N400- section 1.1.2-2) requiring documentation from the bridge designer on the concept selection and the related consequence on environmental impact from the various concepts considered. If this will make any difference in the future on the selection of construction materials remains to see.

3.3.2 Summary interviews - Economy

The discussion around economy issues for a bridge concept in the interviews has not been a major focus but the variables in an economical evaluation has been discussed. The focus has been on challenging the stone arch bridge concept on the economical perspective.

The cost impact on investment, operation, maintenance and removal are the four main elements in a bridge project budget. All define the total investment required for the project in the lifespan of a construction.

The frequency and type of traffic is added to the calculations to define the economical contribution to the society. One can then define the social benefit from a bridge construction.

Longevity for a construction and maintenance cost will influence the calculations strongly. Today the lifespan of a bridge is set to 100 years and all calculations depends on this limitation or framing of the perspective.

Yield of interest rates must be predicted. Also the price development as the cost of materials and services must be considered to enable a vision on the holistic economy picture.

Predicting the future is not always easy. With all the available variables a cost estimate is defined based on the valuation of the variables taken into consideration. If aesthetic values are set to zero they don’t show in the basis for decision making. If a realistic service life is 300 years this is not included in the estimates either.

Many of the old stone arch bridges still serving the modern requirement for functionality are in remarkable good shape if taken care of. The asset managers and owners confirm the low investments required for the maintenance.

An example of investment is the cost estimates made for the Åros stone arch bridge constructed in 1999. The calculated cost estimate for this bridge was 4.5 million NOK compared to 3.0 million for a classic concrete bridge. As this was more like a prototype concept at that time some additional cost was required to complete the bridge and the bill in total ended up close to 6.0 million NOK.

Figure 3-3: Åros bridge - Norway – 1999 – arch span 25 m

Considering that a classic concrete bridge would have no additional cost (which often is not the case), a stone arch bridge is twice the investment cost for this particular project.

At the time of the concept decision the estimated cost of the selected concept was 50 % more expensive than the alternatives. This brings forth the valuation of factors that is often neglected in an economical investment analysis. Additional values were included into the holistic evaluation for investment among stakeholders. These values must be considered when defining the real in facto resulting cost impact. The stakeholders did put in 1.5 million NOK at the time of the final decision for values as aesthetics, harmony with the landscape and the use of local materials.

The future will show if the economical footprint of this bridge will change when the reality of maintenance cost, longevity and possible removal and reuse of materials is implemented in the calculations.

The history can help us with some facts. The first London bridge in stone was built in the 12th century and lasted to the 18th century, a span of 600 years.

The second bridge was also a stone arch bridge and opened in 1831. It stayed for 140 years in service in London. As the bridge was dismantled the external masonry was sold and moved to Arizona in USA for use in a new bridge opened 3 years after sail away from London. The reason for dismantling was due to functional requirements as better flow of marine transport on the river and better capacity for increased road traffic. The main reason for the disappearance of old stone arch bridges is often not due to their poor condition but rather the new requirements to width or change of road layout.

The new and existing London bridge opened in 1973. It is a 3 span prestressed concrete construction with up to now a service life of 51 years. With the relative short experience with prestressed concrete bridged the risk involved with various deterioration processes as corrosion of cables and possible loss of pretension, we do not know today by experience the expected longevity of such structures, but reaching 600 years? Should this bridge last for 120 years (UK), as it is designed for, we would need 5 bridges for the next 600 years. This perspective has major impact in the holistic comparison of cost.

Another example is the Orkla bridge opened for railway service in 1921, see figure 2-12. The bridge is today a functional bridge with almost no registered major maintenance costs on the load bearing construction. This is symptomatic for most of the stone arch bridges in the railways of Norway.

The longevity, low maintenance cost and aesthetic values of a stone arch bridge makes a difference in a holistic investment analysis.

And a new set of factors has entered the scene in the last decade, the cost of carbon footprint, energy consummation and environmental impact. There will also be an economic impact when the cost of the new environmental requirements in the revised guideline N400 is implemented in the estimates, ref chapter 3.3.1.

Anyway, the economical investment analysis for bridge concepts today is not at all considering stone as a building material as confirmed in all the interviews carried out.

An entrepreneur for bridge constructions stated that with good incentives and a will to use this concept, on not only one but in a continuous way, the stone arch bridge can become a relevant business case again. It will depend on initiative from the owners with open involvement and cooperation with the entrepreneurs. Interaction in early phases of projects will be a trigger for finding new solutions, increase involvement and motivation for untraditional solutions.

3.3.3 Summary interviews - Carbon footprint

The 17 sustainable development goals (SDG) on the United Nations are the major subject discussed at most seminars for transport infrastructure today. This is a global issue and affects the agenda of every stakeholder.

The Nordic Road Forum (NVF – Nordisk Vei Forum) is an organization with the main stakeholders in the road and transport sector in the Nordic countries (Denmark, Finland, Sweden, Island, Faroe Islands and Norway).

The last four years program (2020-2024) for the NVF focused on digitalization, asset management and carbon footprint.

The conference Via Nordica arranged this summer (2024) by the NVF for the end of this period was concentrated on the environmental issues and the threat to climate change from the emissions from the industry.

The NVF program for the next four years (2024-2028) will only focus on climate and environment issues. The 17 UN goals on sustainability shall be the basis for all activity.

The pressure and the ambition on this topic are increasing. Up to recently this issue have been more for the headlines and the overall strategies. Now environmental considerations are materialized at all project levels.

The now overwhelming focus on the environmental issues in all ongoing discussions is commonly experienced among all participants in the interviews. The life circle assessment is implemented in projects and all companies report the Environmental Product Declarations (EPD's) for their products emphasizing the carbon footprints and energy consummation.

From 2024 both in the design guidelines and in the project tender documents the requirements for a documented effort on reducing negative environmental consequences are a key factor in the competition between concept selections and tender awards.

"Internal targets for emission reduction are challenged. From getting carbon neutral to 2050 a new and more ambitious target is set to 70 % carbon reduction within 2030" affirm one of the entrepreneurs interviewed.

An increased motivation to contribute to the SDG's are clearly present in the industry and a loyalty to a carbon free industry in the Nordic countries in 2050 is requested.

Tools as the LCA (Life circle assessment) and LCC (Life circle cost) are integrated in the projects to account for the overall project environmental and economic footprint from cradle to grave, or from purchase, use and disposal. The holistic viewpoint is the new grail.

There is a good understanding of the need for change and the complex challenge involved. The solution is not business as usual, and the change will be at a cost.

Optimalization, resilience, robustness, redundance and economy has always been a part of bridge engineering. This is not new requirements. There is a drive in all industries to always reach for a step forward, learn of mistakes and improve.

The new is the need for lower carbon footprint and energy consummation.

There are risks involved in this urge on reducing carbon footprint and energy consumption. To remain robust, optimized, resilient and keep the redundance and longevity will have an impact on economy and quality.

The new solution tends to search for "greener" materials, "greener" vehicles and "greener" logistics.

Implications might lead to lower material quality, increased exposure to deterioration and shorter service life. Change in type of vehicles might lead to increased weights. Change in logistics might lead to increased cargo weights.

This is a split with a great challenge for a bridge designer. Lower quality and "good enough" is lowering the level of safety and increasing the risk.

The concrete industry is putting efforts in to a "greener" concrete. Today a low carbon concrete has 19 % less carbon footprint than the standard quality. In the near future the carbon capture process will produce the CCS-concrete (Carbon Capture & Storage) with a reduction of 50 % carbon footprint in the Norwegian cement production. The energy consummation will on the other hand increase.

The entrepreneurs are also challenged on their tools and methods. Full electrical constructions projects are tested but still in a very small magnitude.

The increased use of wooden bridges from 1990 and up to today has been partly motivated by the environmental issue. Still the reality is that there have been minor effects on the bridge concepts selections looking on the numbers for the last 20 years. For new constructions it is still clearly the concrete material which dominated as seen in table 3-3.

The interviews reveal a shared experience on this topic. The request for sustainable and environmentally friendly solutions in the industry is ubiquitous. The impact of this request is emerging and is now a challenge when selecting future bridge concepts.

The environmental issue will be further discussed in chapter 4.

3.3.4 Summary interviews - Random and closing questions for the future

In this part of the interviews the aim was to open up the discussions and try to get opinions on whether there is a reasonable change and any realism in the idea that the stone arch bridge can become a common concept for future bridges.

In the various discussions throughout the interviews, with the different topics as strategy, organization, economy and the ongoing complexity of environmental issues, the attitude to the idea of the stone arch bridges became proactive and enthusiastic.

In the start of every interview the topic was surprising and as an interviewer I got a sensation that this was a nostalgic idea and not very harmful or threatening to the "business as usual" (concrete and steel). Having discussed the UN 17 goal for sustainable development, the history of stone arch bridges, the possibilities within the stone material as robust and almost maintenance free, the natural availability and the longevity proven by history the answers in this last session opened up toward possibilities, invention and creativity.

Here are some examples of quotes:

"Please do not say that we do not know how. Give us a business case and the incentives. We will find a way with the tools of today " (Entrepreneur 1)

"We need bridge owners who dare to take this risk" (Entrepreneur 2)

"They have built 200 stone arch bridges in Tanzania the last 3 years" (Professor 1)

"There is a fear, negligence and ignorance towards stone arch bridges in general" (Professor 2)

"The numbers show that the maintenance cost is way lower for this type of structures" (Professor 1)

"80 % less maintenance, 80 % less carbon footprint and for the service life – what do we need more?"- (Professor 3)

"Everyone is scared for stone arch bridges" (Bridge maintenance engineer 1)

"The material is brittle, but the stone arch bridge is ductile" (Bridge maintenance engineer 1)

"The guidelines are too conservative and the design rules should be developed for this kind of structures" (Bridge Engineer 2)

"This must be like honey for the environment" (Bridge Engineer 3)

"To get a correct carbon footprint calculation is crucial as this can become a gamechanger" (Environmental engineer 1)

"The Norwegian stone quality is super hard and there are amazing potential and possibilities (Entrepreneur 3 UK)

"In the quarries we are obliged to account for 90% waste of materials to define the carbon footprint. There is no waste in producing such type of stones" (Stone quarry engineer)

Figure 3-4: Old quarry for stone arch bridge – no waste

There is a tendency in the feedback that bring up the "why not?" and "what er we waiting for?"

To finalize the interviews a list of claims for the possibilities and advantages with the stone arch bridge was listed.

Claims:

- Stone arch bridges seems to have longevity beyond other materials.
- Stone quality in Norway is generally good.
- Stone arch bridges seems to have low maintenance cost.
- Stone arch bridges seems to represent a simple and straightforward technology.
- Stone arch bridges have low carbon footprint.
- Stone arch bridges strength and longevity seems unlimited.
- Stone arch bridges can always be constructed of stones from local quarries.

Figure 3-5: Dahne bridge - China

The above stone arch bridge was constructed in 2001, with a span of 146 m and serve in a 4-lane road highway (Dahne bridge – China).

Final question:

Is it possible that such a bridge can be constructed for the Norwegian road system today?

This question brings the discussion into a wider perspective and involves all the earlier discussed topics. This is a challenging question on the holistic picture.

What remains as a common platform of understanding is the fact that the concept of stone arch bridge is neglected today. The new focus on climate and environmental issues are forcing the industry to search for new solutions and the idea of stone arch bridge from the past needs a closer look. It needs a closer look because it seems promising.

It would be of interest to include this concept in coming studies as a competitive alternative and let a concept feasibility study expose advantages and weaknesses in a fair competition with the alternatives.

To repeat the new revised guideline:

§1.1.2-2 N400 (2024-01-01): The choice of bridge concept shall be justified with regards to sustainability. The justification is to be documented.

A quote from an enthusiastic entrepreneur to the very last question is ending this interview summary:

“You should have a pretty good reason for **not** using stone again - Going back to the stone age with modern tools can be the way to the future” (Bridge entrepreneur).

4 Carbon footprint and energy consumption

This chapter is comparing the carbon footprint and energy consumption between the different materials in similar bridge spans with similar functional requirements.

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations (UN) body for assessing the science related to climate change.

According to IPCC the greenhouse gas emissions (GHG) from human activity causes climate change.

The 6th Assessment Report (IPCC AR6 - 2022) concludes that growth and business as usual will rise the global temperature 5 ^{0}C at the end of this century (worst scenario). The main driving force comes from the emissions from fossils fuels.

The report urges for immediate GHG-emission reduction in all sectors and calls for firm climate change mitigation goals. A bleak outlook is given to the future if no change is done.

The list of negative consequence from such a temperature rise is long. 127 different negative impacts of climate change are listed and the most severe are losses of cultivated territory, sea level rising and floods, water scarcity, droughts, possibilities for infection diseases outbreaks, food insecurity, heatwaves and habitat loss.

The Secretary-General of the UN, Antonio Guterres called the report a “code-red” for the humanity and said that the truly dangerous radicals are the countries that are increasing the production of fossil fuels. This is a very strong statement from the UN and it might end up becoming a gamechanger in all sectors.

The world today, if we want it or not, are anyhow very dependent on the fossil fuel to produce the materials, tools and food we need. There is a huge split here and a very challenging situation.

More than 80 % of the primary energy used by human activity is today fossil fuel. The production of food and vital materials as cement, steel, plastic and ammonia are all today highly dependent on fossil fuel. In 2019 the world consumed 4.5 billion tons of cement, 1.8 billion tons of steel, 370 billion tons of plastic and 150 billion tons of ammonia. The production of these four materials consumes 17 % of world energy supply and creates 25 % of the total global CO^2 emissions from human activity (ref./24/).

The cement and steel production are each responsible for 8 % of the world human made carbon emissions.

The above-described international challenge is the main reason for the idea behind this thesis. Every sector is asked to turn every stone to search for mitigating strategies to minimize GHG-emissions. To restart the use of stone in building bridges instead of concrete and steel, where this is possible, can be a contribution in this regard.

The 17 sustainable Development Goals of the United Nations are now in Norway included in the National Transport Plan for 2022-2033. These goals commit all projects for a reduction in carbon footprints when investing in national infrastructure.

The Norwegian Public Road Administration have now a requirement that every project with a investment above 51 million NOK shall have a documented account for carbon footprint using approved and standardized methods.

The life cycle assessment (LCA) is today standardized in Europe and internationally. A method of calculating environmental impact from our production are developed. In Europe products (goods and services) are categorized in defined product category rules (PCR). The producers are obliged to present scientific and comparable declarations on the environmental impact of their products. This is done by issuing environmental product declarations (EPD's). The EPD's are issued in accordance with the European standards (EN15804 & ISO 14025) to assure a harmonized method.

EPD-Norway is coordinating this work in Norway.

The short version of a life cycle is from "cradle to grave". The more detailed version is the different phases defined in an EPD.

Phase	Description	Tag
Production	Raw material – internal transport–processing	A1–A3
Construction – Installation	External transport and construction and assembly	A4–A5
User stage	Use, maintenance, repair, change, renovate, energy consumption, water consumption	B1–B7
End of life stage	Demolition, transport, waste processing, disposal	C1–C4
Beyond the system boundaries	Recycle	D

Table 4–1 Life cycle phases

Product stage			Construction installation stage		Use stage							End of life stage				Beyond the system boundaries
Raw materials	Transport	Manufacturing	Transport	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	MND	MND	MND	MND	MND	MND	MND	MND	X	X	X	X	X

Figure 4-1: Life cycle phases illustration (from Lund AS)

The carbon footprint from a bridge is 70 % represented by the production of construction material and hence the phases A1-A3 is used in the following comparison exercise. Transport (A4) will be a further positive additional advantage for a stone arch bridge if the quarry is located nearby as for the Orkla bridge (max. 9 km transport)

4.1 The natural stone environmental footprint

The natural stone is natural and ready to be used. There is no need for processing with heat treatment and no need for adding chemicals for hardening or corrosion protection. The heat treatment was completed for millions of years ago, and the carbon involved is already captured within the stone itself. It is a material in equilibrium with the environment and there are no risks for pollution. There is only the need of extracting the stone from the quarries and form them.

Many of the stone arch bridges existing today was constructed before the use of fossil fuels became the main source of energy. Only the force of man and horses was used. The Orkla bridge built in 1911-1916 is close to a carbon neutral construction with very low carbon footprint.

Figure 4-2: Orkla bridge – stone quarry 1912– (Rennebu Historielag ref. /33/))

Figure 4-3: Orkla bridge – stone transport 1912 – (Rennebu Historielag ref. /33/)

Today the extraction is done with modern tools (Diamond wire – hydraulic chainsaw - drilling - splitting) using electrical energy or chemical energy. The chemical energy is the energy conversion from combustion of fossil fuel. The electrical energy is the energy conversion from hydro generation, nuclear fission or combustion of coal, oil or gas depending on the location.

The quarries today are delivering stones for floor covering, facades, interiors, pavements, outdoor landscaping, gravel and aggregates for concrete production.

Lund AS is the largest producer of natural stone in northern Europe with 8 operating quarries in south of Norway. At a visit to Lund AS in Larvik in January 2024 they presented the logistic in their production. They also demonstrated the way they document their environmental footprints in accordance with European regulations. Their EPD's (Environmental Product Declaration) are registered in EPD Norway.

It was stated that earlier the carbon footprint was only 10 % of what they declare today. The reason to this is the percentage of waste of material which today must be included in the footprint on the stone that is sold. The waste material was previously not included as it was expected a future possible use of this material. The waste material can be up to 90% of the total mass extracted, but today this percentage is more commonly between 50-75 % depending on the quarry.

When they finally find a customer for the "waste-material" this client can report zero emission. This is because the total emission is reported to stones already sold. This way the natural stone sold get a higher reported value of carbon footprint and energy consumption in the EPD's.

This will not be correct for all stone quarries and certainly not the case for a local quarry for a bridge. In a quarry for a stone arch bridge all the extracted materials will be allocated to the project. There will be no "waste-material" as the stones used for a bridge are bigger and has less requirements on the finishing surface. The backfill between the spandrel walls will also need a huge volume of materials with no requirements to shaping.

The Krukåsen quarry at Lund AS in Larvik, Norway is used as a reference to define the environmental impact for the extraction of stones for a stone arch bridge. This quality is named Ocean. At this location the internal transport in the quarry is similar to what can be expected in a local quarry established close to a bridge construction site. Lund AS has provided their EPD's for the production for blocks delivered with the quality required for their marked for floor covering, facades, interior and pavements. The extracted stones in this quarry have only 50 % waste material accounted for in the EPD.

The EPD for the Ocean stone from Lund AS is presented in the below table. This stone is extracted from the Krukåsen quarry.

LCA: Results

The LCA results are presented below for the declared unit defined on page 2 of the EPD document.

Environmental impact								
Indicator	Unit	A1-A3	A4	C1	C2	C3	C4	D
GWP-total	kg CO_2 -eq	1,88E+01	7,84E-01	4,00E+00	1,39E+01	5,04E-01	1,29E+00	-5,62E+08
GWP-fossil	kg CO_2 -eq	1,87E+01	7,84E-01	4,00E+00	1,39E+01	4,97E-01	1,28E+00	-5,50E+08
GWP-biogenic	kg CO_2 -eq	1,09E-02	3,36E-04	7,50E-04	5,75E-03	4,29E-03	1,09E-03	-1,10E+07
GWP-luluc	kg CO_2 -eq	2,56E-03	2,39E-04	3,15E-04	4,94E-03	6,88E-04	2,52E-04	-3,72E+05
ODP	kg CFC11 -eq	4,94E-06	1,89E-07	8,64E-07	3,15E-06	9,80E-08	6,26E-07	-1,00E+02
AP	mol H+ -eq	2,00E-01	2,52E-03	4,19E-02	3,99E-02	4,02E-03	1,25E-02	-4,95E+06
EP-FreshWater	kg P -eq	9,32E-05	6,24E-06	1,46E-05	1,11E-04	3,14E-05	9,59E-06	-1,46E+04
EP-Marine	kg N -eq	8,46E-02	5,53E-04	1,85E-02	7,90E-03	1,18E-03	4,70E-03	-1,72E+06
EP-Terrestial	mol N -eq	9,42E-01	6,16E-03	2,00E-01	8,83E-02	1,36E-02	5,18E-02	-2,02E+07
POCP	kg NMVOC -eq	2,57E-01	2,42E-03	5,57E-02	3,38E-02	3,64E-03	1,48E-02	-5,33E+06
ADP-minerals&metals[1]	kg Sb -eq	6,62E-05	1,40E-05	6,14E-06	3,84E-04	6,31E-06	1,14E-05	-4,89E+04
ADP-fossil[1]	MJ	3,21E+02	1,27E+01	5,51E+01	2,10E+02	1,54E+01	4,15E+01	-9,31E+09
WDP[1]	m^3	6,52E+02	9,76E+00	1,17E+01	2,03E+02	1,70E+03	8,73E+01	-4,37E+11

GWP-total = Global Warming Potential total; GWP-fossil = Global Warming Potential fossil fuels; GWP-biogenic = Global Warming Potential biogenic; GWP-luluc = Global Warming Potential land use and land use change; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential, Accumulated Exceedance; EP-freshwater = Eutrophication potential, fraction of nutrients reaching freshwater end compartment: EP-marine = Eutrophication potential, fraction of nutrients reaching marine end compartment; EP-terrestrial = Eutrophication potential, Accumulated Exceedance; POCP = Formation potential of tropospheric ozone; ADP-minerals&metals = Abiotic depletion potential for non-fossil resources; ADP-fossil = Abiotic depletion for fossil resources potential; WDP = Water (user) deprivation potential, deprivation-weighted water consumption

Table 4–2 EPD Lund AS – Ocean stone quality

Excluding the 50 % waste from the given values gives 18.8/2= 9.4 kg CO^2-equiv/ton for a block from this quarry. The assumption is that there will be no waste in a bridge stone quarry.

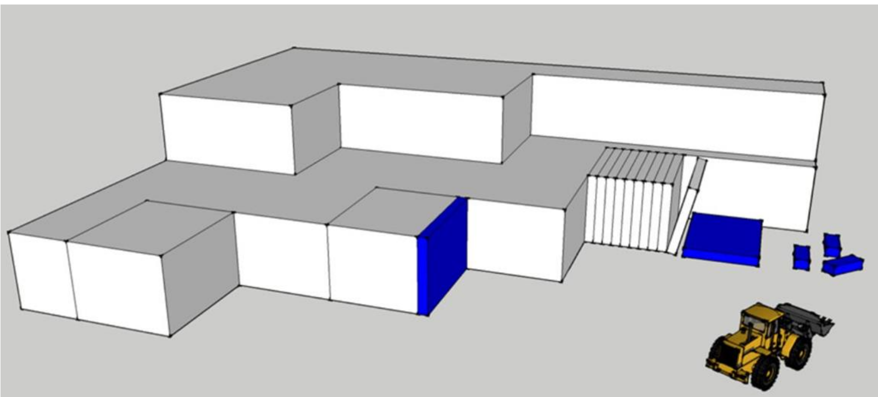


Figure 4-4: Block extraction

Including the process of sawing and splitting given as 9.1 kg CO^2-equiv/ton the total carbon footprint of a stone for a bridge will be 9.4+9.1=18.5 kg CO^2-equiv/ton (ref. Lund AS).

The energy consumption from the table is 321 MJ/ton. Excluding the 50 % waste this is reduced to 160.5 MJ/ton. Estimate the energy in processing stones will be the same ratio as for the carbon footprint gives (160.5+9.1/9.4*160.5=) 316 MJ/ton.

The carbon footprint and energy consumption used for comparison is hence:

Carbon footprint stone **18.5 kg CO^2-equiv/ton or 50 kg CO^2-equiv/m^3**

Energy consumption stone **316 MJ/ton or 853 MJ/m^3**

For a stone of 1 m x 0.6 m x 0.6 m this means 307 MJ representing 8 liters of crude oil.

If the equipment is electrical and the source of energy is waterpower the picture becomes "greener".

A life-circle assessment for external paving is performed by the institute of construction materials at the University of Stuttgart commissioned and issued by the German Natural Stone Association (DNV-Deutscher Naturwerkstein-Verband)(Ref. /43/. In this study the emission to produce natural stone delivered at the factory gate is defined to 71.7 kg CO^2-equiv/m^3 or 28 kg CO^2-equiv/ton. This is for stones cut for outdoor paving with an item size of 100x100x100 (mm). This footprint will be lower for the bigger stone blocks used for a bridge. The conclusion from this paper is that the concrete pavement has more than 7 times the carbon footprint of natural stone delivered at the factory gate for a lifetime of 50 years. For the lifetime 100 years this ratio becomes 11. This is because concrete pavement needs replacement after 30 years and stone does not need any even for the 100 years.

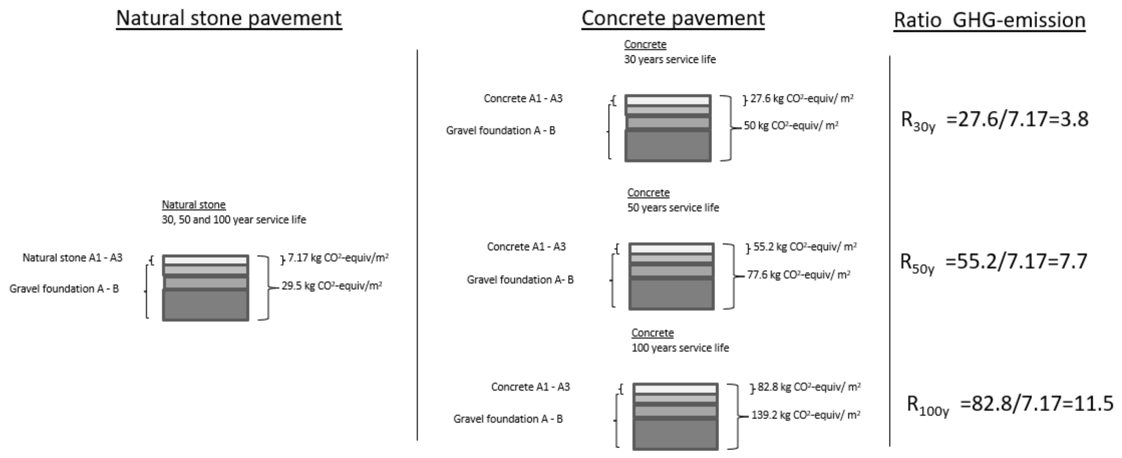


Figure 4-5: GHG-emission ratios between natural stone and concrete pavement

Using a similar approach when comparing a stone arch bridge with a concrete bridge can be justified by the experienced service life of existing bridges. A bridge of concrete is in Norway designed for 100 years. History shows that a stone arch bridge can have a service life of 300 years or more. Some even have been around for more than 2000 years.

Figure 4-6: Pont Julien – Via Domitia – France – year 3 BC - Span 46 m

4.2 The concrete environmental footprint

Since 1824, when Joseph Aspdin patented the modern cement and named it Portland cement after the color of the limestone from Ilse of Portland in the English channel, we have been firing limestone at very high temperatures to make cement for the concrete production.
Today the concrete industry leaves a massive carbon footprint and represents 8 % of the total global anthropogenic (human made) greenhouse gas emission. It requires huge amounts of energy and in most parts of the world this energy comes from fossil fuels. Consider concrete production as a country by itself and you have the third largest emitter on the globe just behind China and USA (ref. think tank Chatman house).
Approximately 60 % of the emission from the cement production is the heating (calcination) of the lime stone and 40 % from fuel combustion. In the energy mix used in Norway a ton of cement generates an emission of 600-900 kg CO^2-equiv. At the homepage of Heidelberg Materials the number given for 1 ton of clinker is 1 ton of CO^2. Adding fly ach, slag, silica fume, or natural pozzolans reduced the carbon footprint. The final emission is depended on location, availability, required quality and other variables.
The Norwegian life cycle assessment program VegLCA use the value of 860 kg CO^2-equiv/ton cement.
In the energy mix used worldwide this number is 1000 kg CO^2-equiv/ton cement.

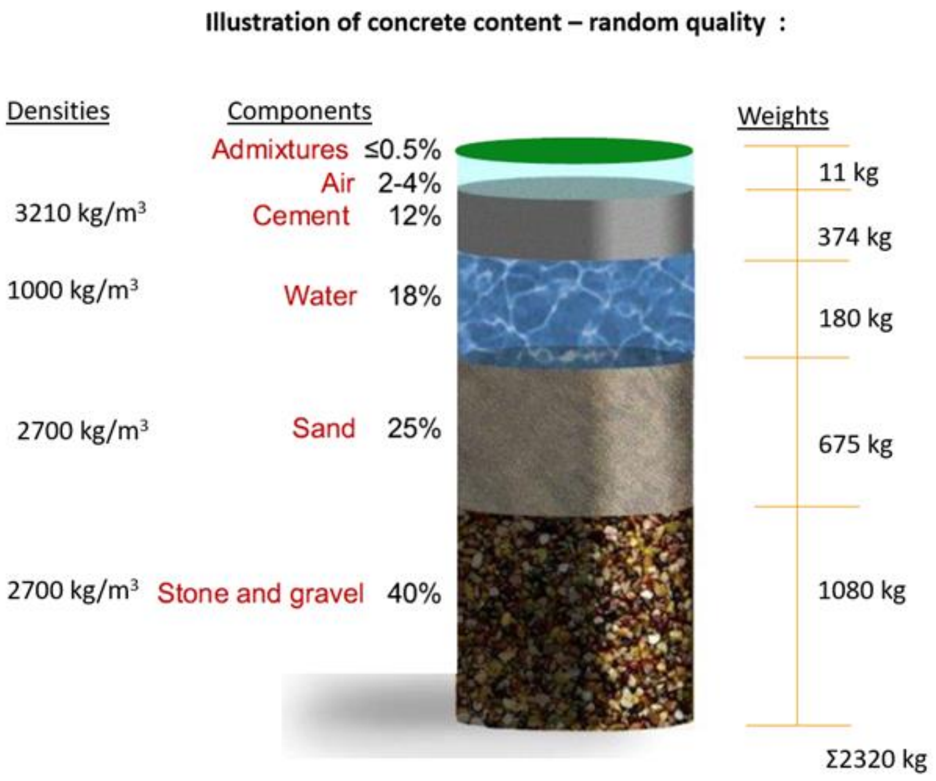


Figure 4-7: Illustration of a random quality of concrete

Accordance to the EIA (USA - Energy Information Administration) the cement industry is the most energy intensive industry of all manufacturing industries.
Globally for the cement production most energy supply comes from crude oil and coal. Biomass (plants and animal waste) is also used but not in a huge scale.
The use of biomass does not reduce the energy required but might reduce the emissions. The modern production of 1 kg plant biomass requires approximately 0.1 liter of crude oil to be produced, 1 kg of chicken 0.3 liter and 1 kg of a grown-up beef cattle ready on the market needs 5 liters (ref /24/). As the energy density of 0.3 liter of crude oil is much higher than biomass, using biomass from meat production can end up as a negative emission contribution. The reduction on emission is all up to how the calculations are set up and where the emission is allocated. Biomass from animals is often described as carbon neutral because it's carbon footprint is taken in to account in the meat sold for food.
This is one way of calculating. The term "green washing" is not yet an exact science and it all depends on a common understanding and an agreed way of defining the calculations.

The concrete industry is now working hard to reduce the huge emissions. The coming CCS-concrete (Carbon capture and storage) is estimated to reduce the CO_2 emissions to the atmosphere by 50 % but will increase the energy consumption. The CO_2 will be captured from the cement production, shipped offshore and pumped down in subsea reservoirs for permanent underground storage. This technology is at this moment under development.

The various emission and energy consumption values for the different qualities of concrete used in Norway today are:

Concrete	Unit	Equivalent CO_2-emission	Accumulated energy spending
		kg CO_2-eq	MJ
Concrete, B45, reference for industry	*m3*	360	2472
Concrete, B45, Low carcon B	*m3*	290	2552
Concrete, B45, Low carcon A	*m3*	220	1796
Concrete, B55, reference for industry	*m3*	370	2476
Concrete, B55, Low carcon B	*m3*	300	2558
Concrete, B55, Low carcon A	*m3*	230	1866

Table 4–3 Carbon footprint – concrete (ref VegLCA)

At Via Nordica 2024 two separate studies on carbon footprints for bridges were presented. One was presented by Efla Island and the other was presented by Rambøll Denmark. Here the estimated values used was respectively 426 and 400 kg CO^2-equiv/m^3 for the concrete footprint.

The reference B45 quality above is used in the comparison for the emission and energy consumption.

Carbon footprint concrete: 360 kg CO^2-equiv/m^3

Energy consumption concrete: 2472 MJ/m^3

4.3 The steel environmental footprint

The steel industry is another energy intensive industry. The volume of steel production is 2,5 times less than the concrete, but the emission is similar and represents 8 % of the global anthropogenic emissions. Steel is the most used metal in the world and has a vide range of usage from constructions to vehicles and from engines to furniture and so on.

The process of making iron demands temperatures up to 1800 ^{0}C and an energy consumption of 17-30 GJ/ton for only the blast furnaces. The production consumes 6 % of the world's primary energy supply.

To conserve outdoor steel constructions an effective cover of corrosion protection is vital for longevity.

The Eiffel tower, build in 1889, is during its lifetime of 130 years been repainted 19 times. The 20th layer of corrosion protection is now in progress and will be completed in 2026. This means that the steel construction is repainted every 7th year. The weight of the remains of the 20 layers of protection coating is estimated to 350 metric ton. For the last layer approximately 50 employees and several companies and experts are involved to the final cost of 85 million Euros. In addition, this repetitive material and cost spendings is a perpetual process (ref/27/).

Another example is the Norhordaland bridge (12-2900) in Norway constructed in 1994. It is now under repainting for a cost of 110 million NKr. The duration for the work is 6 years, and now 3 years past schedule.

Another project ongoing is the Gjemnessundbrua (15-2251) where the cost is close to 40 millions NOK. The duration for the work is estimated to 3-4 years and is ongoing.

The bridge owners know very well about the maintenance consequences for a steel bridge.

The above examples are not the most relevant examples for comparison with a stone arch bridge, but they describe the importance of maintenance costs and additional carbon footprint along the lifespan for this material.

The emission and energy consumption values for steel and steel reinforcement used in Norway are:

Steel	Unit	Equivalent CO_2-emission	Accumulated energy spending
		kg CO_2-eq	MJ
Construction steel	*m3*	19733	249552
Steel reinforcement	*m3*	4445	453495

Table 4–4 Carbon footprint – steel (ref VegLCA)

At Via Nordica 2024 Efla Island used 6421 kg CO^2-equiv/m^3 for the reinforcement and 19625 kg CO^2-equiv/m^3 for the construction steel in their calculations(ref/44/).

4.4 The comparison of carbon footprint

Three different existing stone arch bridges are selected with three different lengths. Then similar constructions in concrete and steel is selected to compare with each for the three length categories. The selected length is for comparison and not the exact length of each bridge.

The stone arch bridges selected are:

Group	Stone arch bridge	Group Lenght	Year of construction	Location
1	Åros bridge - road bridge	45	1999	Norway
2	Åmfoss 1 - road bridge	80	1918	Norway
3	Dahne bridge - road bridge	167	2001	China

Table 4–5 Stone arch bridges for comparison – stone

To compare, bridges with similar lengths are selected from the existing Norwegian road infrastructure. A length and width is defined for each group. This is not the exact length or width of each bridge. This way the calculations is comparing the required mass of each material for a certain road length. As for the Åros bridge, the span is 25 m but the total length with the arch and the abutments is 45 m. For the Åmfoss bridge the total length is 94 m but the two spans are each is 42 m. The length 80 m is selected for the comparison. For the huge Dahne bridge the length 167 m used. This length includes the main span and the two main towers. The main span of the Dahne bridge is 146 m but the total length with all the spans and abutments are more than 400 m.

The following Norwegian bridges of steel and concrete are selected for comparison:

Group	Concrete and steel bridge	Group Lenght	Year of construction	Material
1	Fjerdingelv - road bridge	45	2021	Concrete
	Hovbrua - road bridge	45	2021	Steel
2	Labbdalsbrua - road bridge	80	2014	Concrete
	Forra - road bridge	80	1939	Steel
3	Litlsundbrua - road bridge	167	2006	Concrete
	Imarsundbrua - road bridge	167	2006	Steel

Table 4–6 Stone arch bridges for comparison – concrete and steel

Åros - Stone

Fjerdingelvbrua – Concrete

Hovbrua – Steel

Figure 4-8: Group 1 – road length 45 m

Åmfoss 1 - stone

Labbdalsbrua sørg – Concrete

Forra – Steel

Figure 4-9: Group 2 – road length 80 m

Dahne

Litlsundbrua – Concrete

Imarsundbrua – Steel

Figure 4-10: Group 3 – road length 167 m

The following values are used for the equivalent carbon emission for 1 m^3 for each of the materials:

Carbon footprint input values:		
Stone	50	kg CO^2-equivalent/m^3
Concrete	360	kg CO^2-equivalent/m^3
Steel reinforcements	4445	kg CO^2-equivalent/m^3
Steel construction	19733	kg CO^2-equivalent/m^3

Table 4–7 Carbon footprint – used in comparison

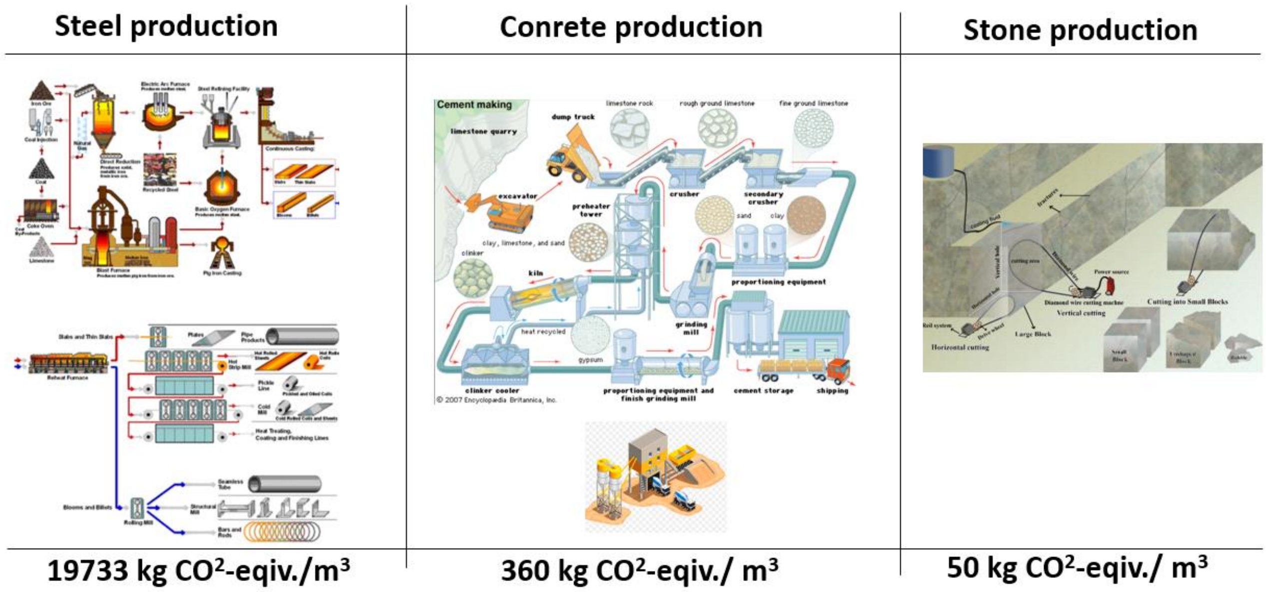


Figure 4-11: Carbon footprint – steel - concrete - stone

Construction name	Material	Selected Lenght for comparison	Selected Width for comparison	Volume material Stone	Concrete	Steel reinforce ment	Steel construction
		m	m	m^3	m^3	m^3	m^3
Åros bridge - road bridge	Stone	45	7.8	1400	22	0	0
Fjerdingelv - road bridge	Concrete	45	7.8	0	655	11	0
Hovbrua	Steel	45	7.8	0	137	9	7
Åmfoss 1	Stone	80	3.9	1498	24	0	0
Labbdalsbrua	Concrete	80	3.9	0	471	9	0
Forra - old bridge	Steel	80	3.9	192	112	2	12
Dahne bridge - road bridge	Stone	167	24.8	40896	630	0	0
Litlsund - road bridge	Concrete	167	24.8	0	6556	136	0
Imarsundbrua	Steel	167	24.8	0	4990	87	160

Table 4–8 Material volumes in bridges

The volumes are estimated from drawings, analysis reports and tender documents depending on availability.

Without considering impact from maintenance in the comparison the following results are obtained for carbon footprint related to the construction materials:

Construction name	Material	Selected Lenght for comparison m	Selected Width for comparison m	Carbon footprint kg CO^2-equivalent kg	Ratio Stone/concrete or steel
Åros bridge - road bridge	Stone	45	7.8	77920	1.00
Fjerdingelv - road bridge	Concrete	45	7.8	284695	3.65
Hovbrua	Steel	45	7.8	227456	2.92
Åmfoss 1	Stone	80	3.9	83540	1.00
Labbdalsbrua	Concrete	80	3.9	209565	2.51
Forra - old bridge	Steel	80	3.9	295606	3.54
Dahne bridge - road bridge	Stone	167	24.8	2271600	1.00
Litlsund - road bridge	Concrete	167	24.8	2964680	1.31
Imarsundbrua	Steel	167	24.8	5340395	2.35

Table 4–9 Carbon footprint comparison – similar longevity

The figures show that for the two shorter lengths the stone arch bridge does have more the 50 % less carbon footprint than the concrete and steel constructions. For the longest bridge the carbon footprint of the stone arch concept does still have the lowest carbon footprint, but the difference is reduced.

If a realistic life expectancy is estimated for the different material based on the experience of today (see discussion in the next chapter), and considering 100 y for steel and concrete and up to 300 years for a stone arch bridge the comparison gives the following results:

Construction name		Carbon footprint - 100 y kg CO^2-equivalent kg	Ratio	Carbon footprint - 200 y kg CO^2-equivalent kg	Ratio	Carbon footprint - 300 y kg CO^2-equivalent kg	Ratio
Åros bridge - road bridge	Stone	77920	1.00	77920	1.00	77920	1.00
Fjerdingelv - road bridge	Concrete	284695	3.65	569390	7.31	854085	10.96
Hovbrua	Steel	227456	2.92	454912	5.84	682368	8.76
Åmfoss 1	Stone	74900	1.00	74900	1.00	74900	1.00
Labbdalsbrua	Concrete	209565	2.80	419130	5.60	628695	8.39
Forra - old bridge	Steel	295606	3.95	591212	7.89	886818	11.84
Dahne bridge - road bridg	Stone	2271600	1.00	2271600	1.00	2271600	1.00
Litlsund - road bridge	Concrete	2964680	1.31	5929360	2.61	8894040	3.92
Imarsundbrua	Steel	5340395	2.35	10680790	4.70	16021185	7.05

Table 4–10 Comparison carbon footprint ratios – different longevity

Construction name		Carbon footprint - 100 y tonn CO^2-equivalent/m^2	Carbon footprint - 200 y tonn CO^2-equivalent/m^2	Carbon footprint - 300 y tonn CO^2-equivalent/m^2
Åros bridge - road bridge	Stone	0.22	0.22	0.22
Fjerdingelv - road bridge	Concrete	0.81	1.62	2.43
Hovbrua	Steel	0.65	1.30	1.94
Åmfoss 1	Stone	0.27	0.27	0.27
Labbdalsbrua	Concrete	0.67	1.34	2.02
Forra - old bridge	Steel	0.95	1.89	2.84
Dahne bridge - road bridge	Stone	0.55	0.55	0.55
Litlsund - road bridge	Concrete	0.72	1.43	2.15
Imarsundbrua	Steel	1.29	2.58	3.87

Table 4–11 Comparison carbon footprint on the ratios of emission/m^2 of a bridge

When comparing the carbon footprint with other studies performed in reference /44/ and /45/, the above emissions defined for concrete and steel bridges seem to be low estimations.

For all of the 3 stone arch bridges above, the average carbon footprint per square meter of bridge is 0.33 ton CO^2-equiv/m^2 on the 100 years perspective.

Comparing the bridges in this study with the two reference papers (ton CO^2-equiv/m^2):

Stone arch bridge	0.33
Concrete bridge	0.70
Steel bridge	1.1
Average Island bridge(ref./44/)	1.2 – 10 % transport = 1.0
Average Norwegian bridge (ref./46/)	2.3-20% construction(A4-A5) = 1.8

The stone arch bridge is proving to be a low carbon footprint concept compared to all the other alternatives.

A comparison for railway bridges is carried out below. The bridges and results are presented in the figure and table following and on only the 100 years perspective.

Orkla – Stone

Kilen - Concrete

Steinkjer - Steel

Figure 4-12: Group 4 – railway bridge

		Selected	Selected	Volume material				**Carbon footprint -**	
Construction name	Material	Lenght for comparison	Width for comparison	Stone	Concrete	Steel reinforcement	Steel construction	kg CO^2-equivalent	Ratio
		m	m	m^3	m^3	m^3	m^3	kg	
Orkla - railway bridge	Stone	80	6	4155	64	0	0	230790	1.00
Kilen bru - railway bridge	Concrete	80	6	192	669	12	0	303780	1.32
Steinkjer - railway bridge	Steel	80	6	474	180	0	36	798888	3.46

Table 4–12 Comparison carbon footprint – railway bridges

4.5 The comparison of energy consumption

The following values are used for the energy consumption for 1 m^3 for each of the materials:

Accumulated energy spending:			
Stone		853	MJ/m^3
Concrete		2472	MJ/m^3
Steel reinforcements		453495	MJ/m^3
Steel construction		249552	MJ/m^3

Table 4–13 Energy consumptions – construction materials – comparison

The comparison between concepts for both road and railway bridges for the energy consumption for delivery of the materials (A1-A3):

Construction name	Material	Selected Lenght for comparison	Selected Width for comparis on	Energy consumption 100 Y	
		m	m	MJ	Ratio
Åros bridge - road bridge	Stone	45	7.8	1248584	1.0
Fjerdingelv - road bridge	Concrete	45	7.8	6607605	5.3
Hovbrua	Steel	45	7.8	6166983	4.9
Åmfoss 1	Stone	80	3.9	1337122	1.0
Labbdalsbrua	Concrete	80	3.9	5245767	3.9
Forra - old bridge	Steel	80	3.9	4342254	3.2
Dahne bridge - road bridge	Stone	167	24.8	36441648	1.0
Litlsund - road bridge	Concrete	167	24.8	77881752	2.1
Imarsundbrua	Steel	167	24.8	91717665	2.5
Orkla - railway bridge	Stone	80	6	3702423	1.0
Kilen bru - railway bridge	Concrete	80	6	7259484	2.0
Steinkjer - railway bridge	Steel	80	6	9833154	2.7

Table 4–14 Comparison energy consumption – 100 years

The tendency shows a higher ratio difference factor than for the carbon footprint. In crude oil energy terms, the Åros stone bridge consume the energy of approximately one lorry (27 ton). The Fjerdingelv concrete bridge would need approximately 5 similar lorries. This is only for the delivery at the gate of the producer of the material.

The stone arch bridge is proving to be a low energy consuming concept compared to all the other alternatives.

5 Service life and maintenance

The life expectancy of different materials is an important factor when a holistic comparison of a life cycle is carried out. The above comparisons for the pavement stones by DNV in section 4.1 states an example on this matter. The fact that you have to replace a concrete pavement 3 times in the expected lifetime of one stone pavement should have a major impact when selecting the material in a project.

This is also clearly demonstrated in the comparison of bridges. To understand and be able to quantify a realistic lifetime expectations is vital for enabling a sound decision of concept. This is not only an impact on the carbon footprint or energy consumption but also for the economic issue.

There is no evidence today of steel and concrete bridges with a service life of more than 100-150 years. Across Europe there are many bridges of stone that remains as evidence of longevity. The Pond du Gard in south of France has been around for about 2000 years.

Figure 5-1: Pont Du Gard – Nimes, France

The Orkla bridge has been operating since 1920 and is now in it's 104th service life. There are no expectations today of any major maintenance projects for this construction. Keeping the drainage system open and there are no further treats for deterioration of this structure.

In comparison, the concrete and steel bridge in Verdal opened in 1974 on the E6 does now after 50 years service require major maintenance. This is a bridge with steel beams and a concrete deck. The estimated cost of this maintenance project is 80-90 million NOK. The concrete deck is proposed replaced and the steel beams need a new layer of corrosion protection. This is certainly making a major change on the original estimation for cost, carbon footprint and energy consumption.

It is fair to state that the knowledge and quality control of the concrete at the time of the construction of Verdal bridge was not at the same level as for today. The lifetime expectations for a concrete bridge built in 2024 is 100 year and this is the lower bound conservative estimate.

Still a well-maintained stone arch bridge does not have the same limits. The weak point is the mortar and the drainage system. Following up these two items properly and the bridge will stand for several hundred years. Building without mortar, as for the Pond Du Gard and one of the two weak point is eliminated. The erosion from the environmental conditions including frost/thawing for the Larvikitt stone quality was defined to negligible over 500 years by the Natural Stone Institute in USA, ref. Lund AS. Using quality stone should then assure a longevity beyond any estimated service life we need to define.

In Devon in England there is a high density of stone arch bridges. Of a total of 3242 bridges 1825 are masonry bridges. At a bridge conference in the UK in 2022 a paper was presented about the longevity and the low maintenance costs for stone arch bridges. The presentation was prepared by the chief engineer Kevin Dentith in the Devon County Counsil, a major bridge owner, and Professor Adrienn Tomor at Bartlett School of Sustainable Construction and University College of London (ref. /45/).

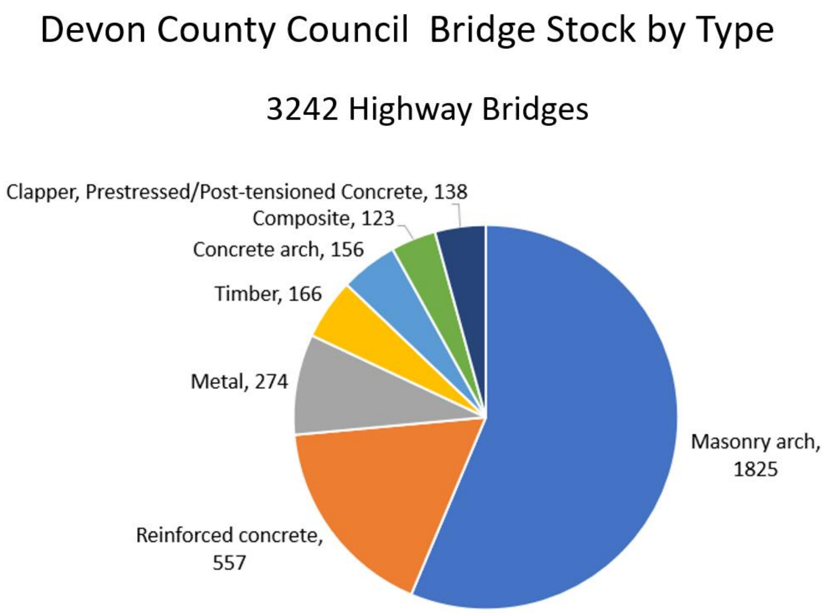


Figure 5-2: Type of bridge structures in Devon County Council

From their experience the maintenance cost was remarkably lower for masonry bridges than concrete and steel.

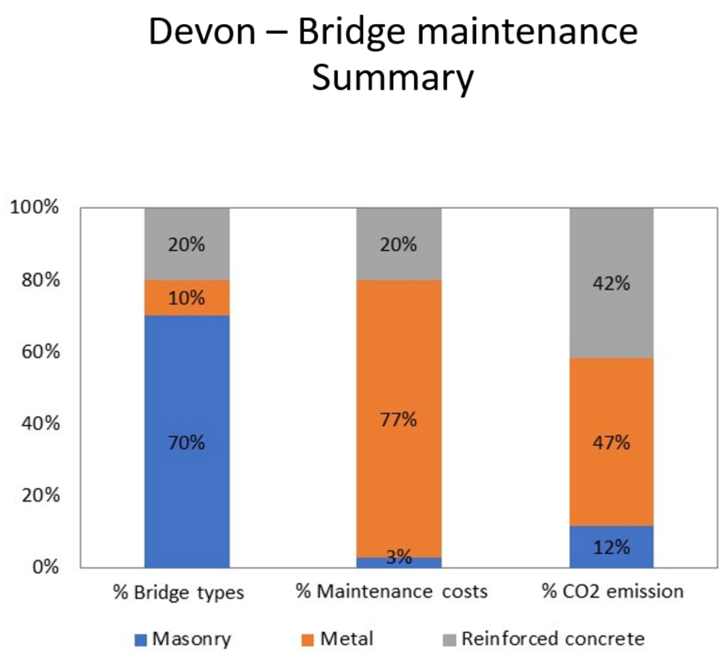


Figure 5-3: Devon UK -Type of bridges – cost of maintenance – carbon emission

This tendency is also confirmed in the PhD thesis issued by T.B.Balogon in 2018 (ref. /49/):

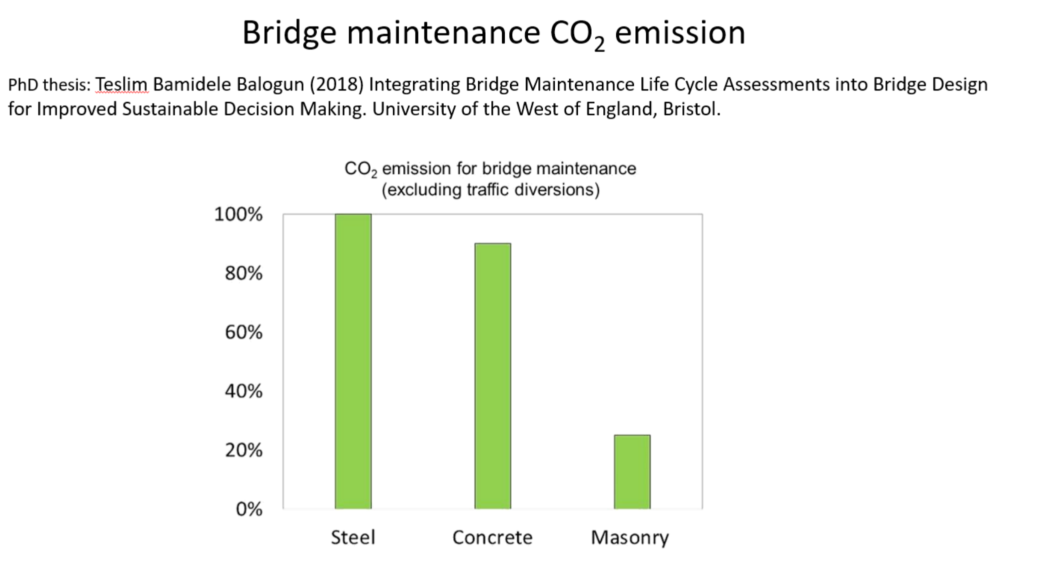


Figure 5-4: Carbon emission for bridge maintenance

It is similarly for the stone arch bridges in Norway with low reported maintenance activity for both road bridges and railways (ref. interviews).

The stone arch bridge is proving to be a low maintenance concept compared to all the other alternatives.

6 A short summary from this master's study trip in Europe

During the work with this master thesis a study tour was carried out in the spring of 2024. The trip was planned based on the topics in the thesis and the aim was to meet professionals in the science of stone masonry technology, visit some sites of interest like structures giving physical evidence of the quality of stone arch bridges, museums and national libraries.

The route of countries was Portugal, Spain, France and England. The sites of interest visited was:

- Porto and the 6 major bridges over the river Duero.
- Segovia with the aqueduct.
- Madrid with its archeological museum.
- Barcelona with the museum of Sagrada Familia.
- Nimes with its Pont du Gard.
- Baux de Provence with the stone quarries.
- Paris with the National library and the industrial museum Arts & Metiers.
- London with its 5 km long masonry arch bridge construction for Greenwich railway line and the ICE library.
- Cambridge with the Wren library of the Trinity College and the many stone arch bridges around the city.

Meating professionals working with bridges and stone a good way to get knowledge and understanding of the history, the status of today and future possibilities. The following meetings and surveys was arranged on this tour:

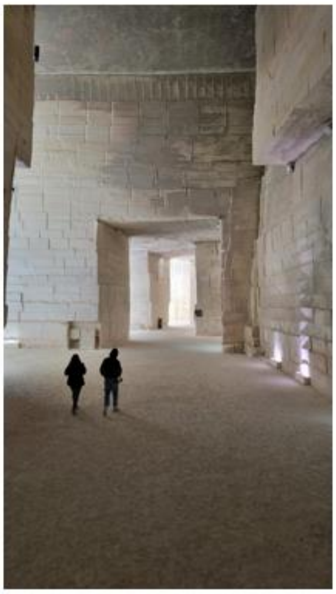
- One day survey together with Santiago Fernández Huerta and Antonio Ruiz Hernando on the aqueduct of Segovia. Santiago is professor at the Polytechnique University of Madrid. Antonio is Emeritus Professor of History of Art at the Polytechnique University of Madrid and Chronist of the City of Segovia.
- A survey together with Hamish Harvey on the 5 km long stone masonry railway line between London and Greenwich. Hamish is operating as bridge engineer and software developer for analysis of stone arch bridges and has his office in Cardiff. He works for Bill Harvey Associates Limited and OBVIS Ltd UK and has developed the software analysis program Arhie-M
- One working day at the Institute of Civil Engineering (ICE) with Hamish Harvey on the software of Arhie-M and a visit together at the ICE-library for a closer look at Thomas Tellford's (1757-1854) original book of Jean-Rudolph Perronet (1708-1794).
- Working meeting at the University college of London with Adrienne Tomor, Collum Gilette and Hamish Harvey on the issue of stone arch bridges, maintenance and carbon footprint. Adrienn Tomor is associated professor at the Bartlett School of Sustainable Construction and the University College of London. Callum Gilette is Bridge engineer working with technical approval and asset management for the Essex Highways, on behalf of Essex County Council.
- Participating on a evening seminar on stone materials at Clerkenwell house in London arranged by Pierre Bidaud, Creative director at the The Stonemasonry Company Limited.

- One day survey in Cambridge with Callum Gilette visiting stone arch bridges around Cambridge and the Wren library with Isaac Newton's Philosophiea Naturalis Principia Mathematica (1687).

Some pictures from the trip:

Bridge Lois I – 1886 Porto

Aquaduc of Segovia – Akvedukt – 2000 year old



Gaudi's model of Sagrada Familia

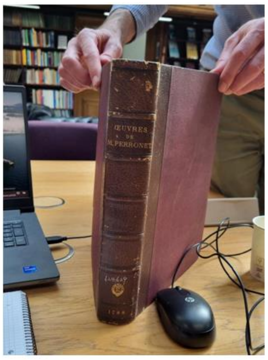
Pont du Gard – 2000 year old -Nimes

Pont Julienne – 2000 year old -Avignon

Stone quarry – Beaux de Provence

National library, Paris

Greenwich railway line, London



ICE library, London

Stone arch bridge, Cambridge

Figure 6-1: Study tour pictures

7 Discussion and further work

There are five major sources of learning in this thesis.

- The history
- The theory
- The stakeholders of today
- The carbon footprints and the energy consumption
- Longevity and low maintenance

7.1 History

It is important to learn from the history of stone arch bridges. There is no doubt that the art of engineering and construction of stone arch bridges was well developed when the erea of this bridge type faded out after the second world war. The structures remaining and still serving us is a testimony of quality and sustainability.

The possibilities arising in the late 19th century with the new energy conversions enabling the production of new materials and hence more slender and lighter constructions in concrete and steel made the way for new logistics. With reduced weights to handle, reduced need for manpower, reduced construction time and possibility for longer span bridges the stone arch lost in this competition.

What has changed since then? The tools we have today for research, design, quality control, production, construction and maintenance are improved. With this new framework built on the knowledge from history and the advantage of the modern available tools and logistics would be a foundation for a new technology for the construction of this type of bridges.

What else has now changed? There is a new global concern on the holistic thinking of how we use our energy resources and how this affects the global climate. There is not room for "business as usual" and the focus on reducing greenhouse gasses from human activity is now becoming a game changer impossible to ignore.

7.2 Theory

At the time of the stone arch bridges the calculators and computers of today was not available. Still the understanding of the structural theories and the art of structural engineering was at a high level.

The engineers managed to utilize the material in optimal ways with well documented calculations and drawings. The Pont de La Concorde in Paris is a testimony of optimal design and sustainable construction practice (1791). The stones used for this bridge was reuse from the famous prison of la Bastille. Several recent studies of the original bridge have confirmed the optimal design and could not find any possibilities for further optimalization. It is enlarged but the original part is still in service and is exposed for dense traffic loading today.

A structural calculation for a stone arch bridge was often presented on just one single drawing, see figure 2-27 for the Orkla bridge. This is a contrast to the voluminous computer models and reports of today.

It is a fact that the lack of building stone arch bridges is reflected in the lack of consistence in national and European codes for such constructions. The analysis carried out today are often to justify limitations on old structures for new functional requirements. A big scale renaissance would require a further development of design rules and common limitation settings for safety.

The stone as construction material, when used correctly, has an high level of strength and capacity. The stone arch bridge has through history been designed for low stress level utilities and hence providing resilience, redundance and robustness (3xR).

As Leonardo De Vinci indicated in his notebook, the strength of the arch is not the essential as the stresses should be kept at a low level compared to the strength of the stone. It is the level of axial thrust in the arch that gives the arch it's strength.

With the computer power in the tools for analysis today and the high level of engineering science the industry should be well prepared, equipped and qualified for a new development for a future sustainable design of stone arch bridges.

7.3 Stakeholders today

It has been an interesting and educational journey to meet stakeholders of the today bridge industry through interviews, meetings and surveys with this focus on stone arch bridges. There is certainly a genuine interest in the idea of again looking at the stone as a construction material. But no stakeholder (owner, engineer or entrepreneur) is in a position to restart a new area of this art from the past alone. There is a need for strategical governance and will to join the different stakeholders on a platform of cooperation and hence finding the path together. The reason to do this must be well described and understood and the strategy must be the adequate sustainable solution.

There is no discussion today around the stone material in the process of conceptual selections in Norway, and rarely elsewhere. At the Via Nordica of 2024 the carbon emissions were in focus, but the different bridge projects highlighted in the conference did not involve the stone as a material. We hear about concrete, steel, wood, aluminum and composite. We hear about the efforts of reducing GHG-emissions from alle these industries providing these materials, but it is all quite about the stone.

There is a need for cooperated effort. The global goals for a "greener" industry can provoke and make this happen. There is always a risk in starting a "new" concept. In an industry the risks are shared among stakeholders but there must be a possibility for a sustainable business case to assure involvement. For the owner it is all about investment costs, maintenance cost and providing value for the society. For the entrepreneur it is about delivering quality and surviving in the competition in the industry.

The holistic strategy when including alle the topics included in this thesis (sustainability, longevity, environmental impact, maintenance impact, energy impact) in investment analysis can for future projects change the outcome.

In the Norwegian Public Road Administration the main strategy is to take good care of the assets you have, maintenance and repair if you can and build new assets where you have to. Investing in a stone arch bridge means that we do not have to put much effort in maintenance and building a replacement would not be any issue for many 100 years (well if the functional requirements does not change).

7.4 Carbon footprint and energy consumption comparison

The results from the comparison of carbon footprint and energy consumption does show a tendency. The stone material has a lover environmental impact than steel and concrete considering the volumes of material required for bridges. Having compared the volume of the materials required and only delivered at the gate of the producer, the results are as expected. The production of steel and concrete are well known to be energy intensive, and their carbon footprint is well documented. The stone is provided to us by nature and we only need to execute the extraction and the forming. The carbon footprint and the energy consumption is hence lower for the stone material.

The concrete and steel construction will be the only concept possible for the bigger bridges due to their quality on elasticity and tension strength capacity. For bridges with lengths up to 100-120 m (multi-span) the stone arch bridge can be an alternative.

The Dahne bridge in China is of course a remarkable demonstration on how much further these limitations can be stretched (ref. figure 2.15).

The comparisons carried out show that it is within the lower ranges of lengths the gain on energy consumptions and carbon footprint is most advantageous for the stone arch bridges.

The advantage of longevity is demonstrated and is an important factor in the holistic view and should be carefully considered also when evaluating the carbon footprint and energy consumption. Constructing with quality for long expectation of service life is an environmentally friendly strategy. The stone arch bridge should be an alternative to consider.

Further work is needed from a wider range of experts to challenge the results in this thesis. The analysis on environmental impact is complex and to position the stone arch bridge correctly in this holistic life cycle analysis is a challenge. Anyhow the results from the method carried out in this report is coherent with the expectations and findings received from other informants who has shared their reporting on the topic (ref. /31/, /43/, /46/).

7.5 Longevity and maintenance

The longevity and maintenance of a construction are two factors of high importance for a bridge owner.

The low maintenance costs for the stone arch bridges are generally agreed by asset managers and the referred study performed in Devon UK confirms this fact (ref /46/).

From experience gained from the construction of Åros stone arch bridge in Norway in 1999 we know the estimates on this prototype project ended up with almost twice the prize of the cost estimate made for a concrete bridge at the same locations. In these calculations there was not included potential cost for neither future maintenance nor the possibilities for the differences in realistic service life expectations. In 1999 the cost of energy was a minor issue, and the carbon footprint was not an issue at all.

It is obvious that longevity and maintenance does have major impact on all aspects when selecting a bridge concept for the future.

Building a bridge once or twice in a time window or three times affects all the estimates. To obtain an equilibrium on a balance bowl you must carefully select the values you put on each side. Selecting the correct values for longevity, maintenance, energy consumption, carbon footprint and consequences of “business as usual” with regards to climate change is a complex exercise. The request from the United Nations is that we must find this equilibrium, not tomorrow, but today.

8 References

Ref. No.	Doc. No.	Title	Issuer	Issued
/1/	V421	Guidelines - Stone arch bridges	Norwegain public road administration	2014
/2/	V230	Guidelines - Stone arch bridges - old revision	Norwegain road public administration	2002
/3/	V270	Guidelines - Dry stone walls and machinery	Norwegain public road administration	2014
/4/	2002-05-BRU	Guidelines - Construction analysis for stone arch bridges	Norwegain public road administration	2002
/5/	V412	Guidelines – Load capacity classification of bridges - loads	Norwegain public road administration	2023
/6/	V413	Guidelines – Load capacity classification of bridges - materials	Norwegain public road administration	2023
/7/	V420	Guidelines – Shaping a bridge	Norwegain public road administration	2023
/8/	BS-EN-1926	Natural stone test methods - determination of uniaxial compressive strength	British Standards Institute	2006
/9/	Book	Safety of Historical Stone Arch Bridges	Dirk Proske and Peter van Gelder	2009
/10/	Paper	Master thesis - New stone vault bridge crossing Farris river	Marianne Hvaal Larsen, NTNU	2009
/11/	Paper	Master thesis – On engineering methods for assessments of load capacity of stone arch bridges	Kristoffer Holmstrøm, Chalmers University	2010

/12/		Manual of bridge engineering	M.J. Ryall,G.A.R Park and J.E. Harding	2000
/14/	Meld.st. 20	National plan for transport (NTP) 2022-2033	The Norwegian ministry of transport	2021
/15/	Paper	Arch Bridges design in eighteenth-century France – The rule of Perronet	Santiago Huerta – Universidad Politecnica de Madrid, Spein	2018
/16/	Paper	Coulomb's theory of arches in Spain ca. 1800: the manuscript of Joaquín Monasterio- presentation ARCH10 – 6th International Conference on Arch Bridges	S. Huerta & A. Albuerne – Universidad Politecnica de Madrid, Spain	2010
/17/	Youtube	Understanding masonry bridges	Hamish Harvey-Director, Bill Harvey Associates Limited, England	2023
/18/	Guidline	BTC Uganda –Manual- Stone Arch Bridges	Sophie Grigoletto / Steven Hollevoet	2013
/19/	Book	Grandes Voutes Volume 1-6	Paul Sejourne	1913
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/22/	Book	Klimaendring i Norge	Knut H. Alfsen, Dag O. Hessen, Eystein Jansen	2013
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/24/	Book	How the world really works	Vaclav Smil	2022
/25/	Book	Klimamytene	Morten Jødal	2017
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/27/	Book	The stone skeleton	Jaques Heyman	1995
/28/	Book	The masonry arch	Jaques Heyman	1982
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/30/	Book	The Irish stone bridge	Peter O'Keeffe T. Simmington	1991
/31/	Paper	The relevance of cut-stones to strategies for low-carbon buildings	T. Tedoldi T. Pester	2022
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/34/	Article	La tour Eiffel est-elle dans un état preoccupant, faut d'entretien - Figaro newspaper	Clair Bommelaer	2024
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/39/	Book	Description des projets et de la construction des ponts De Neuilly, de Mantes, d'Orelans	Jean-Rodolphe Perronet	1782
/40/	Article	Devis des ouvrage a fair pour la construction du pont de Louis XVI	Jean-Rodolphe Perronet	1782
/41/	Note	Memoir sur le cintrement et la decintrement des pont	Jean-Rodolphe Perronet	1777
/42/	Article	Evaluating existing and historic stone arch bridges – Structural magazine	Carl Citto and D.B. Woodham	2015
/43/	Study	External pavement sustainability study	DNV (German Natural stone association)	2021
/44/	Pres.	Presentation at the Via Nordica 2024 – Sustainable bridge design	Magnus Arason Efla, Island, Hans Henrik Christensen Rambøll, Denmark	2024
/45/	Paper	Case study – carbon emission for maintenance projects of concrete bridges	Karla Hornbostell Bob Hamel Roy Antonsen All - SVV	2022
/46/	Paper	Viability of building new masonry bridges	Kevin Dentith - Denon couty Counsil Adrienn Tomor UCL and	2022
/47/	web	www.history.com		
/48/	web	Structural magazine		
/49/	Paper	PhD thesis - Integrating Bridge Maintenance Life Cycle Assessments into Bridge Design for Improved Sustainable Decision Making	Teslim Bamidele Balogun (BSc, MSc)- UWE Bristol University	2018

9 Appendix

-Appendix A -List of informants and interview participants

-Appendix B - Interview procedure and questions

-Appendix C - Structural analysis of Storstraumen bridge

PS: The appendix C is attached as a separate document

Appendix A –List of informants and interview participants

List of informants and interview participants:

No.	Name	Position	Company
1.	Thorstein Kjøs Johnsen	Bridge design engineer	Norwegian Public Roads Administration
2.	Hanne Gundersen	Bridge engineer – inspection and maintenance	Norwegian Public Roads Administration – County of Midt Norway
3.	Dr. Adrienn Tomor	Assosiated Professor	Bartlett School of Sustainable Construction – University College of London
4.	Magne Langeteig	Retired bridge asset manager	Norwegian Public Roads Administration
5.	Callum Gillett	Bridge engineer– Technical Approval and Asset Management	Essex Highways, on behalf of Essex County Council, England
6.	Halvor Uldal Kåsa	Bridge asset manager	Norwegian Public Roads Administration
7.	Håvard Johansen	Bridge design engineer	Norwegian Public Roads Administration (VD)
8.	Hege Elisabeth Lundh	Marketing & Business Director	Lundh AS – natural stone producer
9.	Roar Spets Halstadtrø	Bridge engineer	BaneNor – Norwegian Railway
10.	Helene Fromreide Nesheim	Mining Engineer	Lundh AS – natural stone producer
11.	Hamish Harvey	Bridge engineer and software developer	Bill Harvey Associates Limited, England
12.	Bob Hamel	Climat and environment engineer	Norwegian Public Roads Administration
13.	Pierre Bidaud	Creative director	The Stonemasonry Company Limited – England
14.	Espen Dobakk	Engineering coordinator	Norwegian Public Roads Administration
15.	Tarjei Karlsen Bruaas	Bridge asset manager	Norwegian Public Roads Administration
16.	Klaid Robert Schjetne	Road engineer	Norwegian Public Roads Administration
17.	Harald Inge Johansen	Project manager – Constructions	Norwegian Public Roads Administration
18.	Guri Pedersen Skei	Landscape architect	Norwegian Public Roads Administration

19.	Grzegorz Gucwa	Project manager – bridge and infrastructure – Norway	Skanska Oslo, Norway
20.	Bjørn Snorre Laksforsmo	Division manager – Operations and maintenance	Norwegian Public Roads Administration
21.	Arnt Egil Rørtvedt	Bridge design engineer	Norwegian Public Roads Administration
22.	Bjørn Tangvald	Section manager – Bridge engineering – Complex constructions	Norwegian Public Roads Administration
23.	Dr. Santiago Fernadez Huerta	Professor	Polytechnique University of Madrid – Spain
24.	Antonio Ruiz Hernando	Emeritus Professor of History of Art	Polytechnique University of Madrid and Chronist of the City of Segovia, Spain
25.	Knut Grefstad	Bridge design engineer	Norwegian Public Roads Administration (VD)
26.	Jan Henrik Hansen	Manager – Stone quarry company	Larvikittblokka AS, Larvik, Norway
27.	Sverre Smedplass	Professor II og Rådgiver betongteknologi	NTNU og Skanska
28.	Clemente Pinto	Professor and Structural Engineer	Universidade da Beira Interior – Portugal

Appendix B – Interview procedure and questions

Interview and informant sessions – Procedure and questions

Stone arch bridges – why not now? – A new renaissance? –Stone as a material for bridges? – what does it take? –Is this just nostalgia?

The questions for the interviews are set up with the objective to challenge participants on the topics of this thesis. Most of the participants have no experience with stone arch bridges. This is expected due to the status of this type of bridges. All the participants have dough a position within the bridge industry.

It is a target to create a good platform for discussion, creativity, reveal answers and elicit new questions.

The interview objects and informants covers the following professions or position:

- Division director – Operation and maintenance
- Bridge asset managers in Norway and UK
- Structural design engineers in Norway and UK
- Environmental engineers
- Authorities for rules and regulations
- Professors and researchers in universities in Norway, Spain, Portugal and UK
- Bridge and stone quarry entrepreneurs in Norway and UK

Often interviews in research is set up to enable comparisons between a response from equally set of stakeholders with a static list of questions for this reason.

In this study the aim has been to reveal the opinion on possibilities within the topics of the thesis from a variety of experts related to the bridge industry. It was hence necessary to have a dynamic focus. The background and professional position of each participance are quite different. Not every question is relevant for all the interviews. The intension is anyhow that all the questions together should encourage and allow for a wider reflection for each participant, also outside their own domain.

The learning process from the start of the first interviews to the last interviews, a period of 6 months, was expected to gradually increase the content in the questionary.

In the introduction to each interview the aim of the study is presented.

To narrow the focus the range of construction to consider is restricted to new bridges within the range of span from 3-150 m and an investment budget of 200 million Norwegian krone.

The documentation of the interviews and informant is registered in notes written down during the meetings.

The following questions has been the platform for the communication with the interview objects and informants:

Strategy and organization:

1. Who is the owner of the decision-making process with regard to the choice of concept?
2. Who is in charge when the choice of concept is carried out?
3. Which group of experts have the biggest influence on a bridge concept selection?
4. Can the authorities of rules and regulations influence or override a bridge concept selection?
5. Is there any external stakeholders (political – economical) making influence on a bridge concept
6. What do you experience as the most important factor when selecting a concept for a new bridge?
7. Is factors as national security and defence influencing the process?
8. Is the "copy-paste" effect of importance? (Let us do this as the previous project we have in the drawer)
9. Is there much room for invention?
10. Is the process for concept of a bridge well founded in the quality systems?

Economy:

11. Does the available budget give major restriction/delimitation for a concept?
12. Is the future maintenance cost in focus?
13. Is there a god balance between quality, sustainability and longevity versus budget?
14. Is the limitation of 100-year service life relevant and is longer horizons even considered?
15. Is robustness and resilience issues reflected in the estimates?
16. Carbon footprints seems to have a cost. Is this a factor in the economical evaluation?
17. Longevity and low maintenance efforts are important qualities. Are these qualities rightfully weighted?

Carbon footprint:

18. How does the carbon footprint influence the strategic choice of concept?
19. In 2024 a change in the public procurement regulations is introduced regarding climate and environmental issues. These issues are to be weighted in a tender assessment process by 30 % or more. What consequence can this imply when selection a bridge concept.
20. A new revision of the design guidelines from the Norwegian authorities was issued in 2024 (N400-Bridge design). A new requirement regarding the selection of type of bridge concept was implemented stating the effort towards consideration for sustainability and preparedness should be documented. The selected concept should also be optimized with regards to a sustainable solution. What can be the impact of these new requirements?

Random questions for the future:

21. Is the material selection a highly discussed issue?
22. How are the values with regards to aesthetics and architectural considered?
23. Quality, sustainability and longevity versus budget?
24. Are there political influence on details as choice of material and aesthetics.
25. Which materials are considered today?
26. How does the knowhow among entrepreneurs influence a bridge concept?
27. Can the use of stone as material perform in the competition today?
28. Why is stone not considered as the material when building bridges today?
29. Can a stone arch bridge be a technological step forward?
30. What does it take to select again the stone?
31. In which circumstances does stone seems to be a god alternative
32. Can the new requirements on carbon footprint, environmental considerations and sustainability give the argument for using stone?
33. Do we have quality stone locally in Norway
34. Are regulations, owners, asset managers, entrepreneurs and the quarries rigged for stone arch bridge construction?
35. What is robust?



-One node -one wire -one cable

Closing questions:

Claims:
Stone arch bridges seems to have longevity beyond other materials
Stone quality in Norway is generally good
Stone arch bridges seems to have low maintenance cost.
Stone arch bridges seems to represent simple and straightforward technology
Stone arch bridges has low carbon footprint
Stone arch bridges strength and longevity seems unlimited
Stone arch bridges can always be constructed of stones from local quarries

Dahne bridge – China

The above stone arch bridge was constructed in 2001, with a span of 146 m and serve in a 4-lane road highway.

Is it possible that such a construction can be constructed for the Norwegian road system today?