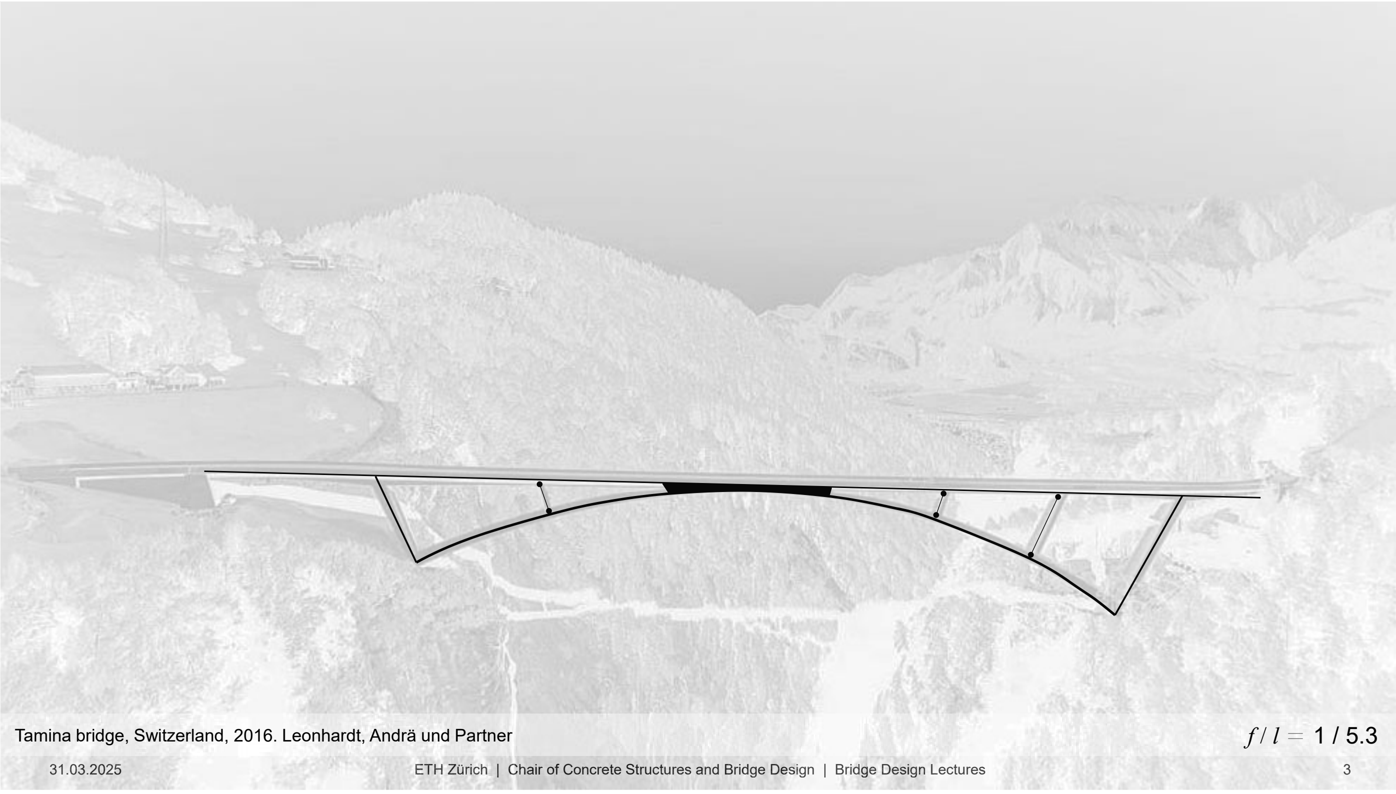
Arch bridges

(Bogenbrücken)

Tamina bridge, Switzerland, 2016. Leonhardt, Andrä und Partner $f / l =$ 1 / 5.3

Video: https://www.youtube.comwatchv=fJCyOFjVvQM

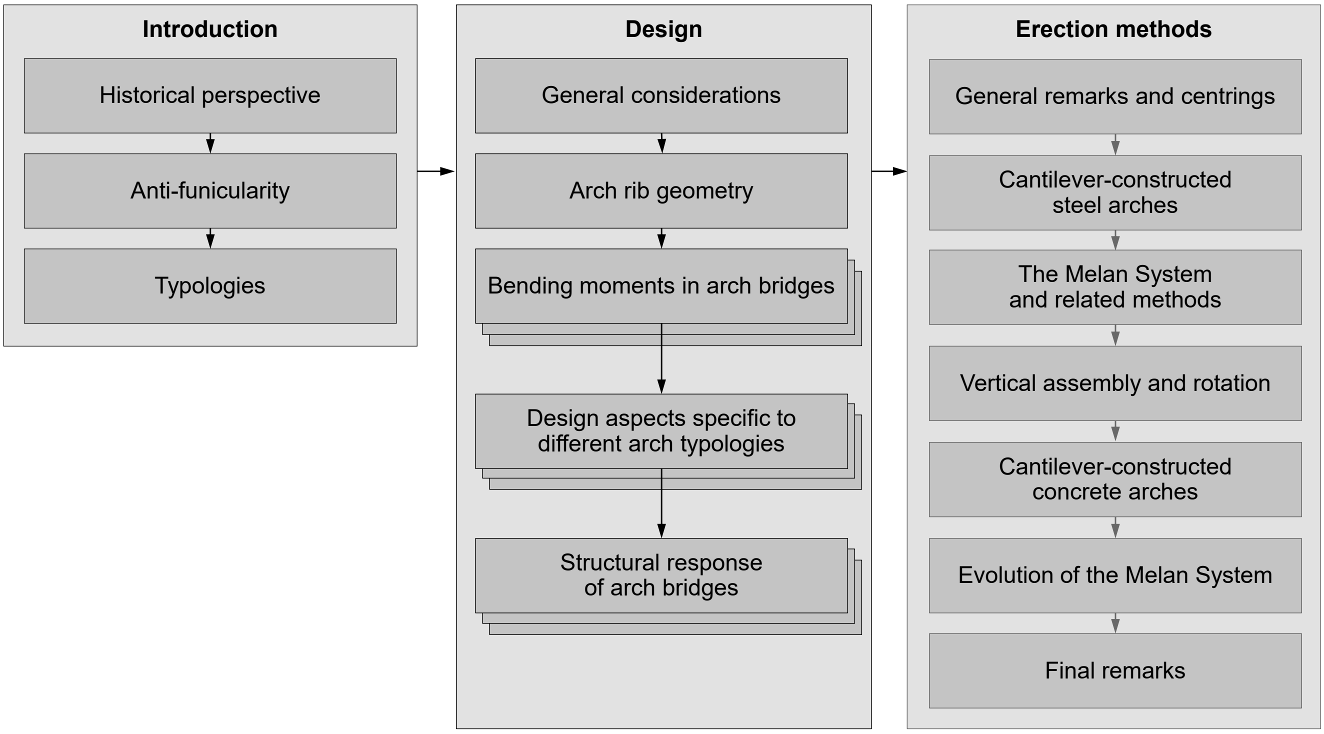


The profile of Tamina bridge is perceived as aesthetically pleasing by structural engineers and laymen alike. As structural engineers, beyond this subjective qualification of a bridge, we are able to judge its structural efficiency by evaluating its behaviour and predicting the response as a function of the actions, the geometry, the support conditions and the relationship between the stiffnesses of the parts of the bridge.

Among others, the following parameters affect the structural behaviour:

- Ratio of rise (f) / span (L)
- Clamped or hinged support at the springing lines
- Hinge at the crown
- Distribution of the columns
- Clamped or hinged columns

This chapters covers the basic knowledge required for conceiving, predimensioning and analysing arch bridges, accounting for these parameters.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Arch bridges

Introduction

Arch bridges

Introduction – Historical perspective and terminology

Arch bridges – Introduction: Historical perspective

- Masonry arches, and masonry arch brides, have been built for centuries, or rather, millennia (photo)
  - → analysis of arches was one of the first topics studied in the history of the theory of structures
  - → da Vinci already studied and measured the horizontal thrust of arches
  - → Coulomb was one of the pioneers, followed by many other (Monasterio, Culmann, Poleni, Heyman, …) (figure)
- Since there is no tensile strength in the joints, masonry structures act primarily in compression → anti-funicular arch geometry (axis geometrically similar to funicular polygon of forces, i.e. corresponding to thrust line = Druck-/Stützlinie) is ideal.

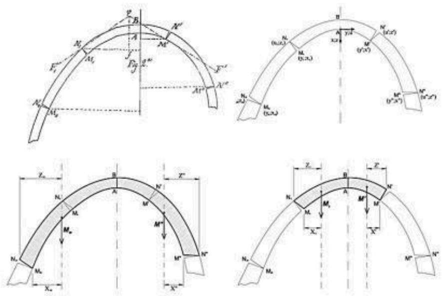


Photo: Puente de Alcántara, Cáceres, Spain (103). Stone masonry arch, length 194 m, main spans 28.8 m, 48 m above Tajo river, width 8.6 m. Photo kfm

Figure: Illustration of Joaquín Monasterio explaining Charles Augustin de Coulomb’s arch theory (here: rotational failure mechanisms), taken from A. Albuerne and S. Huerta: “Coulomb’s theory of arches in Spain ca. 1800: the manuscript of Joaquín Monasterio,” Arch' 10. 6th International Conference on Arch Bridges (Fuzhou, China, October 11-13, 2010), pp. 354-362.

Arch bridges – Introduction: Historical perspective

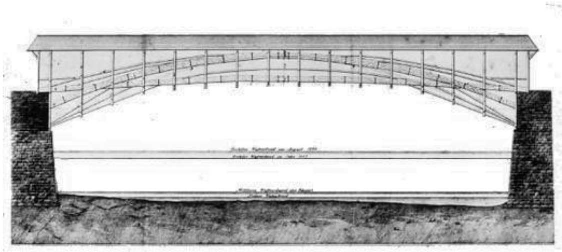
- Masonry arch bridges are part of the cultural heritage of our society and, more specifically, the Swiss railway network.
- For example, the Albula and Bernina lines of RhB are UNESCO World Cultural Heritage, the consistent use of standardised stone masonry arch bridges being one of their main characteristics.

Top photo: Landwasserviadukt Filisur, RhB Albula line, F. von hennings / Müller & Zeerleder, A. Acatos (1902). Masonry arch viaduct, spans 6x20 m. © www.rhb.ch

Bottom photo: Circular viaduct in Brusio, RhB Bernina line, Buss&Cie. AG (1907), length 143 m, spans 9x10 m, 7…17 m above ground. © www.rhb.ch

Arch bridges – Introduction: Historical perspective

- Timber arches have also been built for many centuries. Johannes Grubenmann was one of the pioneers (photo).



- About two centuries ago, iron (photo), steel and concrete arches became economical, significantly increasing the feasible spans.
- With its high compressive, but negligible tensile strength, concrete is perfectly suited for arch bridges.

Top figure: Rheinbrücke Reichenau, J. Grubenmann (1757). Timber arch, span 70 m, destroyed by fire in 1799. © Mario Fontana, Brückenbau.

Bottom photo: Severn bridge in Coalbrookdale, Abraham Darby III. First cast iron bridge, arch span 30 m. Photo © http://www.trover.com/d/1B1dz-ironbridge-england (Brückenbau, Th. Vogel)

Arch bridges – Introduction: Historical perspective

- The first concrete arch bridges were mimicking masonry arches (unreinforced concrete used as inexpensive stone surrogate). More slender, efficient and elegant concrete arches emerged about a century ago (photo).
- Switzerland was at the forefront in these developments, mainly due to:
  → its topography with many steep valleys being well-suited for arch bridges
  → the early development of cement production (with very limited domestic steel production)
  → competent and innovative structural engineers
- The following Swiss bridge designers are internationally recognised as pioneers in concrete arch bridge design:
  → Robert Maillart
  → Alexandre Sarrasin
  → Christian Menn

  The next slides show some of their most prominent bridges. For more examples, see respective presentation "Eminent bridge designer of the week".

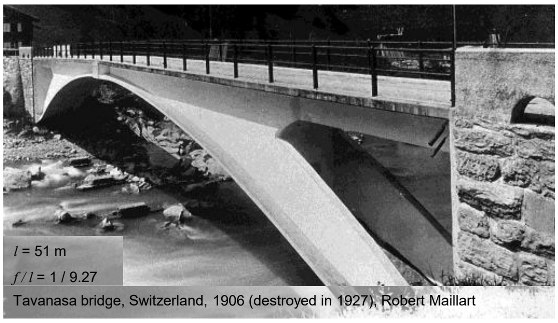
Photo: Lorrainebrücke (road bridge) Bern, Robert Maillart (1930). Unreinforced concrete, length 178 m, main span (elliptic arch) 82 m, 37 m above Aare. In the background, the Aarebrücke of the SBB Lorraineviadukt, (1941), reinforced concrete arc, main span 150 m (Europe's longest span at the time)

Photo © Chriusha, Wikimedia Commons

Arch bridges – Introduction: Historical perspective

l = 37.4 m
f / l = 1 / 6.23
Schwandbach bridge, Switzerland, 1933, Robert Maillart

l = 90 m
f / l = 1 / 6.93
Salginatobel bridge, Switzerland, 1930, Robert Maillart

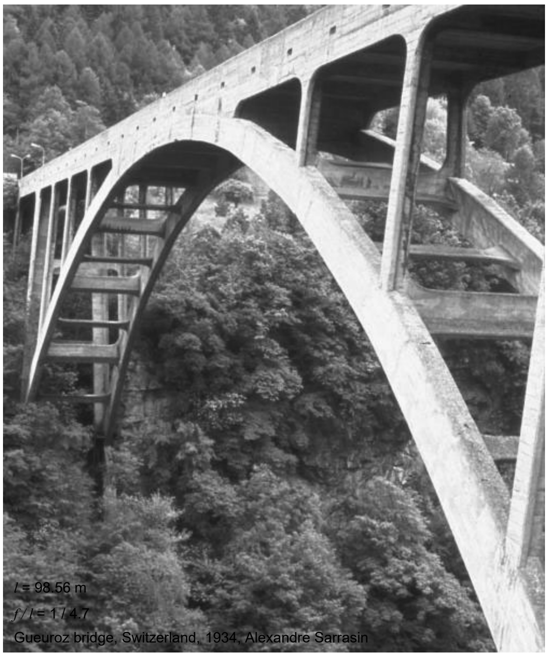


l = 51 m
f / l = 1 / 9.27
Tavanasa bridge, Switzerland, 1906 (destroyed in 1927), Robert Maillart

Robert Maillart: Schwandbachbrücke (1933, l = 37.4 m), Salginatobelbrücke (1930, l = 90 m), Tavanasabrücke (1906, destroyed in 1927, l = 51 m)

Photos © P. Marti, O. Monsch, B. Schillling: Ingenieur-Betonbau

Arch bridges – Introduction: Historical perspective



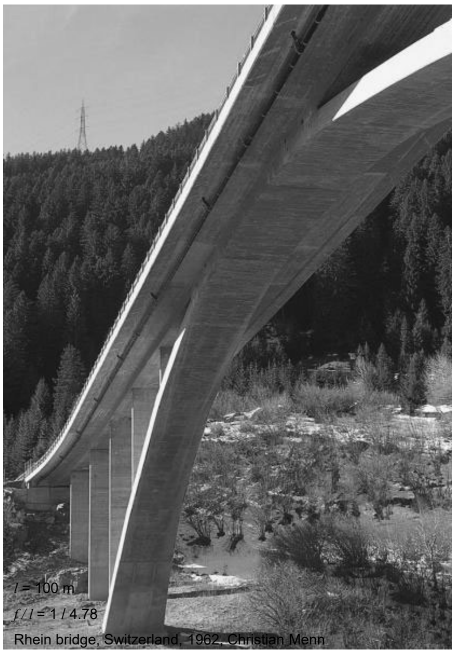
l = 98.56 m
f / l = 1 / 4.7
Gueuroz bridge, Switzerland, 1934, Alexandre Sarrasin

l = 66.3 m
f / l = 1 / 4.14
Merjen bridge, Switzerland, 1930, Alexandre Sarrasin

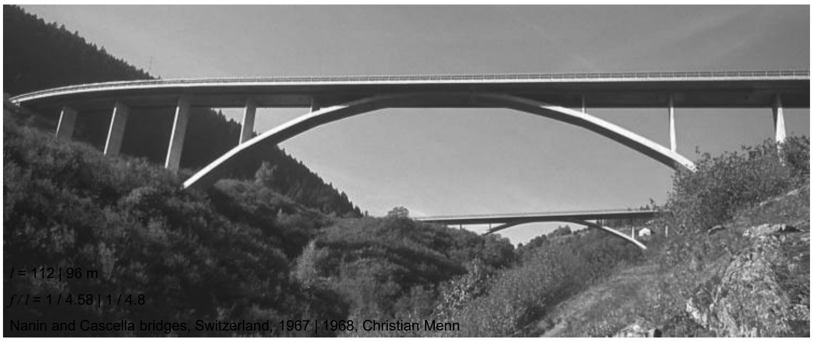
Alexandre Sarrasin: Pont de Gueuroz, Vernayaz (1934, l = 98.56 m, L = 168 m), before the construction of the second bridge; Pont de Merjen, Stalden (1930, l = 66.3 m, L = 117.5 m)

Photos © P. Marti, O. Monsch, B. Schillling: Ingenieur-Betonbau

Arch bridges – Introduction: Historical perspective



l = 100 m
f / l = 1 / 4.78
Rhein bridge, Switzerland, 1962, Christian Menn



l = 112 | 96 m
f / l = 1 / 4.58 | 1 / 4.8
Nanin and Cascella bridges, Switzerland, 1967 | 1968, Christian Menn

Christian Menn: Rheinbrücke Tamins (1962, l = 100 m, L = 158 m); Nanin- und Cascellabrücke (1967 | 1968, l = 112 | 96 m, L = 192 | 173 m)

Photos © P. Marti, O. Monsch, B. Schillling: Ingenieur-Betonbau

Arch bridges – Introduction: Historical perspective

- Of course, spectacular concrete arch bridges were also designed by designers in many other countries.
- As an example, the Tara Bridge (aka Đurđevića-Tara Bridge) designed by Mijat S. Trojanović, opened in 1940

Photos: Tara Bridge (aka Đurđevića-Tara Bridge , Žabljak, Yugoslavia (now Montenegro), Mijat S. Trojanović (1940). Concrete arch, main span 116 m, 140 m above ground. Falsework by R. Coray.

Arch bridges – Introduction: Historical perspective

- Due to their high erection costs and the progress of more economical typologies (cantilever-constructed bridges for shorter, cable-stayed bridges for longer spans), only few large arch bridges were built in the 2nd half of the 20th century.
- The last three decades have, however, seen a revival of long-span arch bridges, driven by the development of CFST-arches in China (CFST = concrete-filled steel tube).
- Since the first CFST bridge with a moderate span of 115 m built in 1990 (Wanchang Bridge), more than 400 such arches were built.
- Currently, the Third Pingnan Bridge is the longest CFST arch @ 575 m span (2020, see photo, succeeding to the Bosideng Bridge, 2013 @ 530 m span, animated photo).

Photo: Third Pingnan Bridge, West River (Xun Jiang), Guangxi (2010). CFST through arch bridge, arch span 575 m, total length 1035 m. World's longest span CFST bridge.

Animated photo: First Hejiang Yangtze River Bridge (aka Bosideng Bridge), Sichuan (2013). CFST through arch bridge, arch span 530 m, total length 831 m. World's longest span CFST bridge before Pingnan Third Bridge was inaugurated, and the 3rd longest arch bridge overall (note that two steel truss arch bridges have longer spans than Bosigeng, but shorter than Pingnan: Chaotianmen 552 m, Lupu 550 m).

Source and further reading: J. Zheng, J, Wang, "Concrete-Filled Steel Tube Arch Bridges in China," Bridge Engineering Review paper, *Engineering*, No, 4 (2018), pp. 143-155.

Photo Iongnan: © IABSE

Photo Bosigeng: © megaconstrucciones.net

Arch bridges – Introduction: Terminology

An arch bridge essentially consists of three fundamental structural elements:

- Arch rib (or simply arch)
  - → main structural element
    … supporting the deck
    … transferring the loads to the arch abutments
  - → anti-funicular geometry for permanent loads (pure compression under these actions)
- Deck girder (or just deck / girder, all are commonly used for arches)
  - → usually continuous girder, transferring its self-weight and the traffic loads to the spandrel columns or hangers
- Spandrel columns or hangers
  - → structural elements connecting deck and arch, acting primarily in
    … compression (spandrel columns)
    … tension (hangers)

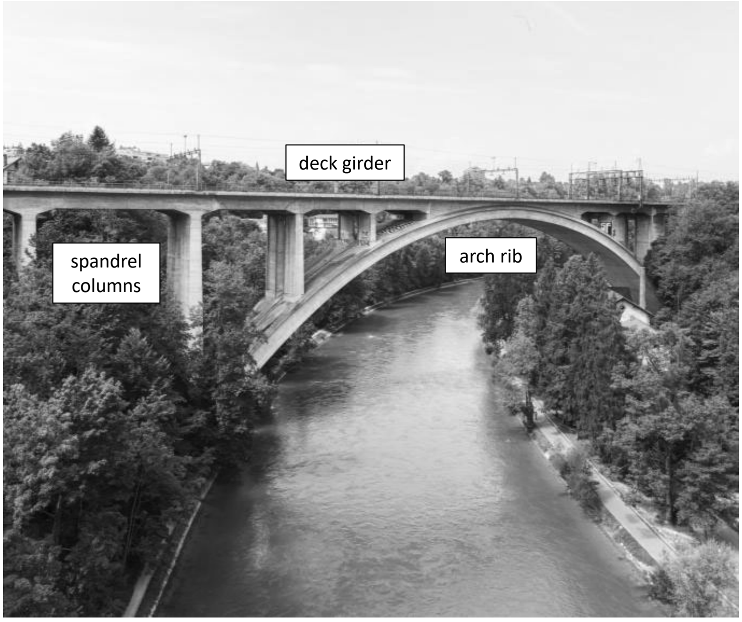
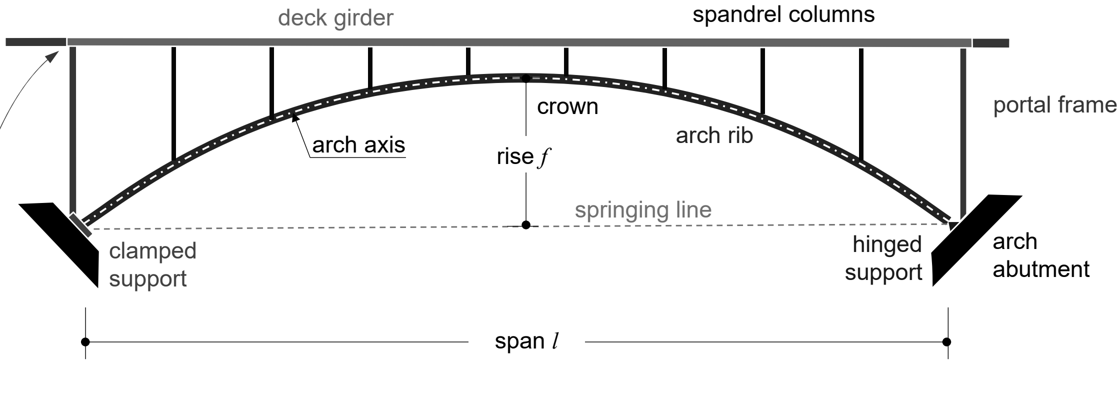


Photo: Aareübergang viaduct © Georg Aerni

Arch bridges – Introduction: Terminology



separation of deck girder above arch abutments (portal frames) common in historical bridges, not adequate for modern bridge design

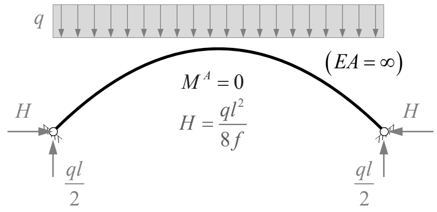
Arch bridges

Introduction – Anti-funicularity

Arch bridges – Introduction: Anti-funicularity

- Arches are highly efficient structures, since they are able to carry loads by "compression only" – provided that the thrust line lies inside the arch cross-section.
  → the ability of arches to carry high loads is primarily due to their shape
- Structures whose axis coincides with the thrust line (i.e., is geometrically similar to the funicular polygon) under a certain load are anti-funicular for that specific load, i.e., they act in pure compression.
- Anti-funicular arches are thus analogous to funicular structures (latin funiculus = rope), but with opposite sign (compression instead of tension).
- In the analysis of masonry arches, and masonry structures in general, graphic approaches are very useful (see notes, figure and next slide).
- The thrust line shows the resultant of compression (in the example on the next slide, for traffic load on the right half of the span).

Parabolic arch under uniform load: Arch axis geometrically similar to funicular polygon, pure compression in arch



Culmann (1866): Explanation of arch thrust and support conditions

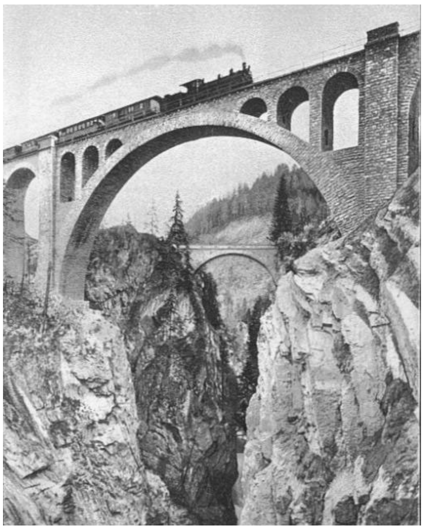
In the graphic analysis of masonry structures (see e.g. Marti, Theory of Structures), the following steps are recommended:

- establish a thrust line for the permanent actions
- deviations of the structure's system axis from the thrust line should be small (otherwise adjust the system geometry)
- check deviations of the thrust line caused by variable actions (if it is outside the structure, adjust loads or structure's geometry)
- check compressive stresses assuming uniform rectangular stress block (compressive force per unit width divided by twice the distance between the structure's edge and the thrust line)

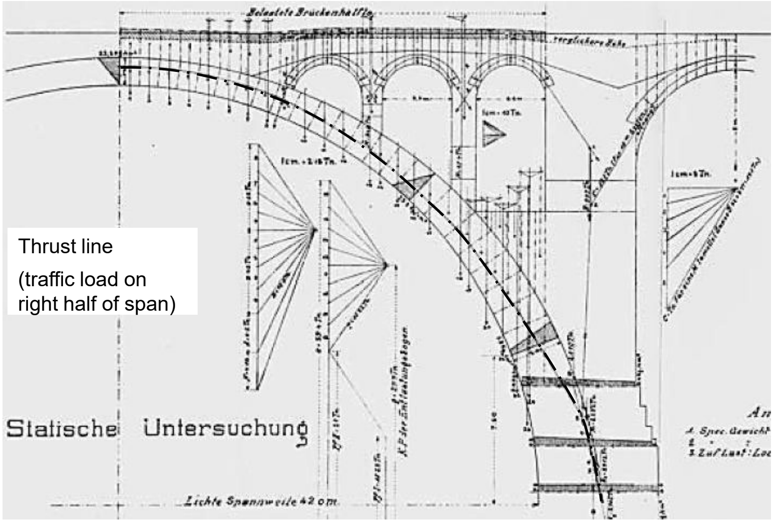
Figurre: C. Culmann: Die graphische Statik. Zürich: Meyer & Zeller, 1866 (Fig. 176).

Arch bridges – Introduction: Anti-funicularity

- Most existing masonry viaducts, such as the Soliser Viadukt (clear span 42 m), were designed using graphical statics.



Deck arch bridge (spandrel arch)



Structural analysis of the Soliser Viadukt by means of graphic statics.

Figure taken from RhB, Kandidatur Unesco Welterbe: Rhätische Bahn in der kulturlandschaft Albula/Bernina, 2008.

AGS0

Arch bridges – Introduction: Anti-funicularity

- However, other than ropes and funicular structures in general, arch ribs (as anti-funicular structures for a specific load)
  - → do not adjust their shape to varying configurations of applied loads
  - → need to resist arch bending moments $M = e{\cdot}N = e_z{\cdot}H$ caused by loads causing deviations e (with vertical component e_z) of thrust line and arch axis

    (M can be resisted jointly by arch and deck, see behind)
  - → in any case require a bending stiffness to prevent buckling (even if globally stabilised by other elements, local buckling must be prevented)

WK1 Three-hinged arch and thrust line for half-sided load (illustration adapted from Marti, 2014)

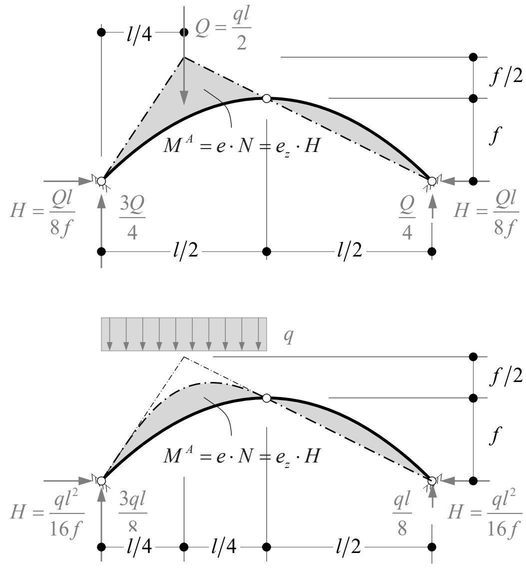
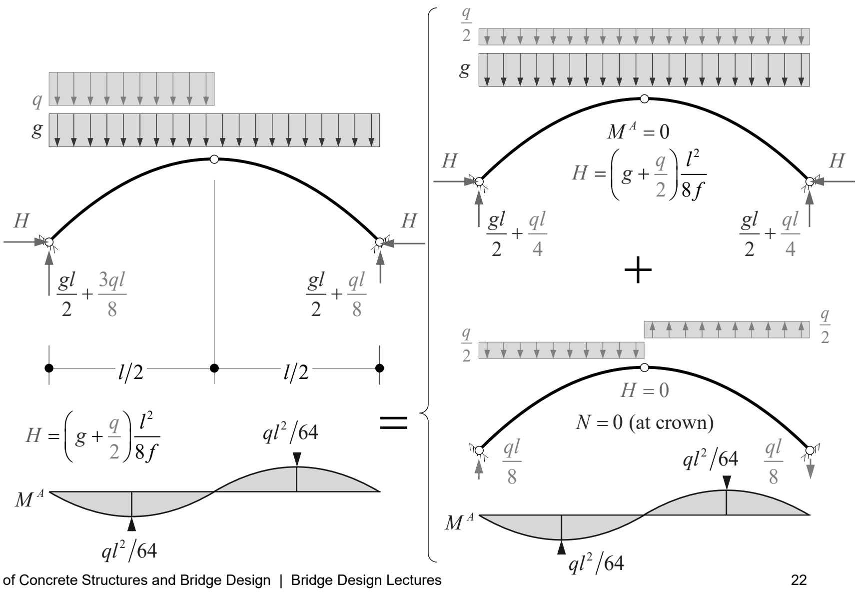


Illustration: P. Marti, Theory of Structures.

Arch bridges – Introduction: Anti-funicularity

- Any arch geometry is obviously anti-funicular for one specific load configuration only.
- All other loads need to be carried by bending
  → of the arch itself ("stiff arch"), figures
  → of the deck girder ("deck-stiffened arch")
  → of arch and deck girder combined (usual)
- In analysis, applied loads can be divided into loads causing pure compression (those for which the geometry was chosen) and loads causing pure bending, see figure.
- Self-weight is the dominant load in bridges
  → the arch geometry should closely match the thrust line under permanent loads
  → arches are then still very efficient as they carry a large portion of the total loads in compression (figures)

Arch, anti-funicular for uniform load, under non-symmetrical load (illustration adapted from Marti, 2014)



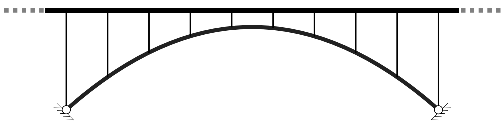
Arch bridges

Introduction – Typologies

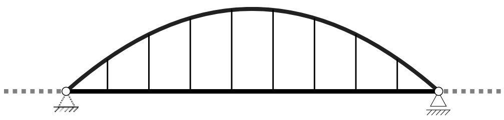
Arch bridges – Introduction: Typologies

- The typology of arch bridges is commonly related to the position of the deck with respect to the arch.
- Accordingly, the following types of arches can be distinguished:
  - → Deck arch bridge: deck above arch
  - → Tied arch bridge: deck below arch (bowstring arch, “Langerscher Balken”)
  - → Through arch bridge: deck and arch intersect (with or without connection)
- Each typology has its structural particularities, but with a common element: The arch.

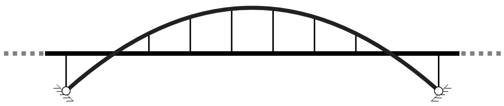
Deck arch bridge (spandrel arch)



Tied arch bridge (bowstring arch, “Langer beam”)



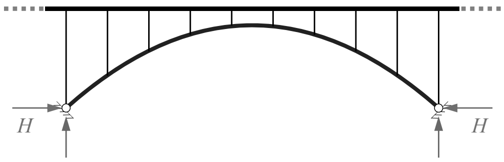
Through arch bridges



Arch bridges – Introduction: Typologies

- Structurally, it makes more sense to distinguish arch typologies based on the way the arch thrust H (horizontal component of arch normal force) is resisted.
- Arches are most efficient if the arch thrust is carried by the ground ("true arches"), which requires stiff soil
  → principle of masonry arch bridges
  (note: high self-weight is beneficial for foundations as it reduces the inclination of the support reaction)
  → principle of deck arch bridges

Deck arch bridge (spandrel arch)



Arch bridges – Introduction: Typologies

Deck arch bridge

→ Deck girder positioned at top of arch
→ Arch supports deck via spandrel columns
→ Solid-spandrel arches or trussed arches are also used (figures)
→ Full arch thrust transferred to arch abutments

Zuoz bridge, Switzerland, 1901. Robert Maillart

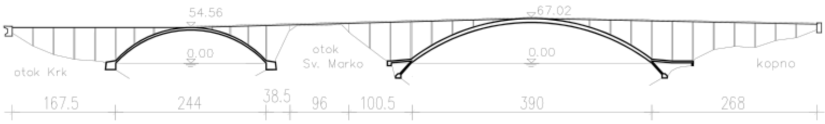
Isorno rail viaduct, Switzerland, 1923. Löhle & Kern

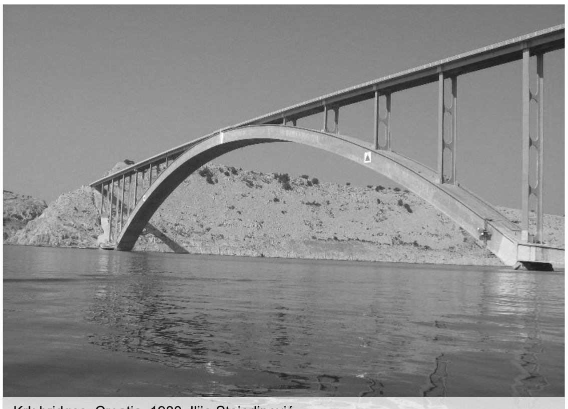
Photos: left: https://structurae.net/; rigth © Georg Aerni

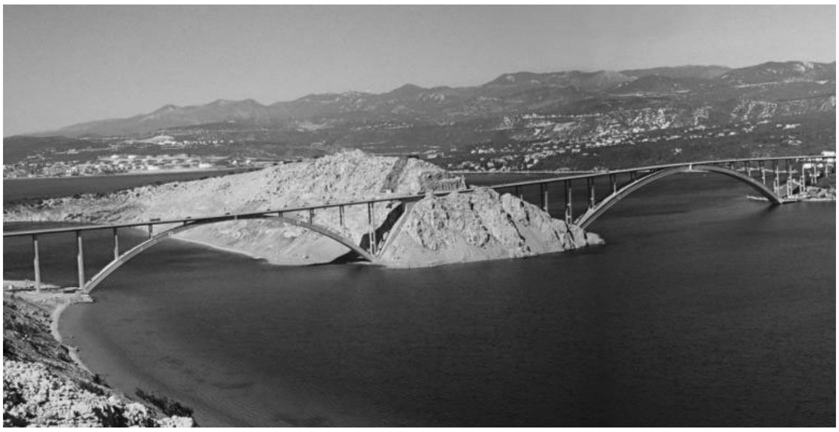
Arch bridge – Introduction: Typologies

Deck arch bridge example

- Reinforced concrete
- Clamped arches
- l = 390 and 244 m
- $f\,/\,l$ = 1 / 5.82 and 1 / 4.47







Krk bridges, Croatia, 1980. Ilija Stojadinović

J. Radic, et. Al.: “Krk bridge consists of two large reinforced concrete arch spans providing a fixed road link to the island of Krk. The larger 390-m span when completed in 1980 extended the world record of reinforced concrete arch bridges from 305 m of Gladesville bridge in Sydney, Australia by more than 80 m.

This is still the largest conventional reinforced concrete arch bridge in the world [note: today, it is still the world’s third largest concrete arch, after Qinglong Railway Bridge with 445 m (2016) and the Wanxian bridge with 420 m (1997), both in China]. The span of the smaller arch is 244 m.

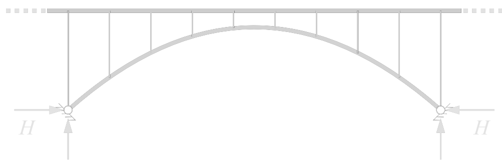
Both arches have a three-cell box cross-section of constant external dimensions: 8 m wide and 4 m deep for the smaller, and 13 m wide and 6,5 m deep for the larger one. The superstructure of the Krk bridge was designed as a series of simply supported grillages comprising three precast prestressed concrete girders joined by cross beams at the supports and in the thirds of spans. The deck plate is only 13 cm thick and was constructed of precast panels with cast-in-place joints at the longitudinal and cross girders. The columns were designed extremely slender in order to reduce the weight carried by the arches as much as possible. They were erected by slip forming. To achieve exceptionally large spans, it was necessary to reduce the dead load as much as possible. The structural members of minimum statically admissible dimensions were utilised, with very small concrete cover of 2,5 cm. Later testing revealed that even smaller concrete cover was executed at some locations.”

Illustration: adapted from J. Radic, et. Al., Repair of the Krk arch bridges, Conference and Brokerage Event. 2006. Photos: Wikipedia

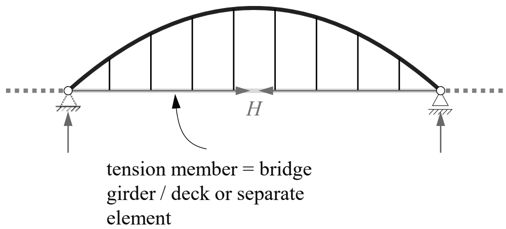
Arch bridges – Introduction: Typologies

- Structurally, it makes more sense to distinguish arch typologies based on the way the arch thrust *H* (horizontal component of arch normal force) is resisted.
- Arches are most efficient if the arch thrust is carried by the ground ("true arches"), which requires stiff soil
  → principle of masonry arch bridges (note: high self-weight is beneficial for foundations as it reduces the inclination of the support reaction)
  → principle of deck arch bridges
- Alternatively, the arch thrust can be resisted by a tension member connecting the supports (along springing line)
  → structurally less efficient, since arch thrust must be resisted in tension
  → principle of tied arch bridges:
  … deck = tension member (more efficient) or
  … separate tension member parallel to deck (less efficient)
  → externally, a tied arch is a simply supported beam

Deck arch bridge (spandrel arch)



Tied arch bridge (bowstring arch, "Langer beam")



Arch bridge – Introduction: Typologies

Tied arch bridge:

→ Arch positioned above deck
→ Deck suspended by arch via hangers
→ Arch thrust fully resisted by deck (→"externally", it is a simply supported beam)
→ Known in German speaking countries as Langer beam (Langerscher Balken) or "versteifter Stabbogen"

Puente sobre el río Guadalete, Barca de la Florida (near Jérez de la Frontera), M. Martínez, 1926.

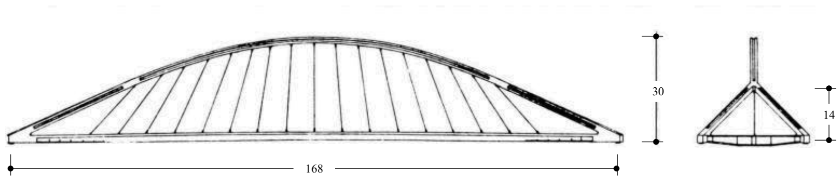
Photos: Puente sobre el río Guadalete, La Barca de la Florida (Jérez de la Frontera), M. Martínez, 1926. Three steel tied arches with 60 m span, total length 180 m. Arches stiffened with X-bracings (built under supervision of J. Botín and E. Torroja, located next to Eduardo Torroja's Acueducto de Tempul).

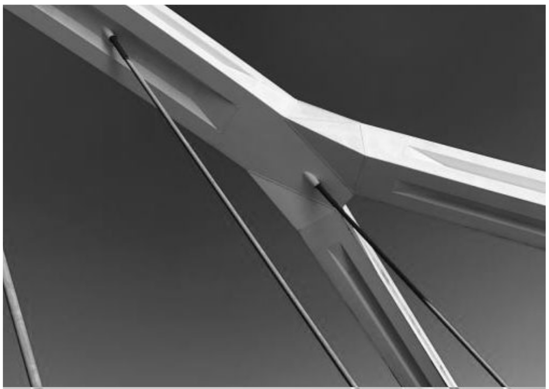
Photos kfm

Arch bridge – Introduction: Typologies

Tied arch bridge example

- Steel arch
- Simply supported (arch + deck = “girder”)
- l = 168 m
- f / l = 1 / 5.60





Barqueta bridge, Sevilla, Spain, 1992. J.J. Arenas and M.J. Pantaleón

An eminent example of tied arch bridges is the Barqueta bridge crossing the Guadalquivir river (Meandro de Ranillas) in Seville, Spain. Unlike typical tied arch bridges, the Barqueta bridge has only one central arch (similar to the Tercer Milenio bridge, Zaragoza, Spain, 2008), where the arch is split by triangular frames into two legs creating “entrance portals” for the users. Thereby, the deck is not separated into two halves by the central arch. The innovative design of the Barqueta bridge is convincing, as it combines functionality and aesthetics.

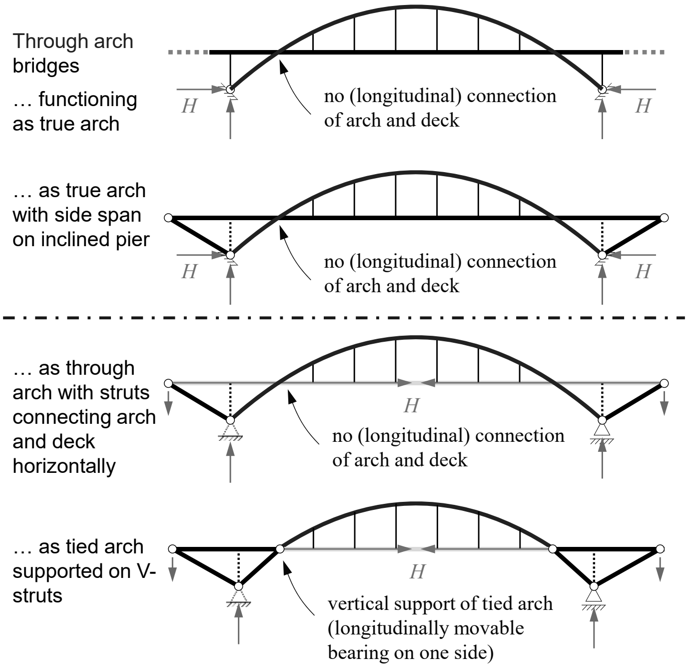
Illustration adapted from Revista de Edificación (RE), N° 7, July 1990

Photos: kfm

Arch bridges – Introduction: Typologies

- In through arch bridges, the thrust may be resisted
  → by the foundations as in a deck arch (true arch)
  → by a tension member connecting the supports as in a tied arch
- If the thrust is resisted by the foundations (true arch, upper figures), the structural system corresponds to a deck arch, with the following aspects to be considered:
  → arch must pass deck without transferring longitudinal forces
  → mix of hangers+spandrel columns (different stiffness)
- If the thrust is resisted by the deck, different layouts are possible (bottom figures):
  → through arch with struts transferring thrust to deck
  → tied arch supported on cantilevered structure

  In either case, such through arches are significantly more complex in design and construction than deck or tied arches.
- The structural concept of through arches is often hard to identify: They lack the logic of form other arches



Arch bridge – Introduction: Typologies

Through arch bridge:

→ Deck and arch overlap in elevation
→ Midspan part suspended from arch via hangers, side spans supported by spandrel columns (if required)
→ Arch thrust resisted by
… foundation (= true arch) or
… deck (= tied arch) or
… both depending on stiffnesses (deliacte to quantify)

Tardis bridge, Mastrils-Landquart, Switzerland, 2003. dsp Ingenieure + Planer

Waal bridge, Netherlands, 1936.

Photos: left © dsp; right: Wikipedia (top: „The Waal bridge and north-east central Nijmegen, damaged during the battle. Photo taken on 28 September 1944 from the Dominican Church”)

Arch bridge – Introduction: Typologies

Through arch bridge example

- Steel arch
- Clamped true through arch
- l = 329 m
- f / l = 1 / 4.7

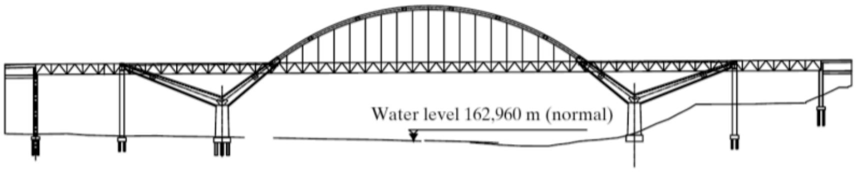
Theodore Roosevelt lake bridge, Arizona, USA, 1990. Howard, Needles, Tammen & Bergendoff

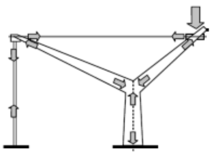
Photos: left:https://www.flickr.com/photos/cedwardbrice/23907070443/; right: https://www.flickr.com/photos/cmhpictures/46625020241

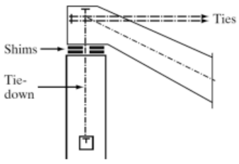
Arch bridge – Introduction: Typologies

Through arch bridge example

- Steel arch on concrete V-struts
- Tied through arch
- l = 420 m
- f / l = 1 / 4.4







Chongqing Caiyuanba Bridge, China, 2007. Chongqing Communications Research & Design Institute / T.Y. Lin International

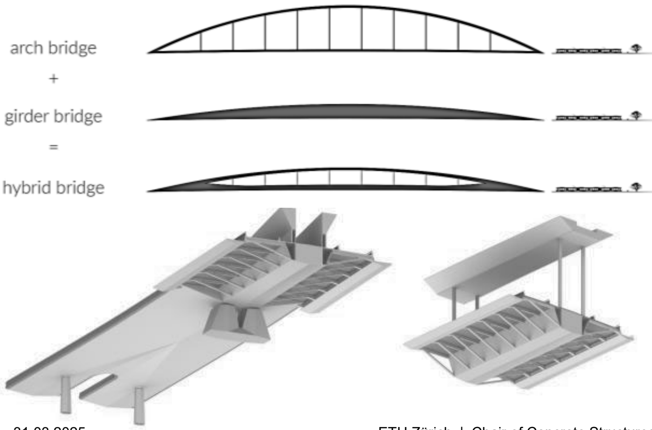
Photos and illustrations: Man-Chung Tang, Guolei Ren, “Design and Construction of the Main Spans of the Chongqing Caiyuanba Bridge, China,” Structural Engineering International, 20:3, 2010, 296-298

Arch bridge – Introduction: Typologies

Slender tied arches are sometimes termed "hybrid arch bridges".

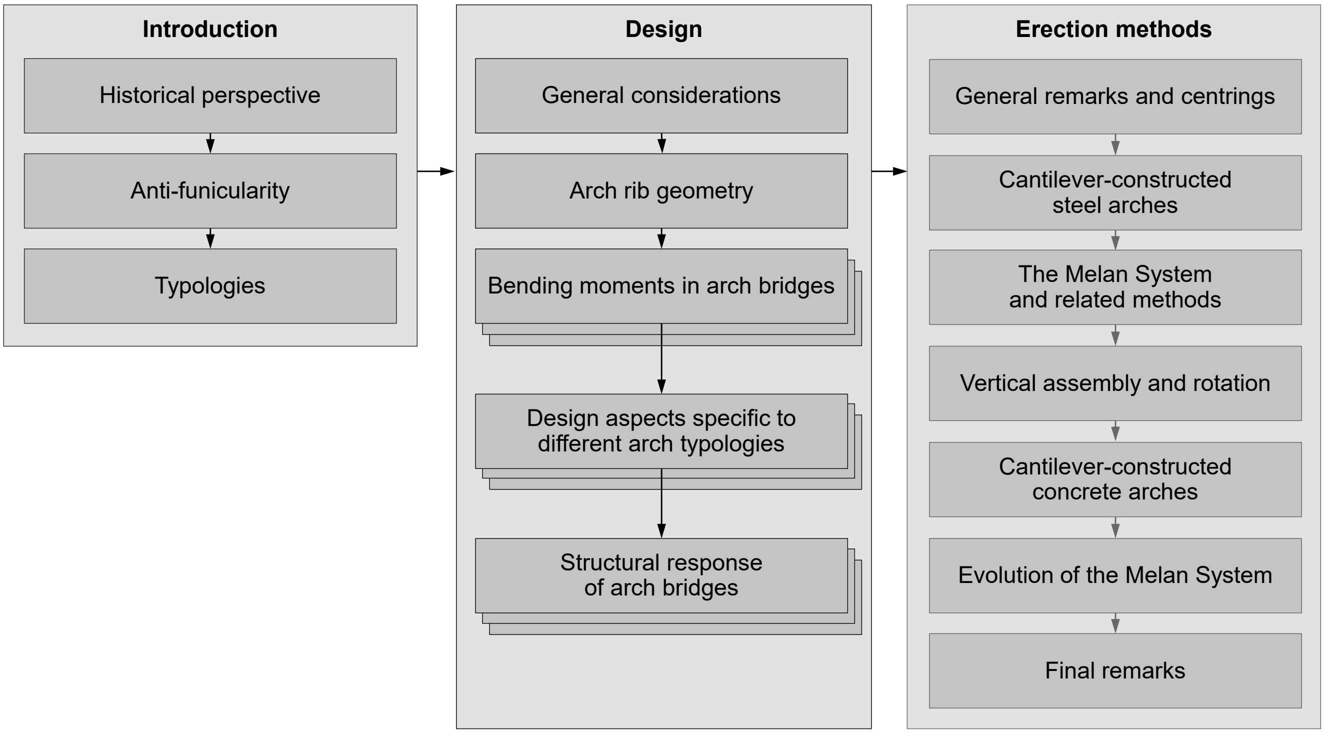
However, while the solutions are attractive, this term is technically ill-founded, see structural response).

(in any arch bridge, arch and deck share the applied loads (arch in bending and arch action, girder in bending). In flat arches, the deck simply carries a larger portion of the applied loads).



Tender design: Bridge over Danube River, Hungary, 2018. Fhecor Ingenieros

Illustration and rendering from © Fhecor Ingenieros http://fhecor.es


Introduction
Historical perspective
Anti-funicularity
Typologies
Design
General considerations
Arch rib geometry
Bending moments in arch bridges
Design aspects specific to different arch typologies
Structural response of arch bridges
Erection methods
General remarks and centrings
Cantilever-constructed steel arches
The Melan System and related methods
Vertical assembly and rotation
Cantilever-constructed concrete arches
Evolution of the Melan System
Final remarks

Arch bridges

Design

Arch bridges

Design – General considerations

Arch bridges – Design: General considerations

- Arches are very efficient structures in their final configuration, but
  - → arch action is only activated at closure
  - → arch centrings are expensive (tailor-made falsework and formwork)
  - → efficient erection methods – important in any structure – are particularly important in arches
- Arch bridges built by cantilevering are considered economical for spans 100 m ≤ l ≤ 300 m (200 m for concrete arches)
  - → for shorter spans, girders are more economical (cost of arch is not compensated by savings in the deck girder)
  - → for longer spans, cable-stayed bridges are more economical due to the efficient erection method
  - → longer spans may be economical if an optimised erection method is used (e.g. CFST arches, see erection methods)
- Other reasons, particularly aesthetical considerations, may still justify arch bridges

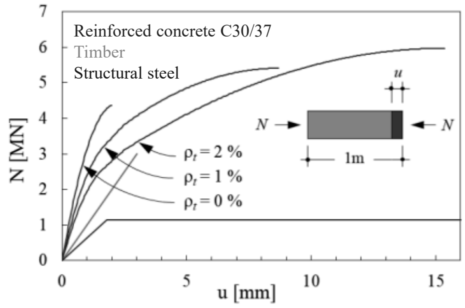
Photo: Viaducto de Almonte, Arenas & Asociados (J.J. Arenas, G. Capellán, M. Sacristán), High Speed Line Madrid-Extremadura-Portugal, Cáceres, Spain (2016, line in service 2022). High speed train concrete deck arch bridge, main span 384 m, total length 996 m, f/L = 1/5.7. Hollow box high strength concrete arch, prestressed concrete box girder.

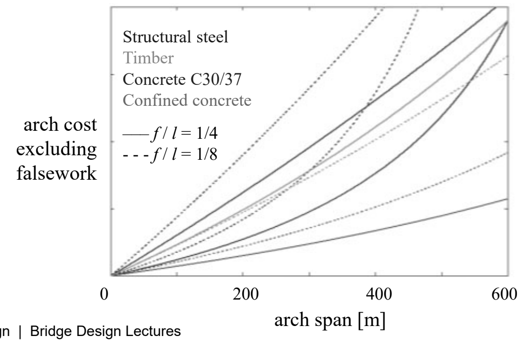
Photo © kfm

Arch bridges – Design: General considerations

Material cost vs erection method

- The figures compare different materials for conventional short span structures (no complicated falsework for concrete, nor large cranes for steel and timber)
  → the load-deformation characteristics of compression members costing 100 CHF/m
  → the total cost of an arch for two rise-to-span ratios
- The concrete compression members are significantly stiffer and stronger at the same cost.
- Even for very large spans, and using normal strength concrete, concrete is by far the most economical material in the final configuration due to its low cost and high compressive strength (despite the better weight/strength ratio of steel and timber, which could be improved for concrete using high-strength concrete).
- However, falsework for long-span arches is very expensive
  → concrete arches built on conventional scaffold are only economical for short spans
  → unless efficient arch construction methods are used, steel arches are thus more economical for medium-large spans





For the calculation of the total arch cost, a characteristic uniform load of 200 kN/m (ca. 12 m wide deck girder, spandrel columns, traffic load) has been assumed in addition to the arch self-weight.

Input data for cost calculation of compression members:

Material	E [GPa]	f_c, f_y [MPa]	ρ [kg/m^3]	[CHF/kg]	[CHF/m^3]
Concrete	30	30	2400	0.25[1)]	600[1)]
Reinforcing steel	200	500	7850	1.50[2)]	11775[2)]
Structural steel	200	360	7850	4[3)]	31400[3)]
Timber	10	30	500	2[4)]	1000[4)]

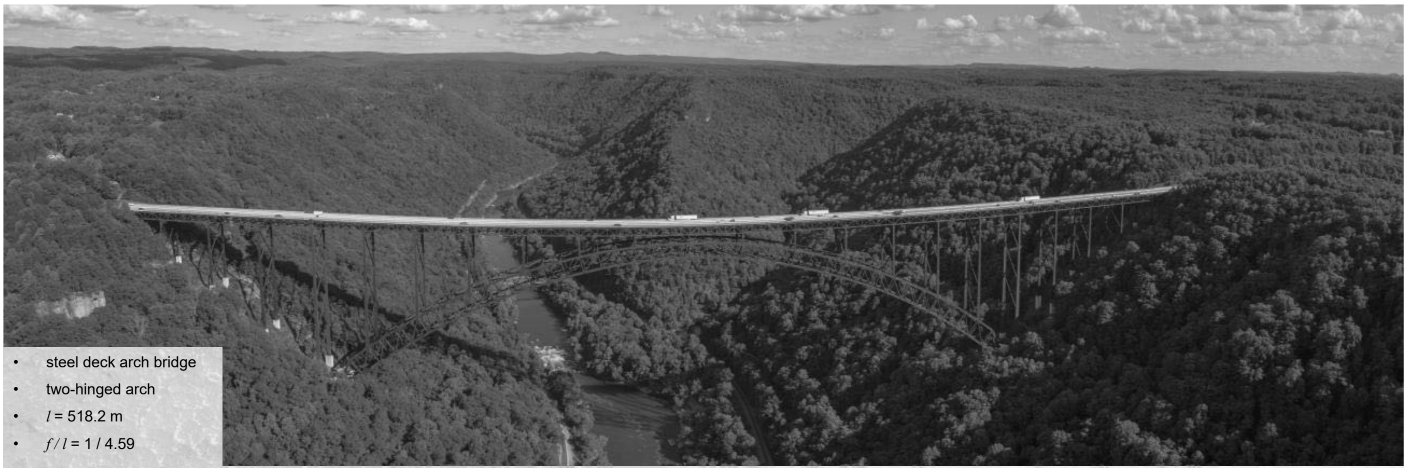
1) incl. formwork
2) Incl. erection
3) incl. coating and erection
4) incl. erection and connectors

Element	A [m^2]	m [kg]	N_u [MN]	m / N_u [kg/MN]
Reinforced Concrete[5,6] ρ_t = 0 %	0.130	323	4.37	74
Reinforced Concrete[5,6] ρ_t = 1 %	0.100	263	5.41	49
Reinforced Concrete[5,6] ρ_t = 2 %	0.081	226	5.97	38
Structural steel	0.003	25	1.15	22
Timber	0.100	50	3.00	17

5) incl. 1% active and 0.5% inactive longitudinal reinforcement
6) circular Cross-Section

Arch bridges – Design: General considerations

- An example of a bridge where higher cost of an arch bridges was justified by the superior aesthetics quality and where a steel truss arch was more economical than a concrete arch (lighter weight = erection by stayed cantilevering of the arch possible, see erection methods – is the New River Gorge Bridge (1977, record span arch bridge until 2012).



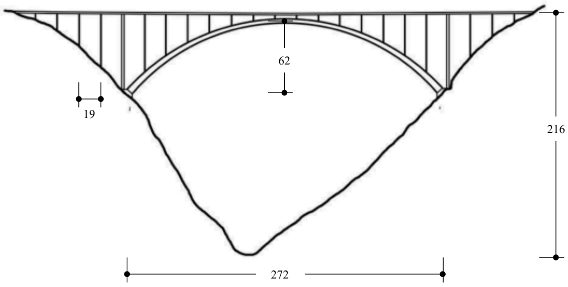
New River Gorge bridge, West Virginia, USA, 1977. Michael Baker

Photo: https://www.reddit.com/r/WestVirginia/comments/6jyhh7/new_river_gorge_bridge/

Arch bridges – Design: General considerations

Deck arch bridges (and true arch through arch bridges) transfer important horizontal forces – the arch thrust – to the foundations, which is the most efficient solution. However

- → the viability of deck arch bridges depends on the soil conditions
- → the arch thrust increases with decreasing rise-to-span ratios f/l
- → Long span and slender arches require solid rock at the arch abutments



Bloukrans bridge, Western Cape, South Africa, 1983. Liebenberg & Stander

"Perfect" site for deck arch bridge:

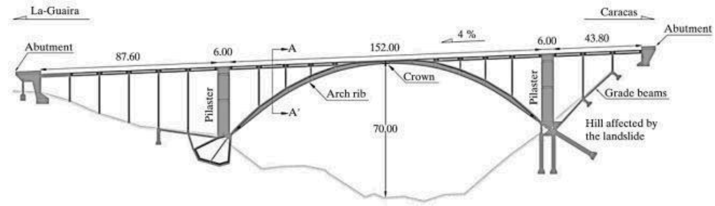
- strong soil (solid rock)
- steep valley
- relatively large span

Illustration adapted from http://www.highestbridges.com/

Photo: top: A. Giraldo Soto; bottom: Wikipedia

Arch bridges – Design: General considerations

- If true arch bridges are built in inadequate sites (soft soil, unstable slopes), consequences may be drastic.
- This is particularly due to their sensitivity to (horizontal) movements of the arch abutments
  - → horizontal movements of the arch abutments cause changes in the horizontal reaction = deviations of the thrust line and corresponding bending moments along the arch
  - → the importance of these effects depends on the magnitude of the movements and the rise-to-span ratio f / l (see structural response).



Caracas-La Guaira bridge, Venezuela, 1953. Jean Muller and Eugène Freyssinet

At the Guaira Bridge, Freyssinet built a two-hinged arch, both for the requirements of the foundation of one of the slopes and because it was the first bridge to be built by cantilever construction using temporary stays: Hinges at the arch abutments allowed correcting the alignment during the construction process. Modern arches are usually cantilevered with clamped abutments from the beginning, which requires an accurate determination of pre-camber during the erection process.

Illustration adapted from L.B. Fargier Gabaldón, Rehabilitation and Lessons Learned from the Collapse of Viaduct 1 Located on the Caracas–La Guaira Highway in Venezuela. Structural Engineering International Nr. 3/2017.

Photos:

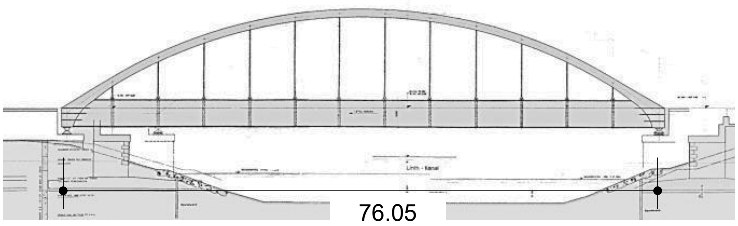
left: https://www.flickr.com/photos/fitosumbate/1429928079/lightbox/

right: https://civilgeeks.com/2011/08/09/viaducto-caracas-la-guaira-una-obra-100-venezolana-4/

Photos of the bridge a few hours before it collapsed:
https://www.flickr.com/photos/lubrio/115137384/in/photostream/

Arch bridges – Design: General considerations

- Tied arch bridges, on the contrary, are simply supported girders “externally” (the deck girder acts as tension member = tie, only vertical reactions under gravity load)
  - → suitable for locations with soft soil
  - → generally worth considering in single-span bridges (more transparent than simply supported standard girder bridges)
  - → generally appropriate for single-span bridges with low clearance above traffic lines
  - → particularly suitable for bridges spanning rivers where often the following conditions apply:
    … low clearance above flood level
    … no piers in river possible
    … soft soil layers to considerable depth
- The elements connecting deck and arch are often pin-jointed, acting in pure tension
  - → referred to as “hangers” (even if they carry bending moments, see design)



Linthkanalbrücke Biberlikopf, Ziegelbrücke-Weesen, 1967. SBB Bauabteilung Kreis III

Arch bridges – Design: General considerations

Materials
- Concrete
- Steel
- Composite
- Timber
- …

Shape
- Single arch
- Double arch (in cross-section)
- Straight in plan
- Curved in plan
- Polygonal in plan
- Spatial arch
- …

Cross section of the arch rib(s)
(constant or depth and/or width increasing towards abutments)
- Box
- Solid rectangular
- Tubular
- Truss
- …

Cross section of the deck
(usually constant)
- Box
- Slab
- T or double T
- …

Geometry of hangers / spandrel columns
- Number
- Inclination
- Hinges at top and/or bottom

Hinges in the arch rib
- Clamped ("zero-hinge") arch
- Two-hinged arch
- Three-hinged arch

Rise-span ratio f / l
- High arch $f / l \approx 1/2$
- Standard arch $f / l \approx 1/6$
- Low arch $f / l < 1/10$

Distributions of rigidities
- Stiff arch – flexible deck
- Flexible arch – stiff deck
- Intermediate solutions

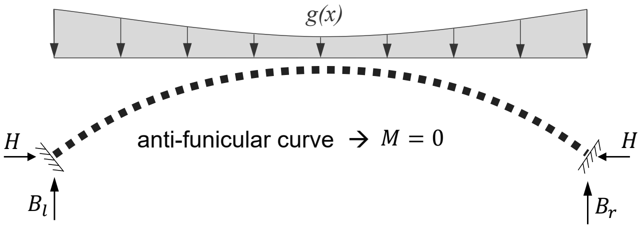
The different parameters are grouped into the categories shown on the slide.

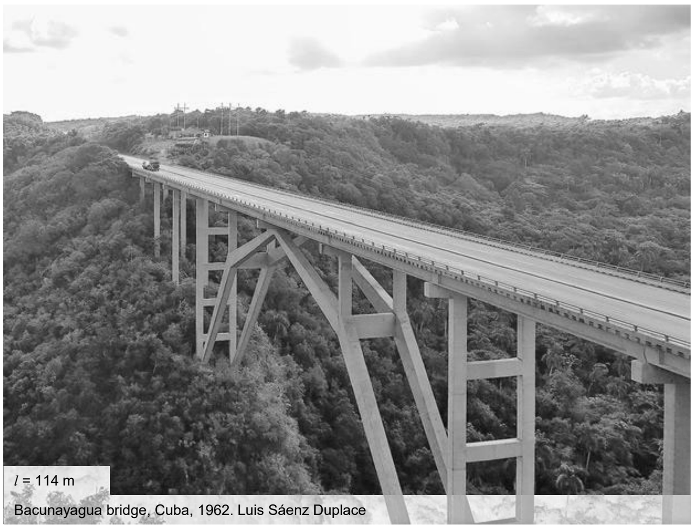
Arch bridges

Design – Arch rib geometry

Arch bridges – Design: Arch rib geometry

- Most of the following slides show deck arches, but they equally apply to tied arches unless indicated otherwise.
- The arch axis should closely correspond to the thrust line due to permanent load, such that no bending moments are caused by this (usually most important) action
  → arch geometry geometrically similar to funicular polygon of permanent loads
- The arch is not uniformly loaded, but rather, receives most loads via the spandrel columns
  → "classic" curved arch reasonably anti-funicular only for closely spaced columns (8…10 over span)
  → if fewer spandrel columns or hangers are provided, a polygonal arch geometry should be chosen





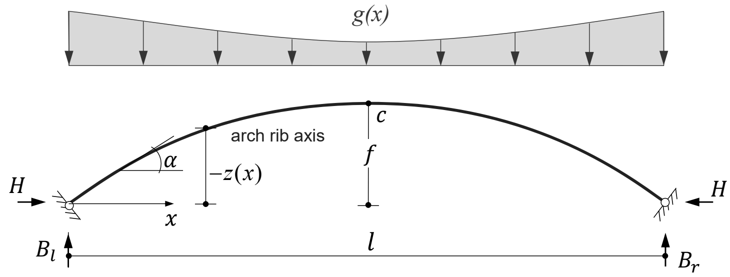
Bacunayagua bridge, Cuba, 1962. Luis Sáenz Duplace

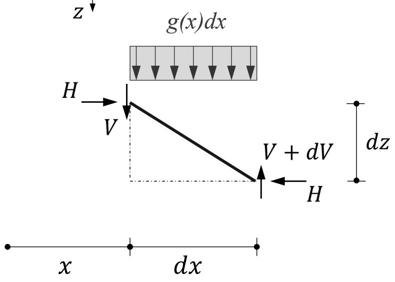
Photo: http://esculturasymonumentos.com/c-cuba/puente-de-bacunayagua/

Arch bridges – Design: Arch rib geometry

Determination of the geometry of the arch

- The analytical equation to determine the anti-funicular geometry for a given load $g(x)$ is a 2nd order ordinary differential equation (see figure).
- The arch thrust H (horizontal component of arch normal force) is constant if only vertical loads act.
- For any value of the arch thrust $H > 0$, (positive H = compression in arch rib), an anti-funicular geometry is obtained (all are geometrically similar):
  $\rightarrow$ small $H \leftrightarrow$ large rise *f* (high arch)
  $\rightarrow$ large $H \leftrightarrow$ small rise *f* (low arch)
- If the arch axis (centre of gravity of the arch rib) coincides with the resulting curve, the load $g(x)$ causes pure compression in the arch rib.





Vertical equilibrium

$$g(x)\cdot dx - dV = 0$$

Moment equilibrium

$$V\cdot dx - H\cdot dz = 0$$

$$V = H\frac{dz}{dx} = H\cdot z'$$

Derivative (H = const)

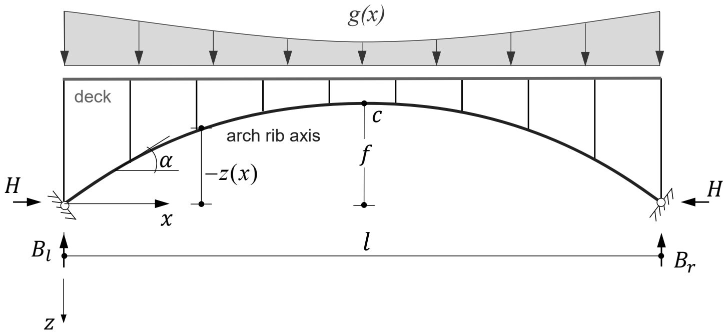
$$dV = H\cdot z''dx = -g(x)dx$$

$$z'' = \frac{g(x)}{H}$$

Arch bridges – Design: Arch rib geometry

Determination of the geometry of the arch

- Generally, the differential equation has to be integrated numerically since $g(x)$ is not constant:
  - → the self-weight of the arch is proportional to $1/\cos\alpha$ (relevant weight: per horizontal length)
  - → the arch normal force for constant thrust H is also proportional to $1/\cos\alpha$; the arch section is often increased towards the springing lines accordingly (→ arch self weight increasing ≈ with $1/\cos^2\alpha$)
  - → point loads applied by spandrel columns differ even if "smeared" over column spacing due to varying column height
- The "exact" anti-funicular geometry can be determined numerically in many different ways, even accounting for arch compression / second order effects (geometrical non-linearity).
- On the following slides, a method for determining the funicular curve by simple hand calculations, useful for pre-dimensioning, is presented.



common arch geometry in plan and/or elevation
(area ~$1/\cos\alpha$ according to normal force)

typical arch self-weight distribution
(~$1/\cos^2\alpha$ if arch section is adjusted to normal force)

WK0

Arch bridges – Design: Arch rib geometry

Determination of the geometry of the arch

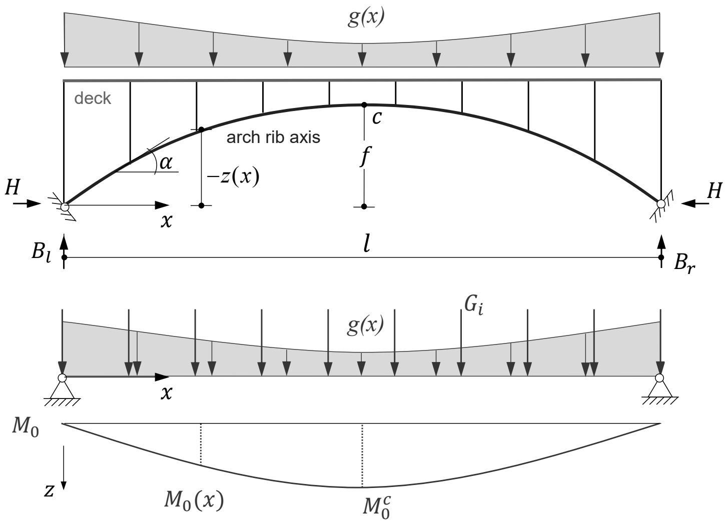
1. Determine the bending moments $M_0(x)$ in a simply supported girder (span = arch span), loaded by all permanent loads of the arch (arch rib, spandrel columns, deck girder, superimposed dead load)
2. The bending moments in the arch rib $M^A(x)$, differ from $M_0(x)$ by the moment due to the horizontal thrust H:

$$M^A(x) = M_0(x) + H \cdot z(x)$$

3. Imposing the condition $M^A = 0$ (anti-funicularity), with the bending moment at the crown $M_0^c = M_0(l/2) = H \cdot f$, the arch thrust = reaction H and the anti-funicular geometry $z(x)$ follow for a chosen value of the rise f:

$$\left.\begin{aligned} z(x) &= -\frac{M_0(x)}{H} \\ H &= \frac{M_0^c}{f} \end{aligned}\right\} \quad z(x) = -\frac{M_0(x)}{M_0^c} f$$

(as postulated, the anti-funicular geometry is geometrically similar to the funicular polygon)



Arch bridges – Design: Arch rib geometry

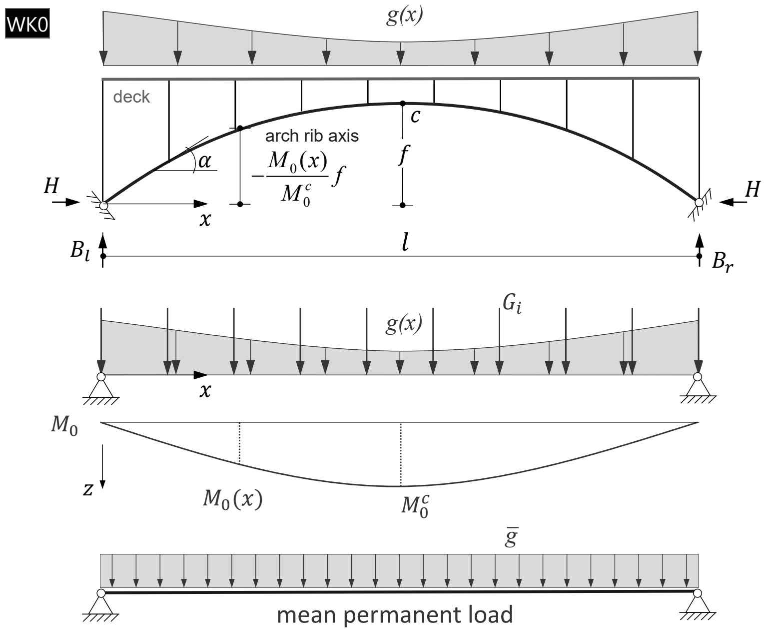
Determination of the geometry of the arch

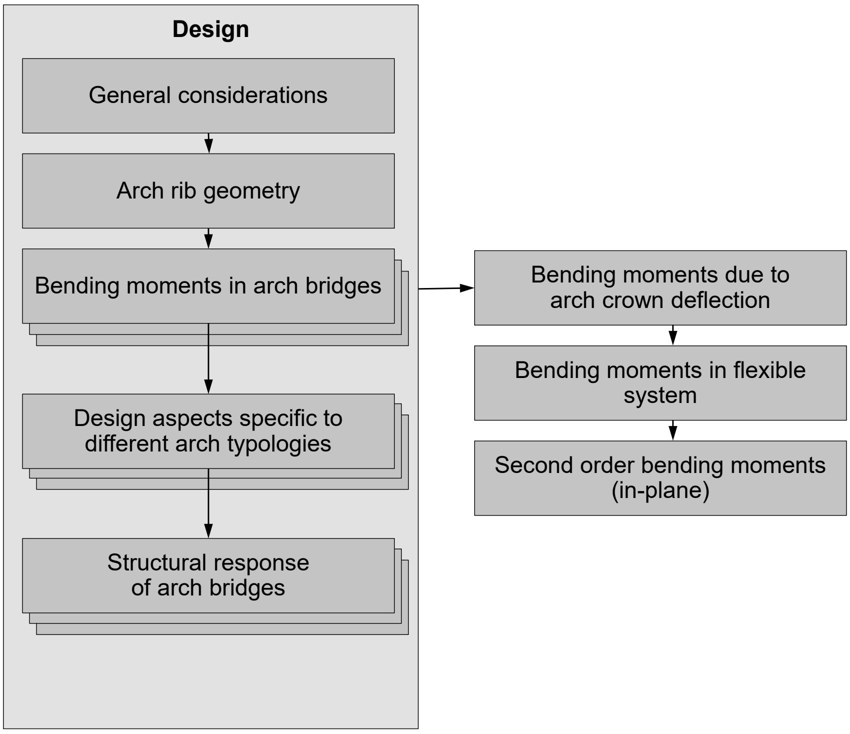
- An iterative procedure is required since the weights of the arch rib and spandrel columns depend on the geometry of the arch rib.
- As a first approximation in preliminary design, the mean permanent loads $\overline{g}$ over the entire length of the arch can be used for further simplification.
- Hence, the arch is subjected a uniformly distributed load (corresponding to the total permanent load of the structure supported by the arch divided by its span), resulting in a quadratic parabola for the arch axis:

$$H(\overline{g}) \cong \frac{\overline{g} \cdot l^2}{8f} \qquad z(x) = -\frac{8f}{\overline{g} \cdot l^2} M_0(x)$$

And the axial force in the arch is:

$$N(\overline{g}) = -\frac{H(\overline{g})}{\cos\alpha}$$




Design
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Bending moments in arch bridges
Design aspects specific to different arch typologies
Structural response of arch bridges
Bending moments due to arch crown deflection
Bending moments in flexible system
Second order bending moments (in-plane)

Arch bridges

Design – Bending moments due to arch crown deflection

(“Biegemomente infolge Scheiteleinsenkung”)

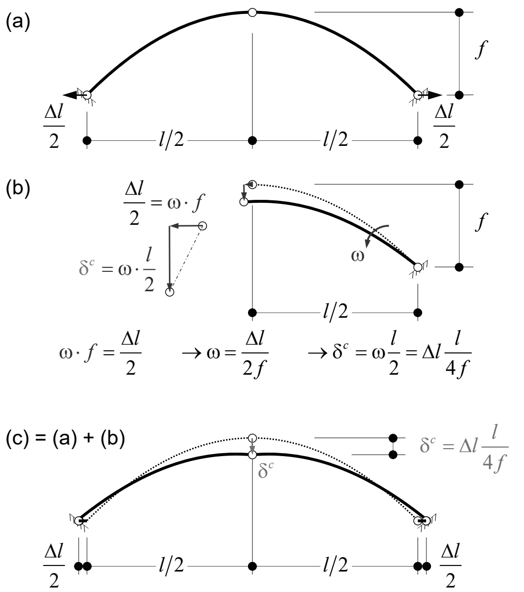
AGS0

Arch bridges – Design: Bending moments due to arch crown deflection

Deflections due to horizontal support displacements Δl

- Arches can accommodate horizontal support displacements Δl with little axial restraint by adjusting their shape
  - → deflection at arch crown δ^c
  - → stress-free arch crown deflection in three-hinged arches (see figures): $\delta^c = \Delta l \dfrac{l}{4f}$
  - → causing bending moments in two-hinged and fixed arches, similar arch crown deflection: $\delta^c \approx \Delta l \dfrac{l}{4f}$

WK1 Three-hinged arch with horizontal support displacement Δl



AGS0

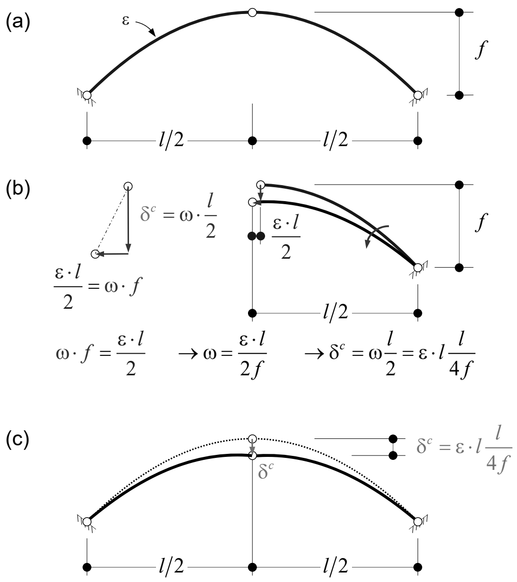
Arch bridges – Design: Bending moments due to arch crown deflection

Deflections due to imposed deformations ε

- A contraction (and, with opposite sign, expansion) of the arch rib due to imposed deformations ε (temperature change, shrinkage, …) has a similar effect as horizontal support displacements
- With $\Delta l = \varepsilon \cdot l$, the deflection of the crown is approximately equal to: (exact for three-hinged arch)

$$\delta^c \approx \varepsilon \cdot l \frac{l}{4f}$$

WK1 Three-hinged arch with imposed strain $\left(\varepsilon = \alpha_T \Delta T, \varepsilon_{cs}, \ldots \ll 1\right)$



WK0

Arch bridges – Design: Bending moments due to arch crown deflection

Deflections due to arch compression N/EA

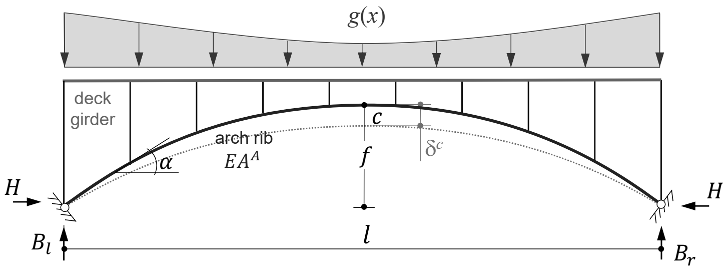
- The arch rib is axially very stiff, but not perfectly rigid
  $\rightarrow$ arch rib is compressed by arch normal force N
  $\rightarrow$ deflections under permanent load even if a perfectly anti-funicular geometry has been chosen
- In preliminary design, the vertical deflection of the arch crown due to permanent loads g can be estimated based on the arch compression at the crown $\frac{H(\bar{g})}{EA^{A,c}}$ (with $A^{A,c}$ = cross-sectional area of arch at the crown) as

$$\delta^c \cong \frac{H(\bar{g})}{EA^{A,c}} \frac{1+3(f/l)^2}{4f/l} l \qquad (\text{for } EA^A = EA^{A,c} = \text{const.})$$

  if the arch rib has a constant cross-section A (i.e., normal arch compression $\approx$ proportional to $N=H/(\cos\alpha)$, and as

$$\delta^c \cong \frac{H(\bar{g})}{EA^{A,c}} \frac{l}{4f} l \qquad (\text{for } EA^A = \frac{EA^{A,c}}{\cos\alpha} \rightarrow \frac{H(\bar{g})}{EA^A} \approx \text{const.})$$

  if the arch rib cross-section A is proportional to $1/(\cos\alpha)$ (i.e., constant arch compression as in case of imposed ε).



NB. The deflections due to arch compression (caused by dead load, imposed deformations or displacements) are much higher in flat arches (low ratios *f/l*):

$\frac{f}{l}$	$\frac{l}{4f}$	$1+3\left(\frac{f}{l}\right)^2$	$\frac{1+3(f/l)^2}{4f/l}$
1/2	0.5	1.750	0.875
1/4	1.0	1.188	1.188
1/6	1.5	1.083	1.625
1/8	2.0	1.047	2.094
1/10	2.5	1.030	2.575
1/12	3.0	1.021	3.063
1/14	3.5	1.025	3.554
1/16	4.0	1.012	4.047

(example: for f/l = 1/8, the crown deflects twice as much as the arch rib contracts)

(see also diagram on slide 120, case study)

Note: The approximations for the deflection at the crown can be obtained using the work theorem. Considering a fixed arch (anti-funicular geometry, no contribution of bending moments), the virtual force state (unit vertical force at crown) can applied in an isostatic system (e.g. three-hinged arch). The equations follow from assuming a constant normal force $N = H$ in the virtual force state, and approximating the integration of $1/\cos\alpha$ (N in the deformation state, for the case EA=const.) e.g. using Taylor series, which yields the factor 3 in the term $(f/l)^2$.

Arch bridges – Design: Bending moments due to arch crown deflection

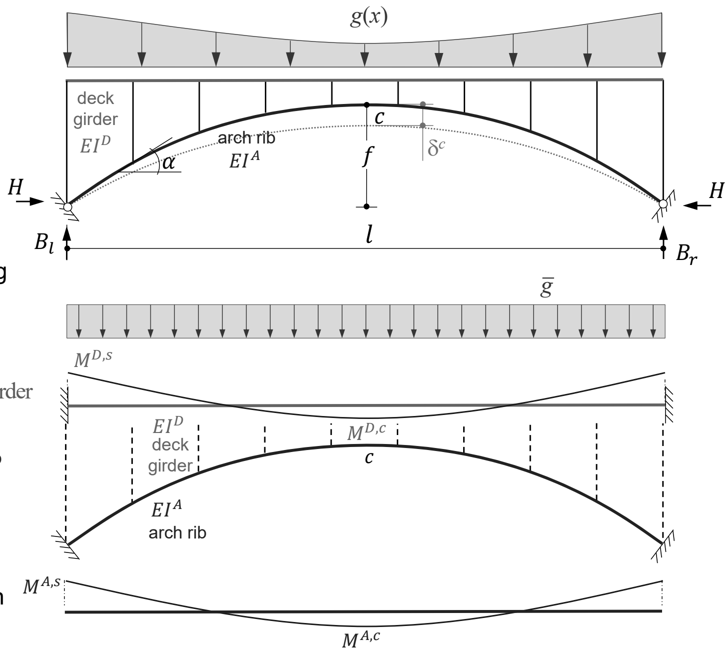
Bending moments due to arch compression

- The arch rib is much stiffer axially than arch rib and deck girder in bending
  - → deflections of arch rib (due to N/EA, ε and/or Δh) are imposed to arch rib and deck girder
  - → bending moments in arch rib and deck girder proportional to their stiffness and crown deflection δ^c
  - → In clamped arches (with continuous deck), the bending moments can be estimated from δ^c as follows (analogous $M \leftrightarrow \delta^c = \delta_{midspan}$ in a continuous girder):

$$\left.\begin{array}{l} \delta^c = \dfrac{\bar{g}l^4}{384EI} \\ M^c = -\dfrac{1}{2}M^s = \dfrac{\bar{g}l^2}{24} \end{array}\right\} \rightarrow \left\{\begin{array}{ll} M^{D,c} = -\dfrac{M^{D,s}}{2} \cong \dfrac{16EI^D}{l^2}\delta^c & \text{deck girder} \\ M^{A,c} = -\dfrac{M^{A,s}}{2} \cong \dfrac{16EI^A}{l^2}\delta^c & \text{arch rib} \end{array}\right.$$

$$\left(\frac{M^c}{\delta^c} = \frac{\bar{g}l^2}{24}\cdot\frac{384EI}{\bar{g}l^4} = \frac{16EI}{l^2} \text{ is independent of } \bar{g}\right)$$

where M^D = moment in deck girder, M^A = moment in arch rib, c = crown, s = springing line (arch abutment)



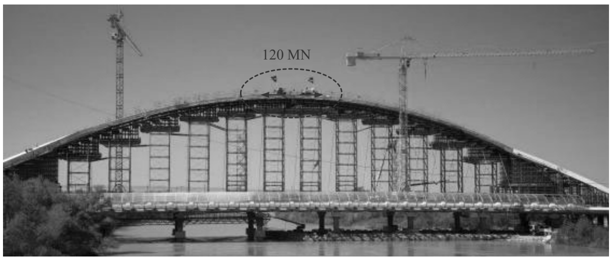
These moments produced in the girder must be superimposed with the fixed system moments (deck as continuous girder supported by stiff spandrel columns).

$\bar{g}$: uniformly distributed load

Arch bridges – Design: Bending moments due to arch crown deflection

Bending moments due to arch compression

- Bending moments due to arch compression generally occur in arches built on conventional centrings.
- In concrete arches, the crown deflection increases with time due to creep, but the bending moments remain constant (one casting system, see Advanced Structural Concrete)
- If the arch is lifted off the formwork by opening it in the crown (with hydraulic jacks, see figure), or the arch is built by stay cantilevering, the arch rib is already compressed at closure
  - → no crown deflection at $t = 0$ (time of closure), but
  - → in concrete arches, crown deflections and corresponding bending moments build up over time due to creep
  - → bending moments of up to 80% of the values of the arch built on centring (= one casting system, see Advanced Structural Concrete) can result at $t = \infty$
- The benefit of opening concrete arches in the crown can be increased if the jacks are kept installed, adjusting the jacking force over a long period of time (as done e.g. in the Krk Bridges during 5 years, see section *Erection*).



Photos: Opening the arch of the Puente del Tercer Milenio, Zaragoza, in the crown (Arenas y Asociados, 2008, 216 m span. In this case, the jacking force of 120 MN (corresponding to about 80% of the permanent loads at the time of jacking) was not used to lift the arch off the formwork, but primarily to simplify the subsequent tensioning of the hangers).

Arch bridges

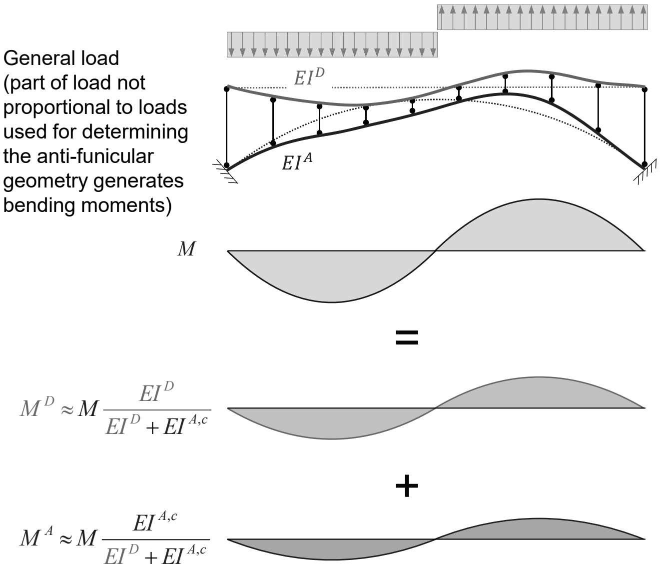
Design – Bending moments in flexible system

Arch bridges – Design: Bending moments in flexible system

General behaviour – Load sharing

- Under loads causing bending moments in the arch (≠ proportional to loads used for determining the anti-funicular geometry, see Slide 22 for decomposition of load), the system acts like a flexible frame
  - → deflections of arch rib and deck girder equal (deck arch, stiff columns) or very similar (tied arch, flexible hangers)
  - → bending moments shared among deck girder and arch rib in proportion to their stiffness
- Generally, the bending stiffness of deck girder and arch rib is of similar magnitude, and both elements carry a portion of the total bending moments, see figure.

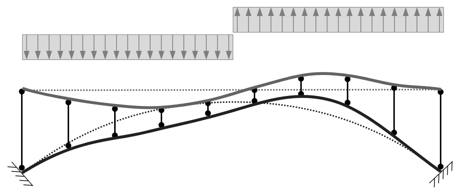
Note that this “load sharing” also applies to the bending moments due to arch compression, as these are proportional to the stiffnesses as well.

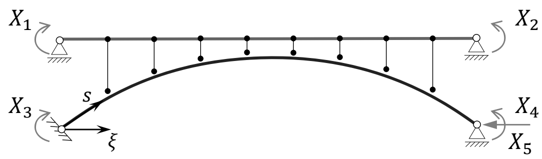


Arch bridges – Design: Bending moments in flexible system

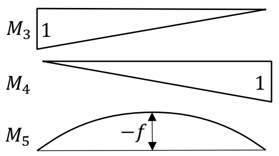
Solution using force method – General case

- Basically, the bending moments in the flexible system can be determined using the force method
  - → select isostatic basic system and introduce redundant variables
  - → determine flexibility coefficients
  - → formulate compatibility and solve for redundant variables
- However, even if the columns (hangers) are idealised as pin-jointed members, the solution is tedious in the general case
  - → use frame analysis software
  - → for preliminary design, estimate bending moments using values shown on slide 63





Redundant moments:



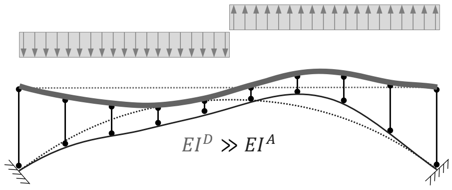
$$\delta_{ik} = \int_0^l M_i \frac{M_k}{EI^D} d\xi + \int_0^l M_i \frac{M_k}{EI^A} ds$$

δ_{ik} : flexibility coefficients
D : deck girder
A : arch

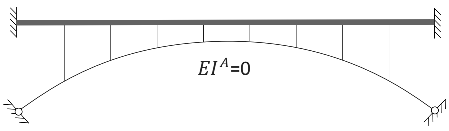
Arch bridges – Design: Bending moments in flexible system

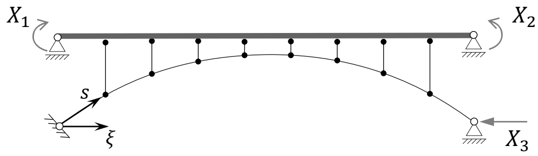
Solution using force method – Deck-stiffened arches

- If the bending stiffness of the deck girder is much higher than that of the arch rib, the latter can be neglected
  - → “deck-stiffened arch”
  - → bending moments carried (almost) by the deck girder alone
  - → reduced degree of statical indeterminacy
- If the columns (hangers) are idealised as pin-jointed members, the system is three times statically indeterminate
  - → solution using force method possible, but obsolete
  - → use frame analysis software
  - → for preliminary design, estimate bending moments using values shown on slide 63



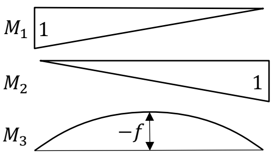
→ idealisation: deck-stiffened arch





$M^A = 0$ (but consider moments due to arch compression!)

Redundant moments:



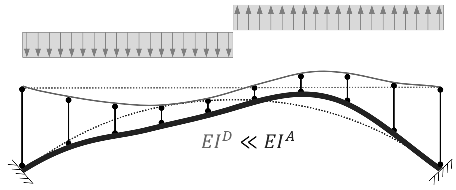
$$\delta_{ik} = \int_0^l M_i \frac{M_k}{EI^D} d\xi$$

δ_{ik} : flexibility coefficients
D : deck
A : arch

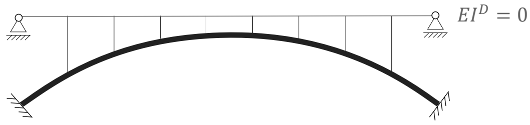
Arch bridges – Design: Bending moments in flexible system

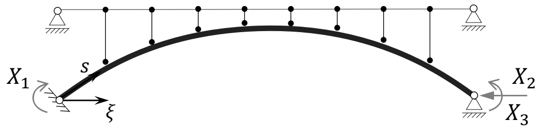
Solution using force method – Stiff arches

- If the bending stiffness of the deck girder is much lower than that of the arch rib, the former can be neglected
  - → "stiff arch"
  - → bending moments carried (almost) by the arch rib alone
  - → reduced degree of statical indeterminacy
- If the columns (hangers) are idealised as pin-jointed members, the system is three times statically indeterminate
  - → solution using force method possible, but obsolete
  - → use frame analysis software
  - → for preliminary design, estimate bending moments using values shown on slide 63

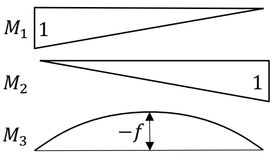


→ idealisation: stiff arch





Redundant moments:



$$\delta_{ik} = \int_0^l M_i \frac{M_k}{EI^A} ds = \int_0^l M_i \frac{M_k}{EI^{A,c}} d\xi$$

(for $EI^A \cos\alpha = EI^{A,c}$)

δ_{ik} : flexibility coefficients
D : deck
A : arch
A,c : arch at crown

$M^D = 0$ (but consider moments due to arch compression!)

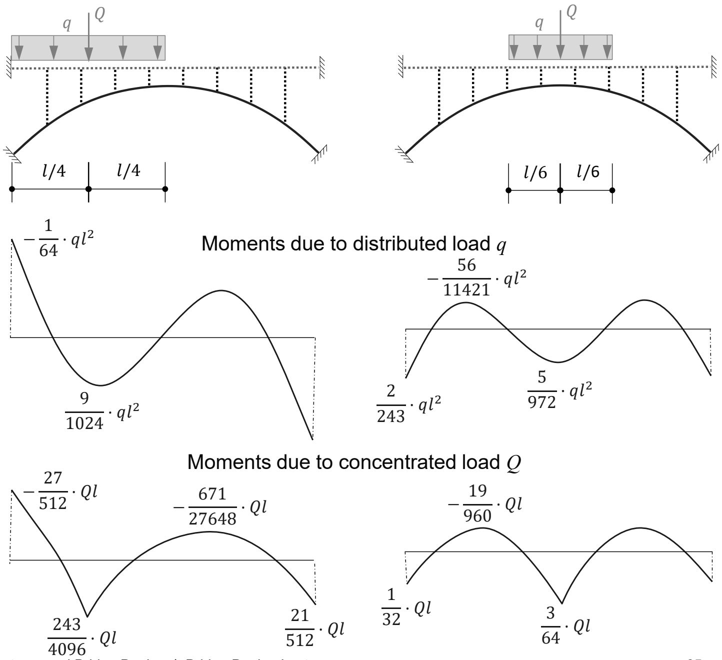
Arch bridges – Design: Bending moments in flexible system

Approximate values of bending moments due to traffic load (clamped arch with continuous deck girder)

- Generally, the maximum bending moments need to be determined considering different load positions (e.g. using influence lines)
- In preliminary design, it is sufficient to check the maximum bending moments
  - → at the springing lines (arch abutments)
  - → at the quarter-points
  - → at the crown
- These may be estimated using the two load cases illustrated in the figure:
  - → symmetrical load over middle third of span
  - → asymmetrical load on one half span

  and distributed among arch rib and deck girder according to their stiffnesses

$$M^D \approx M \frac{EI^D}{EI^D + EI^{A,c}} \qquad M^A \approx M \frac{EI^{A,c}}{EI^D + EI^{A,c}}$$



Note that these load cases do not give the extreme values of the internal forces. Additional load cases must be considered in detailed design.

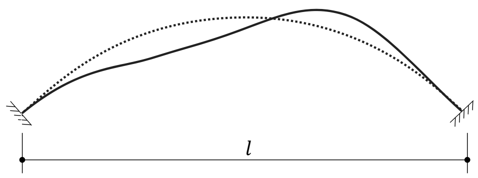
Arch bridges

Design – Second-order bending moments

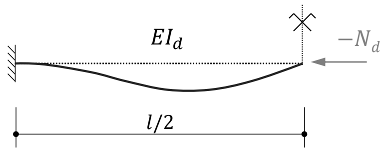
Arch bridges – Design: Second order bending moments

- Arches are compression members
  - → in addition to the (first order) moments in the flexible system, see previous slides, second order bending moments must be considered unless the arch is very stiff and they are negligible
  - → for deck arches, second order analysis can usually be limited to in-plane bending moments (deck girder provides lateral stability)
  - → for tied arches, out-of-plane stability (transverse buckling of the arch resp. corresponding 2nd order bending moments) are typically more critical
- In detailed design, a second-order analysis is carried out, assuming suitable imperfections (see substructure chapter) and the governing load positions, which typically are:
  - → in-plane stability: traffic load in one half-span
  - → out-of-plane stability: traffic load in full span
- In the preliminary design of deck arches, it is sufficient to consider anti-symmetrical in-plane buckling see figures and next slide.

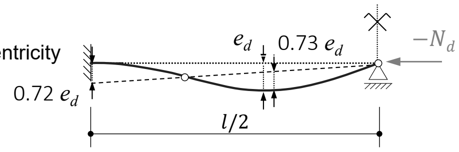
In-plane buckling of (deck) arch



Approximate in-plane buckling length and deflected shape (clamped-hinged)



Maximum eccentricity



The critical load case for in-plane buckling normally consists of dead load plus live load applied to one half of the arch span. For out-of-plane buckling (tied arches), live load applied over the full span is usually more critical.

Arch bridges – Design: Second order bending moments (in-plane)

- In the preliminary design of concrete deck arches, 2nd order in-plane bending moments can be determined using the curvature based method of SIA 262, see substructure chapter, considering arch rib and deck girder together as a compression member.
- If the deck is prestressed and the arch stiffness increases towards the abutments in line with the arch normal force, i.e.

  $$EI^A(x) \approx \frac{EI^{A,c}}{\cos\alpha(x)}$$

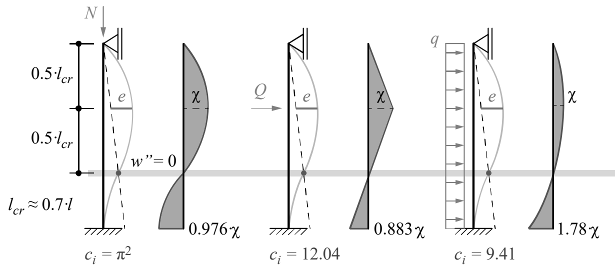
  a constant bending stiffness may be assumed:

  $$EI_d \cong \frac{1}{4}\left(EI^{A,c} + EI^D\right) \rightarrow \chi_d = 4\frac{M_{Rd}^{A,c} + M_{Rd}^{D,c}}{EI^{A,c} + EI^D}$$
- The first-order eccentricities correspond to the bending moments for traffic load on one half span (previous slides), and the total eccentricity is as usual: $e_d = e_{0d} + e_{1d} + e_{2d}$
- The c-factors (superposition of actions) are given in the figure, and the resulting bending moments are resisted by arch rib and deck girder jointly, i.e.

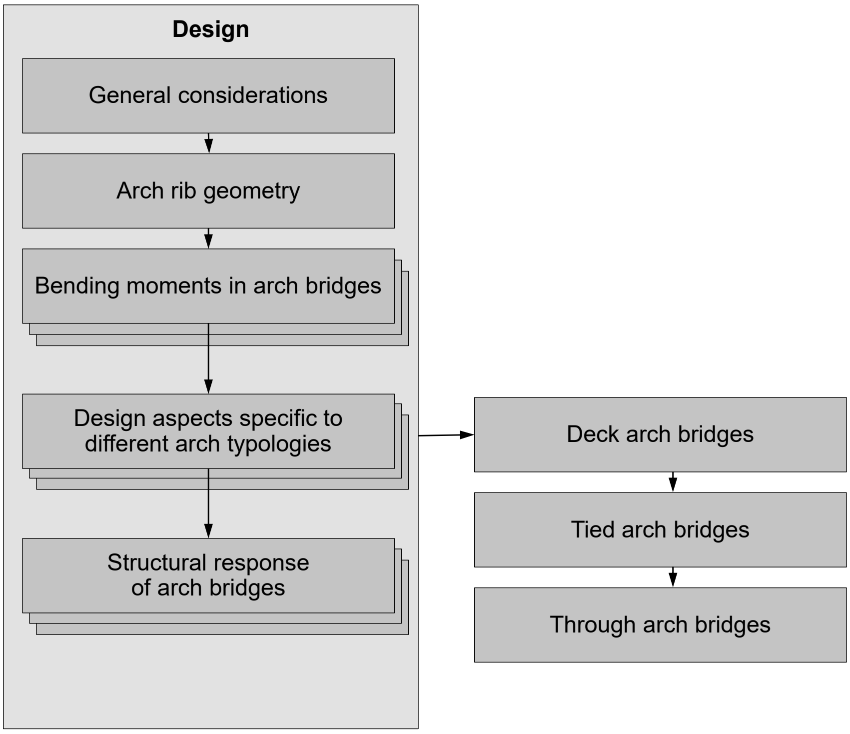
  $$M^D \approx -N_d e_d \cdot \frac{EI^D}{EI^D + EI^{A,c}} \quad M^A \approx -N_d e_d \cdot \frac{EI^{A,c}}{EI^D + EI^{A,c}}$$

Approximate verification of in-plane 2nd order moments in deck arch

$$e_d = e_{0d} + e_{1d} + e_{2d} \begin{cases} e_{0d} = \alpha_i \cdot \frac{l_{cr}}{2} & \text{eccentricity due to geometric imperfection} \\ e_{1d} = \frac{M_{1d}}{-N_d} & \text{first order eccentricity of action} \\ e_{2d} = \chi_d \frac{l_{cr}^2}{c} & \text{eccentricity due to member deformation} \end{cases}$$



Note that the assumed stiffness differs from that usually adopted in compression member design, since the prestressed deck girder is beneficial.


Design
General considerations
Arch rib geometry
Bending moments in arch bridges
Design aspects specific to different arch typologies
Structural response of arch bridges
Deck arch bridges
Tied arch bridges
Through arch bridges

Arch bridges

Design – Deck arch bridges

Arch bridge – Design: Deck arch bridges

Deck girder – General

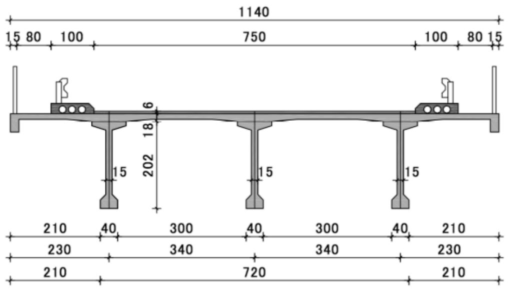
- The deck girder is supported by the arch through the axially stiff spandrel columns
  - → deck girder and arch share the same deflections
  - → the cross-sections of girder and arch must be chosen in consideration of their interaction:
    … stiff arch ↔ slender deck girder
    … slender arch ↔ stiff deck girder
  - → the stiffness ratio of deck and arch EI^D/EI^A is highly relevant for the structural response
- The girder depth is usually kept constant over the entire length of the bridge, and the girder needs to resist additional bending moments due to frame action (crown deflects due to arch compression, see structural response)
  - → less slender than in girder bridges
  - → for prestressed concrete $1/15 \leq h\,/\,l \leq 1/12$

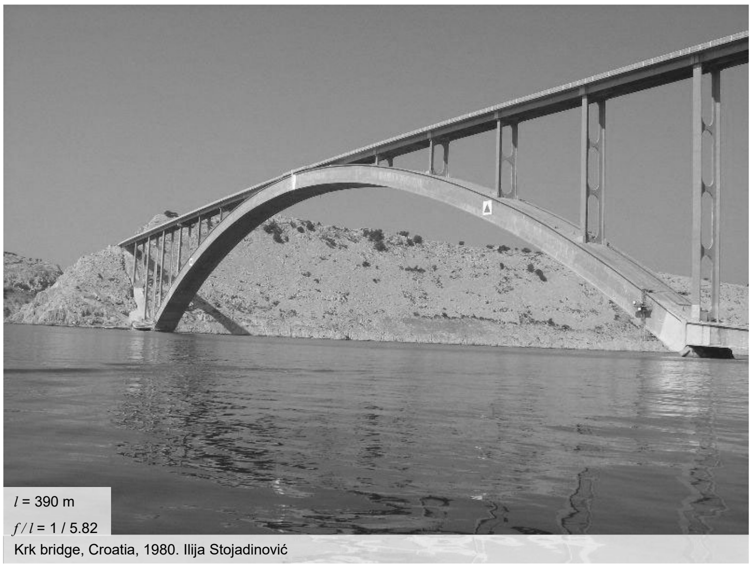
Photo: Wikipedia, Tilos bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Arch bridge – Design: Deck arch bridges

Deck girder – Cross-section

- For reasonably stiff arches ($EI^D << EI^A$), double-T or solid slab deck girders can be used, regardless of the arch span
  - $\rightarrow$ frame moments primarily resisted by arch
  - $\rightarrow$ bending moments in the girder depend mainly on the spandrel column span
  - $\rightarrow$ behaviour similar to continuous girder bridges (hogging moments $\approx$ 2·sagging moments)





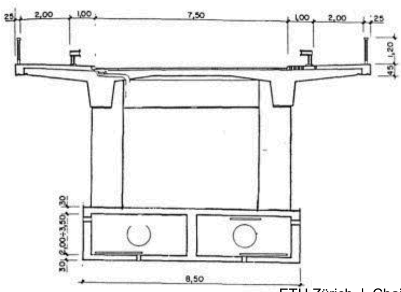
Krk bridge, Croatia, 1980. Ilija Stojadinović

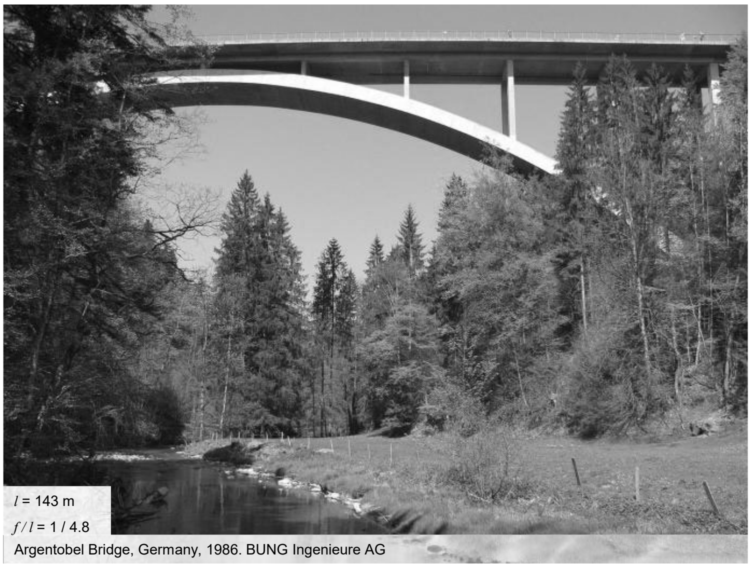
Illustration: adapted from C. Ieva, Practical Optimization Strategies In Cantilever Launching Method of Arch Bridges, Politecnico di Milano, 2014. Photos: Wikipedia

Arch bridge – Design: Deck arch bridges

Deck girder – Cross-section

- For reasonably stiff arches ($EI^D << EI^A$), double-T or solid slab deck girders can be used, regardless of the arch span
  - $\rightarrow$ bending moments in flexible system primarily resisted by arch rib
  - $\rightarrow$ bending moments in the deck girder depend mainly on the spandrel column span
  - $\rightarrow$ behaviour of deck girder similar to continuous girder bridges (hogging moments $\approx 2 \cdot$sagging)





l = 143 m

f / l = 1 / 4.8

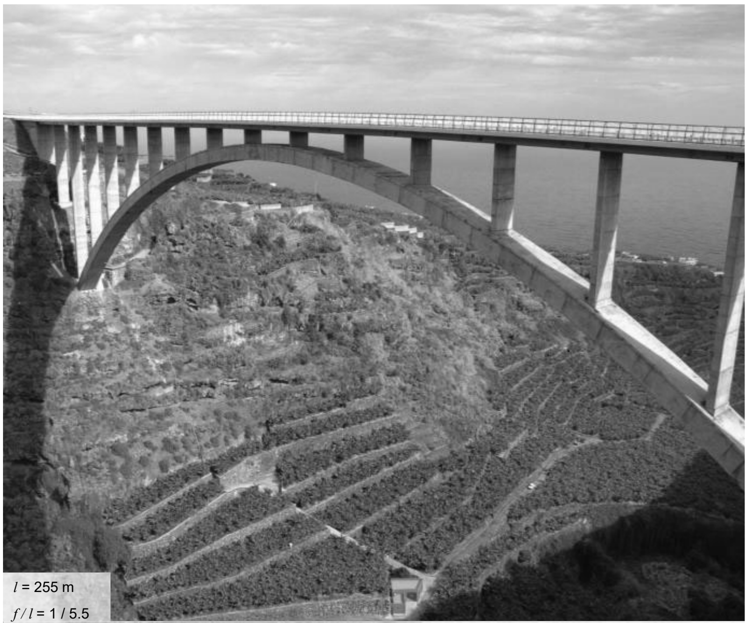
Argentobel Bridge, Germany, 1986. BUNG Ingenieure AG

Illustration: adapted from J. Manterola, Puentes II. Photo: https://www.wikiwand.com/en/Obere_Argen

Arch bridge – Design: Deck arch bridges

Deck girder – Cross-section

- For stiff arches ($EI^D << EI^A$), slender steel-concrete composite decks are also possible, regardless of the arch span.



l = 255 m

f / l = 1 / 5.5

Arco de los Tilos, S. Pérez Fadón / J.E. Herrero Beneitez, Isla de La Palma, Canarias, 2004.

Arco de los Tilos, S. Pérez Fadón and J.E. Herrero Beneitez, San Andrés y Sauces, Isla de La Palma, Canarias (2004). Concrete hollow section arch with steel-concrete composite deck, deck arch, span 255 m, length 353 m, 150 m above ground.

Photo © Ferrovial / Detail photo © https://diariodeavisos.elespanol.com/wp-content/uploads/2019/02/rapel2.jpeg

Arch bridge – Design: Deck arch bridges

Deck girder – Cross-section

- In flexible arches ($EI^D \approx EI^A$ or even $EI^D > EI^A$), the stiffness of the deck girder has a significant influence on the behaviour of the frame system
  - → significant part of frame moments resisted by deck girder
  - → higher deck girder stiffness required
  - → box girder cross-sections for deck of long-span arches
  - → sagging and hogging moments in the girder of similar magnitude over the entire length of the arch

l = 162 m

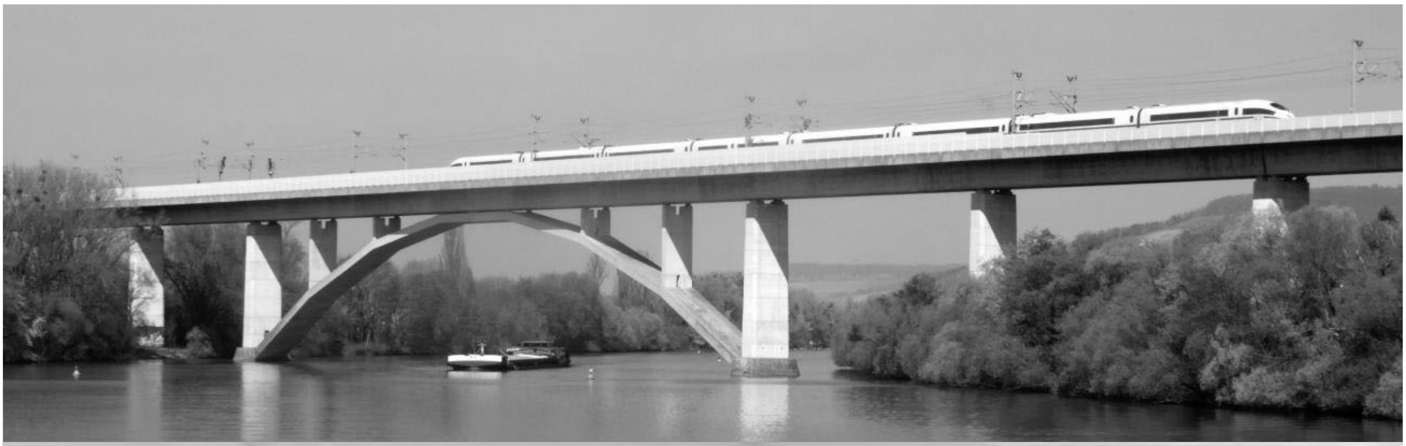
f / l = 1 / 5

Veitshöchheim viaduct, Germany, 1986. ILF Beratende Ingenieure & Leonhardt, Andrä und Partner

Photo: https://mapio.net/pic/p-49715382/

Arch bridge – Design: Deck arch bridges

NB. Aesthetics (arch abutments in river)?



Veitshöchheim viaduct, Germany, 1986. ILF Beratende Ingenieure & Leonhardt, Andrä und Partner

Photo:
https://commons.wikimedia.org/wiki/File:Maintalbr%C3%BCcke_Veitsh%C3%B6chheim_von_S%C3%BCden,_5.jpeg

Arch bridge – Design: Deck arch bridges

NB. Aesthetics (arch abutments on shore)!

Viaducto del Embalse de Alcántara (Río Tajo), Extremadura, Spain, 2016. CFCSL.

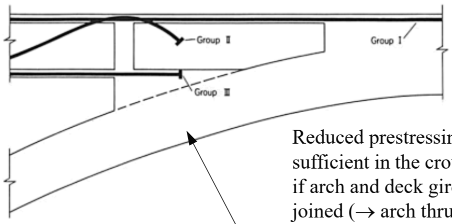
Photo: Viaducto del Embalse de Alcántara, CFCSL (Carlos Fernández Casado S.L., J. Manterola, A. Martinez Cutillas), High Speed Line Madrid-Extremadura-Portugal, Cáceres, Spain (2016, line in service 2022). High speed train concrete deck arch bridge, main span 324 m, total length 1488 m, f/L = 1/5.7. Hollow box high strength concrete arch, prestressed concrete box girder.

Photo © kfm

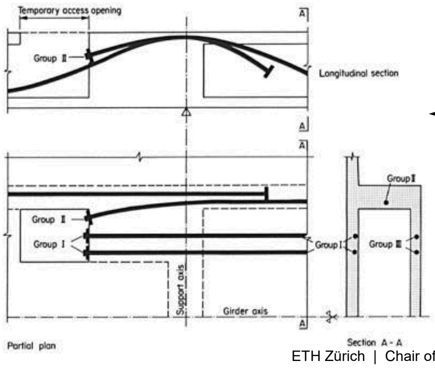
Arch bridge – Design: Deck arch bridges

Deck girder – Prestressing

- Concrete deck girders are commonly fully prestressed for permanent loads
  → higher, uncracked stiffness improves global stability of the frame system (cracked-elastic second-order analysis is subjected to many uncertainties)
  → enhanced durability



Reduced prestressing is sufficient in the crown region if arch and deck girder are joined (→ arch thrust provides compression)



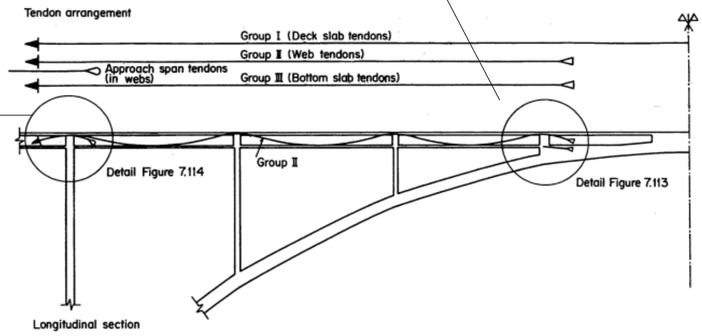


Illustration adapted from C. Menn, Prestressed Concrete Bridges, 1990.

WK0

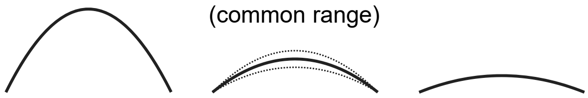
Arch bridge – Design: Deck arch bridges

Arch rib

The arch transmits a significant horizontal reaction to the supports $\rightarrow$ a strong soil is ideal

The structural response of the arch depends strongly of the ratio of rise-span $f\,/\,l$

high arch | standard arch (common range) | low arch



$f\,/\,l = 1/2$ | $1/4 \geq f\,/\,l \geq 1/7$ | $f\,/\,l < 1/10$

The structural response of the arch depends strongly on the supports and hinge arrangement:

- clamped arch
- two-hinged arch
- three-hinged arch

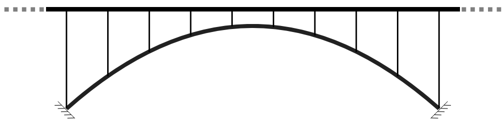
Tilos Bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Photo: Wikipedia, Tilos bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Arch bridge – Design: Deck arch bridges

Arch rib

- Clamped arch:



→ robust (specially during construction)

→ superior for non-symmetric actions

→ low clamped arches f / l < 1/10 are sensitive to imposed deformations and movements of the foundation (see structural response)

→ high arches are more economical (but low arches often aesthetically more satisfactory).

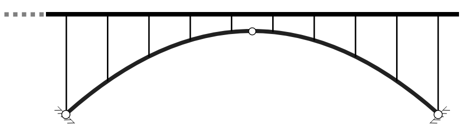
Tilos Bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Photo: Wikipedia, Tilos bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Arch bridge – Design: Deck arch bridges

Arch rib

- Two and three hinged arches:



→ hinges should basically be avoided (maintenance), but

→ if substantial movements of the foundations are expected, hinges at the springing lines may be beneficial (avoid high bending moments in the arch rib, see structural response)

→ hinges at the crown should be avoided where possible (durability, construction process)

Juan de Austria bridge (two-hinged arch), Spain, 1986. CFCSL

Photo: https://www.flickr.com/photos/casiopea15/28241837679

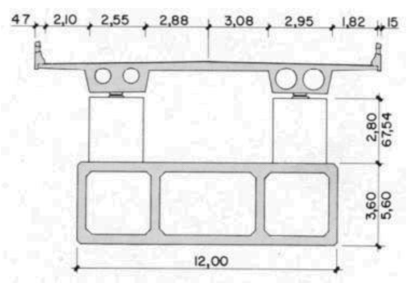
Arch bridge – Design: Deck arch bridges

Arch rib

Usual cross sections of large-span arch ribs are:

- Hollow sections (single- or multi-cell)
  … low weight
  … high stiffness (radius of gyration I/A)
- Trusses (in steel bridges)

For shorter spans l < 150 m, solid cross sections or U-shaped cross sections are suitable



Bloukrans bridge, Western Cape, South Africa, 1983. Liebenberg & Stander

Illustration: adapted from C. Ieva, Practical Optimization Strategies In Cantilever Launching Method of Arch Bridges, Politecnico di Milano, 2014. Photo: A. Giraldo Soto

Arch bridge – Design: Deck arch bridges

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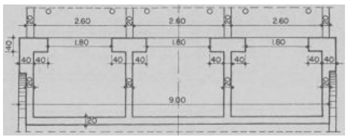


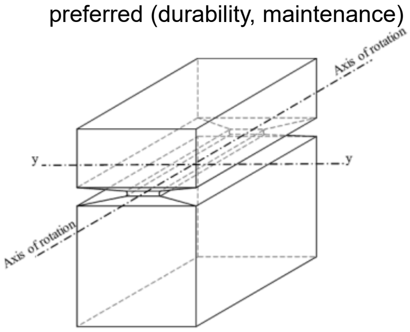
Serrieres-sur-ain bridge, France, 1959. Jean Courbon

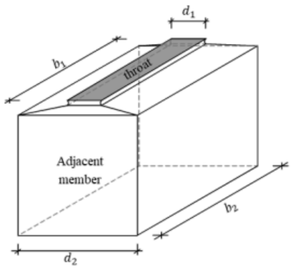
Illustration: Puente sobre el río Ain, Informes de la Construcción Vol. 15, nº 147 Enero, febrero de 1963. Photos: https://structurae.net/en/structures/serrieres-sur-l-ain-bridge

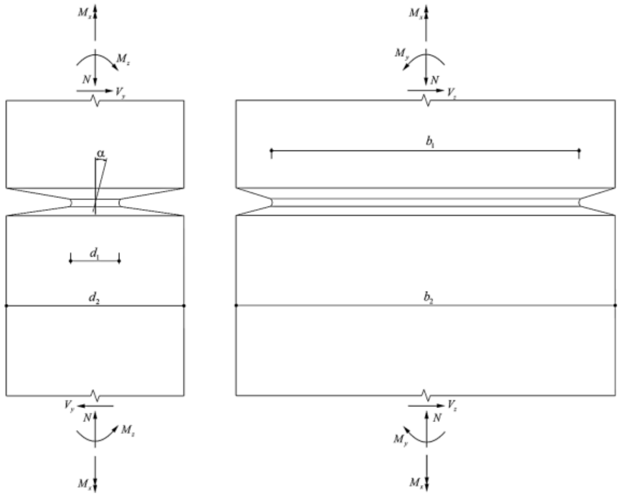
Arch bridge – Design: Deck arch bridges

Spandrel columns

- Spandrel columns should be monolithically connected to deck girder and arch where possible, e.g. using slender columns
  - → enhanced durability
  - → simpler construction
  - → higher stiffness (frame) under non-anti-funicular load
- If hinged connections are required, concrete hinges are preferred (durability, maintenance) to bearings







Design of concrete hinges usually according to: Leonhardt, F., Mönnig, E., “Vorlesungen über Massivbau. Teil 2: Sonderfälle der Bemessung im Stahlbetonbau”, Springer, 1986. Marx, S., Schacht, G., “Betongelenke im Brückenbau – Bericht zum DBV-Forschungsvorhaben 279”, Deutscher Beton- und Bautechnik-Verein E.V, 2010.

Illustration adapted from Tomislav Markic

Arch bridge – Design: Deck arch bridges

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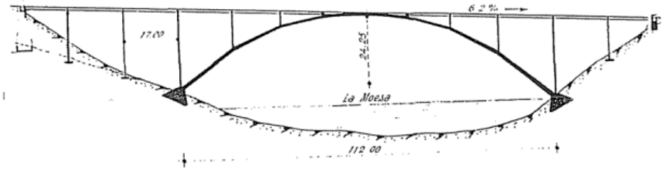
Photo: © TBA Kanton St. Gallen

Arch bridge – Design: Deck arch bridges

Stiffness of deck girder vs arch rib

- Basically, the required bending stiffness (stability, flexible system moments) can be arbitrarily allocated to the arch rib or the deck girder
- Concrete arch ribs have a high moment capacity without extra cost due to the compressive normal force, and a high stiffness EI^A of the arch rib is also favourable during construction
  - → for structural efficiency, the concrete arch rib should be stiffer in bending than the deck (such that it will carry most of the moments)
- On the other hand, the deck girder always provides a minimum stiffness
  - → very slender arches possible if built on centring
  - → “secret” of the elegance of arch bridges designed by Christian Menn
  - → however, arches built on centring are uneconomical (even if still built occasionally, if economy is of little importance)



Cascella and Nanin bridges, Switzerland, 1968. Christian Menn

Photo: Marti, P., Monsch, O., und Schilling, B., Ingenieur-Betonbau, Gesellschaft für Ingenieurbaukunst, Band 7, vdf Hochschulverlag AG, ISBN 3-7281-2999-2, Zürich, 2005 (© Orlando Monsch)

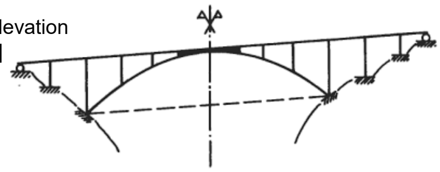
Arch bridge – Design: Deck arch bridges

Aesthetics

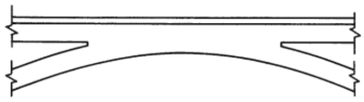
When designing a deck arch bridge, the following points – mostly proposed by Ch. Menn – should be considered; note that these are no rules, but merely points of orientation:

- The connecting line of the arch abutments (springing line) resp. the arch intersection with the ground should be parallel to the girder (top figure).
- Providing at least 4-6 spandrel columns at equal distance (5-7 equal parts) is preferable (if less spandrel columns are required, check feasibility of strut-frame bridge, see frame bridges, and if not possible, provide polygonal arch).
- If arch and deck (stiffening girder) are separated, no column should be provided at midspan.
- If arch and deck (stiffening girder) are joined monolithically, a satisfactory appearance is obtained by using the same depth for girder and arch and making sure that the arch axis is tangent to the (extended) girder soffit line (intrados), see bottom figure).

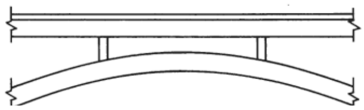
Deck arch elevation
[Menn 1990]



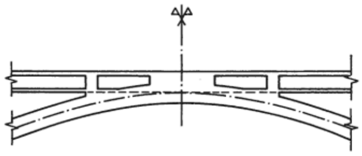
Joined crown
[Menn 1990]



Separated crown
[Menn 1990]



Proposed geometry
of joined crown
[Menn 1990]



Arch bridges

Design – Tied arch bridges

Arch bridge – Design: Tied arch bridges

- As already outlined (general considerations), tied arch bridges are suitable for
  - → locations with soft soil
  - → single-span bridges with low clearance
- The in-plane stability of the arch rib is ensured by the deck girder acting in tension.
- Other than in deck arches, the arch rib is not commonly stabilised by the deck girder

→ out-of-plane stability (transverse buckling) is a governing design parameter of tied arches

- Transverse stability can be ensured by:
  - → transverse bracings between two arch ribs running along the outside of the deck
  - → inclined arches connected at midspan
  - → transverse U-frames consisting of (stiff) “hangers” and deck (as in classic trough-section girder bridges)
  - → arches with high transverse stiffness (for short spans)

Fort Pitt bridge, Pittsburgh, USA, 1959. George S. Richardson

l = 229 m

Photo:

left: http://www.brooklineconnection.com/history/Facts/FtPittBridge.html;

right: https://upload.wikimedia.org/wikipedia/commons/1/1a/Pittsburgh_From_The_Incline_Peak_2%3B_5.30.2005%3B_549pm.jpg

Arch bridge – Design: Tied arch bridges

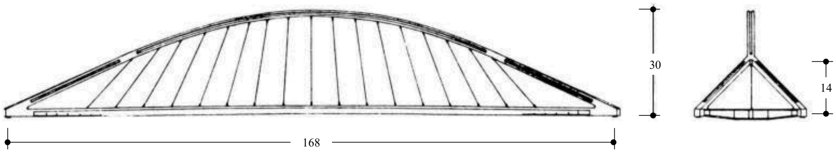
Tied arches are often steel bridges. The Rheinhauser Brücke in Duisburg is the longest tied arch in Germany (since 1988 “Brücke der Solidarität”).

Rheinhauser Bridge, Duisburg, Germany, 1950. Krupp Stahlbau Rheinhausen.

Photos: © Wikimedia commons

Arch bridge – Design: Tied arch bridges

The Barqueta Bridge was the first tied arch with one central arch rib above the roadway (rather than joining two continuous arch ribs).



Barqueta bridge, Sevilla, Spain, 1992. J.J. Arenas and M.J. Pantaleón

Illustration adapted from Revista de Edificación (RE), N° 7, July 1990

Photos: © J.J. Arenas

Arch bridge – Design: Tied arch bridges

Concrete tied arch bridges are less frequent. The Puente del Tercer Milenio in Zaragoza is one of few large-span concrete tied arches.

f = 36 m
l = 216 m
f / l = 1 / 6

Puente del Tercer Milenio, Zaragoza, Spain, 2008. Arenas & Asociados / Juan José Arenas

Arch bridge – Design: Tied arch bridges

- Arches with transverse bracings or connected arch ribs (previous two examples) require a minimum height of the to provide sufficient clearance on the bridge.
- In smaller span arches, such bracings can be eliminated if the "hangers" act as frames, stabilising the arch ribs
  → provide hangers with transverse stiffness
  → transverse frame action of deck-hanger-arch
- Such arches can be very slender, and are attractive to cross as they generate a «curtain effect» to the user (bottom photos).

Puente sobre el río Pontones, Cta. Hoznayo-Villaverde, Spain, Arenas & Asociados (2005).

Right: Puente sobre el río Pontones, Cta. Hoznayo-Villaverde, Cantabria, Spain, Arenas & Asociados (2005). Steel tied arch with steel-concrete composite deck, span 60 m, f/L = 1/8. Photo © Arenas & Asociados.

Photos: Arenas y Asociados / W. Kaufmann

Arch bridges – Design: Tied arch bridges

- Aesthetically, the elevated arch ribs of tied arch bridges should be slender and are thus flexible
  → stiffness (for non-anti-funicular loads) of tied arch bridges must be ensured by other elements
- Conventionally, stiff deck girders were used to ensure sufficient stiffness (previous examples)
- Alternatively, the hangers can be used to this end, with the following options
  → Hangers inclined in elevation forming a truss together with arch rib and deck girder
    … hangers forming a Warren truss (Strebenzug) without intersections = Nielsen arch
    … hangers intersecting = Network tied arch
  → Stiff “hangers” forming a Vierendeel girder together with arch rib and = Vierendeel arch
- Network tied arches have gained increasing popularity in the recent years due to their high structural efficiency (photo and next slides).

Steel arch over highway AP-68, Spain, 2009. Torroja Ingeniería

l = 71 m

f / l = 1 / 4.73

Note that Nielsen patented arches with intersecting hangers in 1926 as well, but never built one with this typology.

Photos: http://torrojaingenieria.es

Arch bridge – Design: Tied arch bridges

The Fehmarnsund bridge was the first long-span network tied arch bridge (conversion to local traffic only planned for 2028, new tunnel across Fehmarnsund connecting to Fehmarnbelt).

f = 45 m
l = 248 m
f / l = 1 / 5.51

Fehmarnsund Bridge, Germany, 1963. G. Fischer, T. Jahnke und P. Stein, Sterkrade AG.

Photos: © Wikimedia commons

Arch bridge – Design: Tied arch bridges

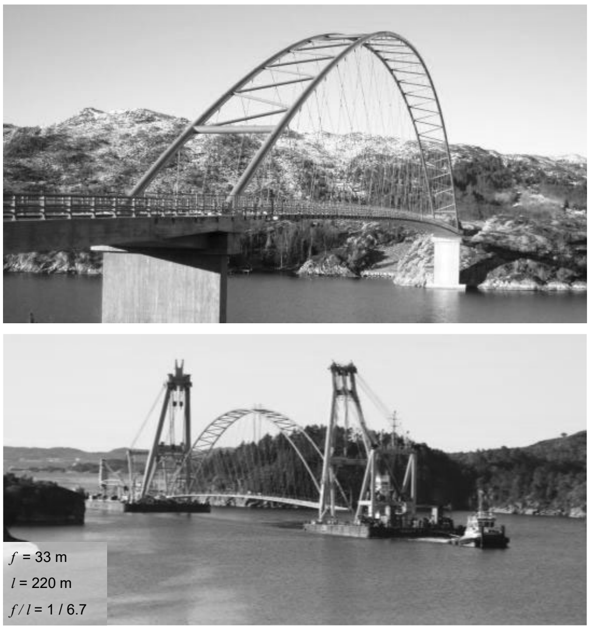
- Network tied arch bridges are very efficient and can thus be used for very long spans.
- They are aesthetically attractive and very economical if an efficient erection method can be used.
- The slide shows the currently longest span network arch bridge.

Bugrinsky bridge, Novosibirsk, Russia, 2014. Albert Koshkin / Sibmost

Photos: Top Structurae.net / Bottom © http://siberiantimes.com/

Arch bridge – Design: Tied arch bridges

- Thanks to their efficiency, network tied arch bridges can be designed extremely slender and lightweight (photos).
- However, they are challenging for analysis and detailing
  - → sign reversals in the hanger forces, resulting in sagging hangers, must be avoided (critical for high live load to dead load ratio and flat hangers)
  - → hangers are prestressed, analysis needs to account for hanger preload (similar as in cable-stayed bridges)
  - → steep hangers are prone to fatigue (high load variation due to slender deck)
  - → hanger arrangement requires complicated details (no standard connections)
- For these reasons, designers were reluctant using this efficient bridge typology for many decades.
- However, with modern analysis, drafting and fabrication methods, these challenges can be mastered.



Brandanger Bridge, Norway, 2010. Aas-Jakobsen.

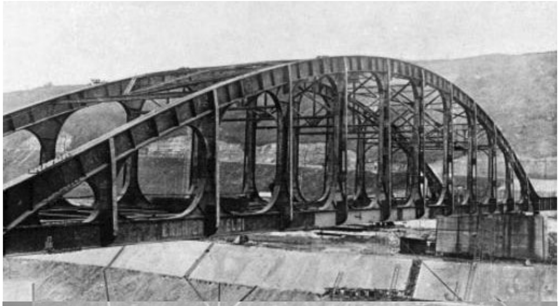
Photos: https://www.hsm-steelstructures.com/

Further reading on network arch bridges: Per Tveit, “How to Design Economical Network Arches,” IOP Conf. Ser.: Mater. Sci. Eng. 471 052078, 2019.

Arch bridge – Design: Tied arch bridges

Vierendeel arches have only been used in few bridges, despite a large number of such bridges being built in Belgium in the 1930s over the Albert Canal.

Gellik Railway Bridge (Spoorbrug bij Gellik), Albert Canal, Belgium, 1934. Span 112.75 m



Lanaye Bridge, Albert Canal, Belgium, 1932. Span 68 m

Herentals-Lier Bridge, Albert Canal, Belgium, 1934. Span 57.5 m

Photos: Bernard Espion, “The Vierendeel bridges over the Albert Canal, Belgium,” Stell Construction 5(4), 2012, pp. 238-243, except Gellik Railway Bridge © Wikimedia Commons

Arch bridges

Design – Through arch bridges

Arch bridge – Design: Through arch bridges

- The logic of form is a strong positive point of deck arches – which are obviously true arches.
- At least to structural engineers, the force flow is equally clear in tied arches (laymen often think they are true arches).
- In through arches, however, it is often impossible to tell whether they act as true or tied arches, even to experienced bridge designers, without closely inspecting the bridge ends or even consulting drawings.
- As an example, consider the Castelmoron Bridge:
  → well-known bridge (as it is one of the few original Nielsen arch bridges) in the bridge community
  → arch exhibits no kink at the hinges at deck level: indicates that any tie force in the deck girder would be continuous (equal in main span and adjoining part of the bridge)
  → but the adjoining part of the bridge might act as V-struts

Castelmoron bridge, France, 1933. Christiani & Nielsen

Photo:

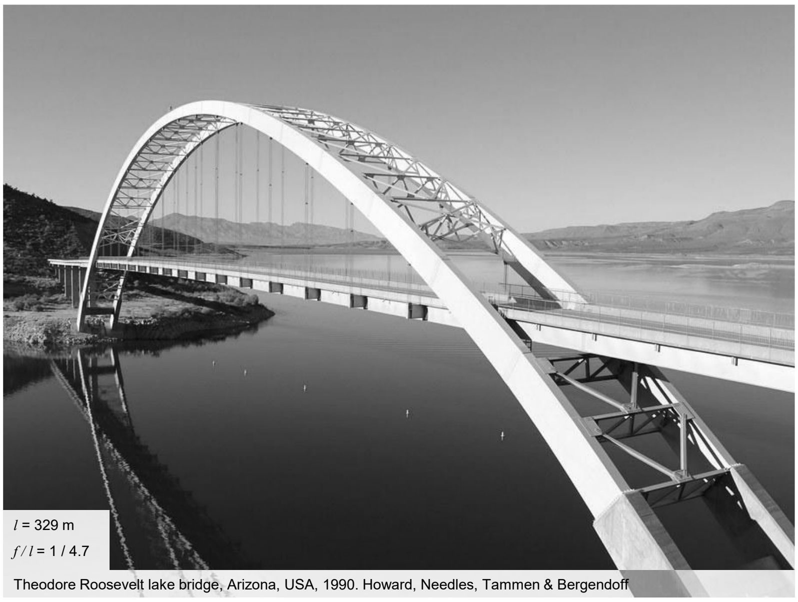
https://fr.wikipedia.org/wiki/Pont_sur_le_Lot_de_Castelmoron-sur-Lot#/media/Fichier:Castelmoron-sur-Lot_-_Pont_sur_le_Lot_-1.JPG

Arch bridge – Design: Through arch bridges

- Few bridge designers would thus bet much on how this bridge carries the loads without knowing more.
- Only a virtual visit to the bridge reveals that
  → it is (most likely) acting as true arch, as there is no element that could transfer the arch thrust from the springing line back up to the girder
  → its soffit is also worth having a closer look

Arch bridge – Design: Through arch bridges

- When designing a through arch, which makes sense in many cases (clearances vs road alignment), it should be ensured that the force flow is legible.
- This slide shows a clear example of a through arch acting as true arch.

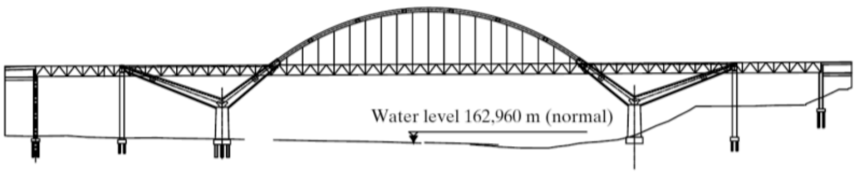


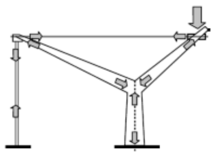
Theodore Roosevelt lake bridge, Arizona, USA, 1990. Howard, Needles, Tammen & Bergendoff

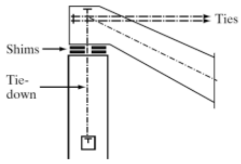
Photos: left :https://www.flickr.com/photos/cedwardbrice/23907070443/; right: https://www.flickr.com/photos/cmhpictures/46625020241

Arch bridge – Design: Through arch bridges

- This slide shows an equally clear example of a through arch acting as tied arch on V-struts.





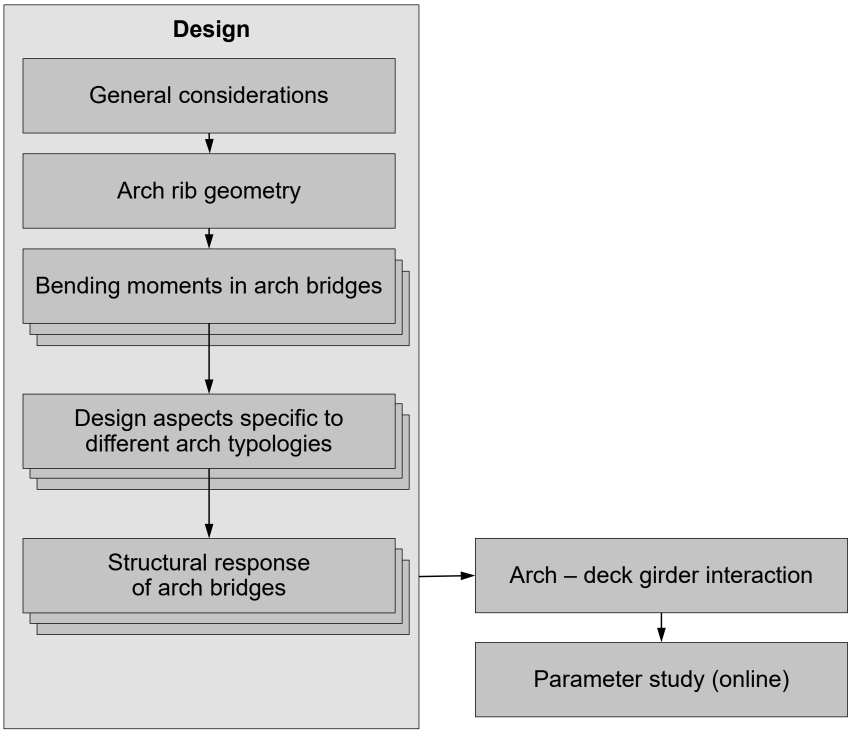


Chongqing Caiyuanba Bridge, China, 2007. Chongqing Communications Research & Design Institute / T.Y. Lin International

Photos and illustrations: Man-Chung Tang, Guolei Ren, “Design and Construction of the Main Spans of the Chongqing Caiyuanba Bridge, China,” Structural Engineering International, 20:3, 2010, 296-298

Arch bridges

Structural response



A parameter study (in the online available Appendix) shows an overview of the influence different arch support conditions, hinges on the structural behaviour of the arch.

Arch bridges

Structural response – Arch-deck girder interaction

Arch bridges – Structural response: Arch-deck girder interaction

If an anti-funicular arch geometry is chosen, usually for permanent loads, arch bridges carry the corresponding loads efficiently.

However, non-anti-funicular loads need to be accounted for in design. Under such loads, the arch – arch rib, deck girder and spandrel columns or hangers – act as a frame system, whose behaviour depends on

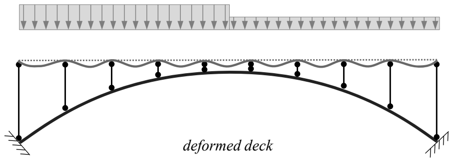
→ the stiffness ratio of arch rib and deck girder

→ the type of connection between arch rib and deck girder (clamped or pin-jointed spandrel columns resp. "hangers" – see notes)

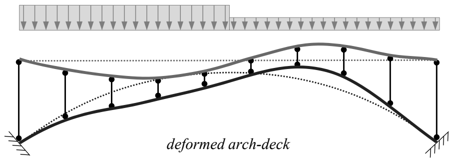
To better understand the behaviour, the bending moments in the frame system can be subdivided into two components:

- fixed system
- flexible system

fixed system



flexible system

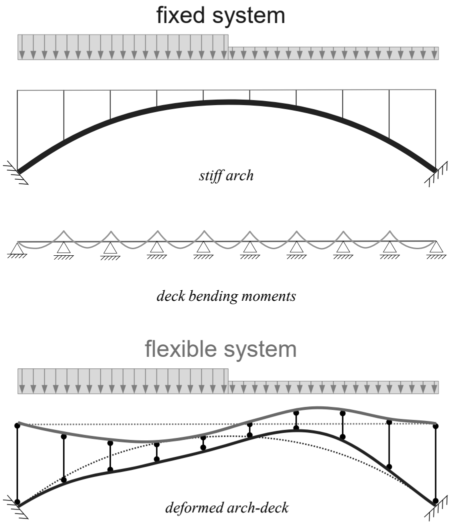


Note that in the case of steel hangers, their axial stiffness becomes relevant, in that the vertical deflection of the deck and arch are not exactly equal. While in the case of concrete spandrel columns this is not an issue. The effects of creep need to be considered in the latter case of course.

Arch bridges – Structural response: Arch-deck girder interaction

The following points have essentially been outlined in the *Design* section. Here, they are repeated and a case-study is presented to highlight some specific aspects.

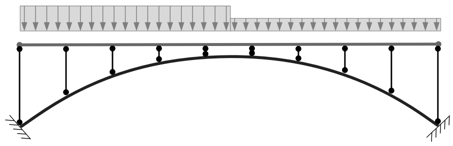
- fixed system
  → assume a perfectly rigid arch
  → bending moments in deck girder corresponding to those in a continuous beam (replacing spandrel columns by supports).
- flexible system
  → bending moments in the flexible system involve arch deflections due to non-anti-funicular loads
  → generally, these bending moments are shared by arch rib and deck girder in proportion to their bending stiffnesses
  → two ideal limiting cases can be considered:
    → *deck-stiffened arches (“versteifter Stabbogen”)*, where the entire flexible system moments are resisted by the deck girder (“Versteifungsträger”)
    → *stiff arches* resisting the entire flexible system moments alone



Arch bridges – Structural response: Arch-deck girder interaction

In this study, a clamped deck-arch bridge, with expansion joints of the deck above the arch abutments (intersection of springing line with arch axis) is considered (unlike Slide 63: deck continuous).

In the first part, pin-jointed spandrel columns are assumed.

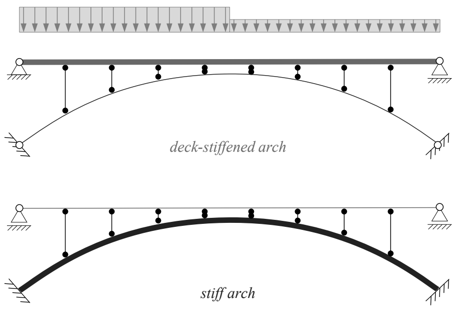


columns $\begin{cases} N \neq 0 \\ V = 0 \\ M = 0 \end{cases}$

Two limiting cases:

- deck-stiffened arch
  → flexural deck girder stiffness EI^D >> flexural arch rib stiffness EI^A
- stiff arch
  → flexural arch rib stiffness EI^A >> flexural deck girder stiffness EI^D

In these limiting cases, either the stiffening girder or the stiff arch resists (almost) the entire bending moments.



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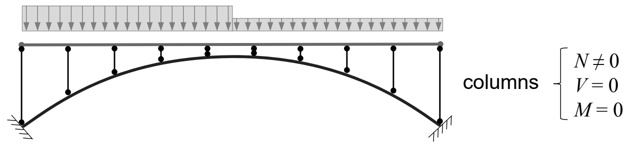

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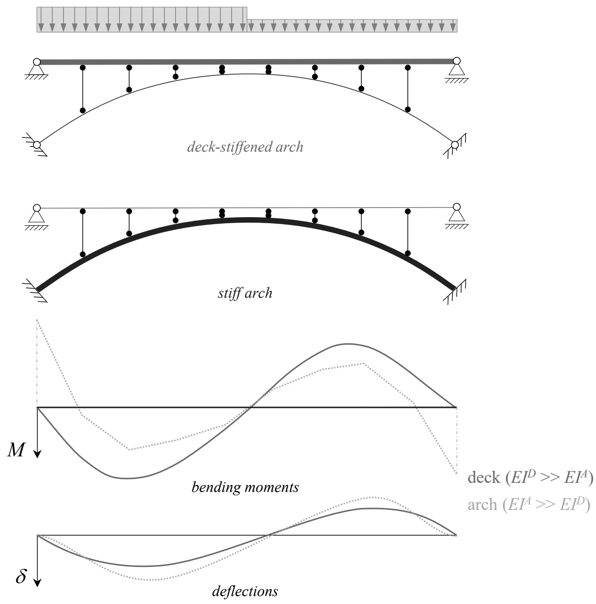

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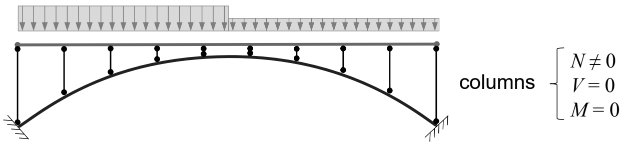

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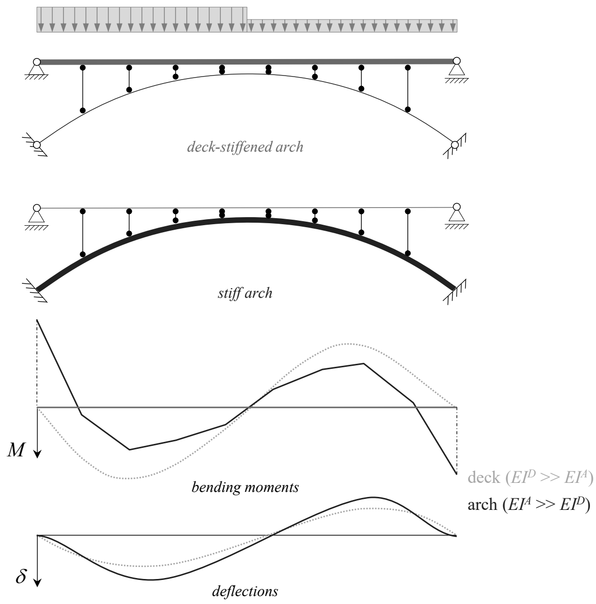

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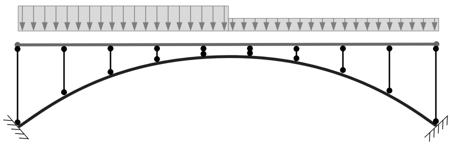


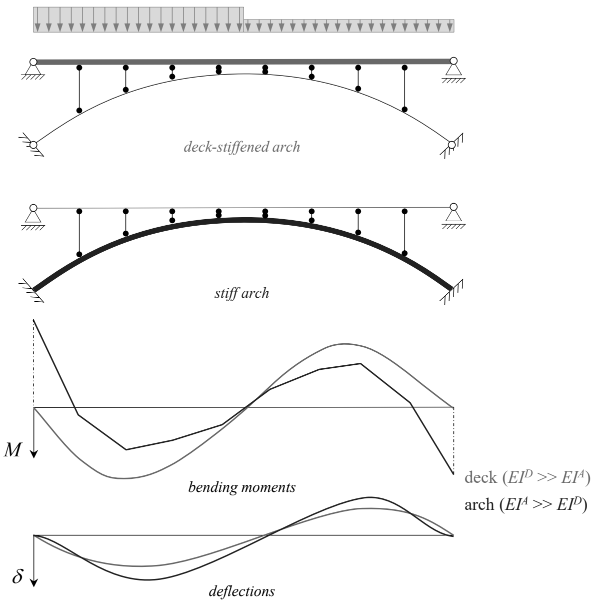
columns $\begin{cases} N \neq 0 \\ V = 0 \\ M = 0 \end{cases}$

Two limiting cases:

- deck-stiffened arch
  → flexural deck girder stiffness EI^D >> flexural arch rib stiffness EI^A
- stiff arch
  → flexural arch rib stiffness EI^A >> flexural deck girder stiffness EI^D

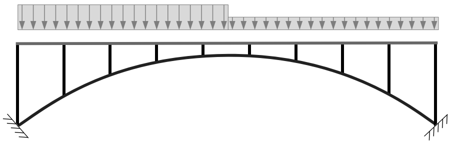
In these limiting cases, either the stiffening girder or the stiff arch resists (almost) the entire bending moments.

The differences of bending moments and deflections between arch rib and deck girder are due to the different support conditions assumed here (clamped vs. simply supported). In the design section (Slide 63), both are assumed to be continuous.



Arch bridges – Structural response: Arch-deck girder interaction

If the spandrel columns are clamped, rather than pin-jointed, arch rib and deck are not only coupled in terms of vertical deformations, but act as frame system.



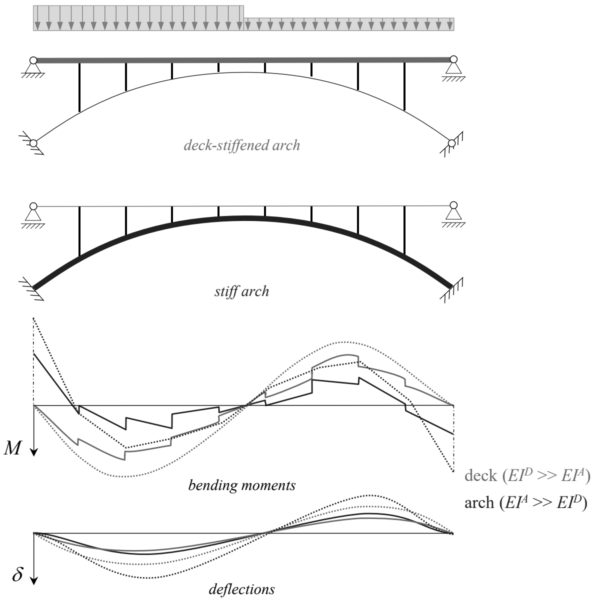
Clamped spandrel columns, together with deck girder and arch rib, act as Vierendeel girder

→ significantly stiffer than sum of deck girder and arch stiffness

→ deflections significantly reduced

The short clamped spandrel columns close to the crown have a high flexural stiffness and transfer the axial normal force from the arch rib to the deck.

In some cases, shear forces and bending moments in such spandrel columns may be excessive → (concrete) hinges may be provided to reduce these actions (e.g. Tamina bridge)



Arch bridges – Structural response: Arch support conditions / hinges

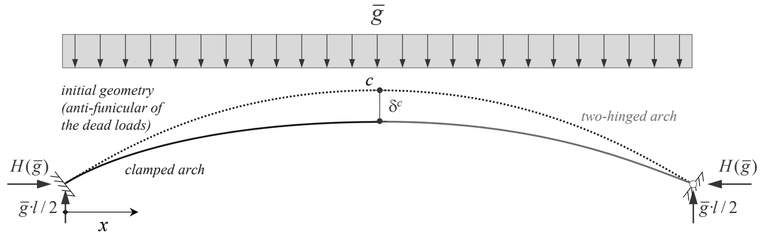
Effect of rise-to-span ratio $f\,/\,l$ on bending moments

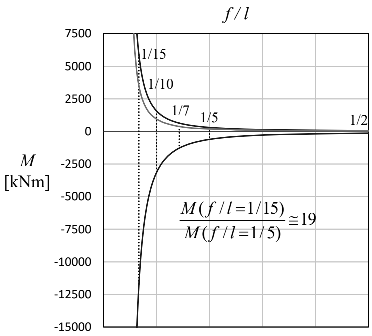
Here, a uniform permanent load g and a linear analysis is used. The arches considered are:

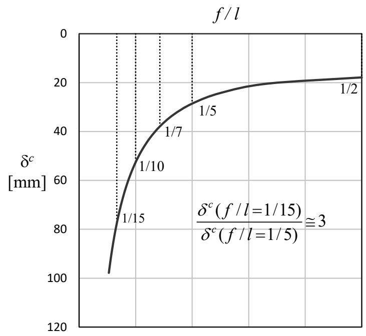
- two-hinged arch
- clamped arch

Using these assumptions and equations in the numerical example (l=100 m; h=1.20 m; DL = 140 kN/m), the following results are obtained (see graphs):

- The rise-span ratio $f\,/\,l$ is highly relevant, having a strong impact on structural behaviour, particularly for small values of $f\,/\,l$ (low arches)
- Bending moments increase exponentially with smaller values of $f\,/\,l$, particularly pronounced for $f\,/\,l$ < 1/10. For $f\,/\,l$ =1/15, bending moments are up to 15 times higher than for $f\,/\,l$ = 1/5.
- The crown displacement also grows progressively as $f\,/\,l$ decreases, especially for $f\,/\,l$ < 1/10
- Clamped and two-hinged arches show similar tendencies.







Arch bridges – Structural response: Arch support conditions / hinges

Effect of rise-to-span ratio $f\,/\,l$ on bending moments

Here, a uniform permanent load g and a linear analysis is used. The arches considered are:

- two-hinged arch
- clamped arch

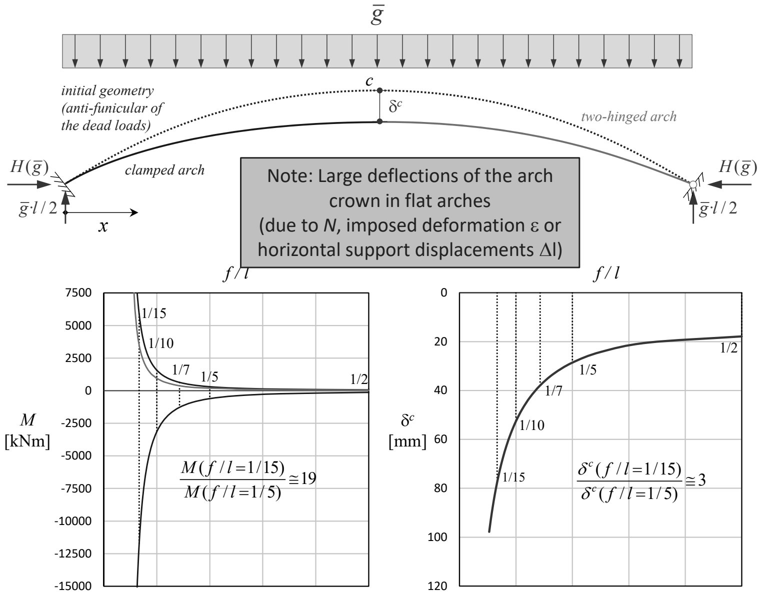
Note that similar results are obtained when the arches are subjected to horizontal displacements of the supports.

The resulting bending moments, for a low arch (rise-span ratio lower than 1/10), may exceed the moments produced by the gravity loads.

Conversely, the influence of imposed deformations are relatively small in arches which rise-span ratios > 1/7.

The numerical results correspond closely to the approximation (slide 55) for *EA*=const., i.e.

$\delta^c \cong \frac{H(\bar{g})}{EA^{A,c}} \cdot l \cdot \frac{1+3(f/l)^2}{4f/l}$ is a good approximation.



Arch bridges – Structural response: Arch support conditions / hinges

Permanent load + imposed deformation
1st and 2nd order analysis

- reinforced concrete
- three-hinged arches → two-hinged arches
- central span: 72.5 m
- f / l = 1 / 15


Le Veurdre bridge, France, 1910. Eugène Freyssinet

Le Veurdre bridge (1910), designed and built by Eugène Freyssinet, consists of 3 three-hinged arches with a central span of 72.5 m, and an extraordinary slenderness of *f/l*=1/15.

Due to the high slenderness of the arch, the deflection at the crown already amounted to 13 cm (l/550) in the year of its inauguration and kept increasing continuously. This observation was essential to the discovery of creep in concrete (or the recognition of its existence, which had been denied by academics “believing” in elasticity initially). Freyssinet solved the problem in the Veurdre bridge by opening the arches in the crown by means of jacks and subsequently eliminating the hinges at the crown by grouting them. He had used jacks in the crown as early as 1907 for de-centring a small arch bridge (span 26 m) at Prairéal-sur-Bresbre, not far from the Veurdre bridge.

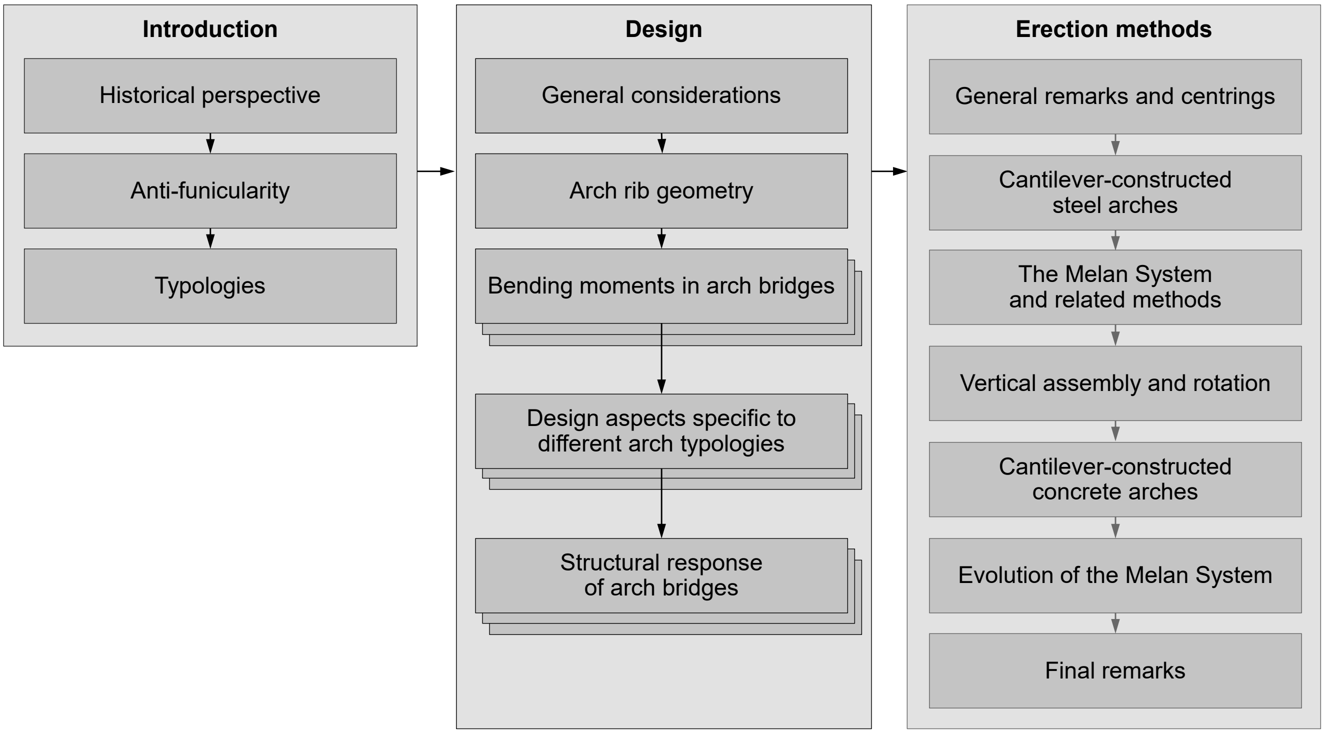
If this bridge had been built with two-hinged arches instead of three hinges per arch, the creep deformations would have been more difficult to discover. When Maillart designed and built three-hinged arch bridges, he extended the arch-deck connection until approximately to a quarter of the span to get more stiffness in the zones where the bending moments due to vertical displacements are significant.

The Veurdre bridge was unfortunately destroyed in World War II.

Photo: left: https://www.ce.jhu.edu/perspectives/protected/ids/Buildings/Le%20Veurdre%20Bridge/; right: A. Hilaire, Étude des déformations différées des bétons en compression et en traction, du jeune au long terme : application aux enceintes de confinement, 2014.

Arch bridges

Erection methods


Introduction
Historical perspective
Anti-funicularity
Typologies
Design
General considerations
Arch rib geometry
Bending moments in arch bridges
Design aspects specific to different arch typologies
Structural response of arch bridges
Erection methods
General remarks and centrings
Cantilever-constructed steel arches
The Melan System and related methods
Vertical assembly and rotation
Cantilever-constructed concrete arches
Evolution of the Melan System
Final remarks

Arch bridges

Erection methods – General remarks and centrings

Arch bridges – Erection methods: General remarks and centrings

High relevance of erection method in arch bridges

- The construction process is an essential part of the conceptual design of any bridge
- While arches are very efficient structures in the final configuration
  - → the efficient arch action is only activated once the arch is able to transfer the arch thrust, i.e., after closure (Bogenschluss)
  - → the load transfer during construction differs strongly from that in the final configuration, undermining economy (see Conceptual Design)
  - → the construction process is particularly relevant for the economy of arch bridges

Gmündertobel Bridge, Switzerland, 1908, Emil Mörsch

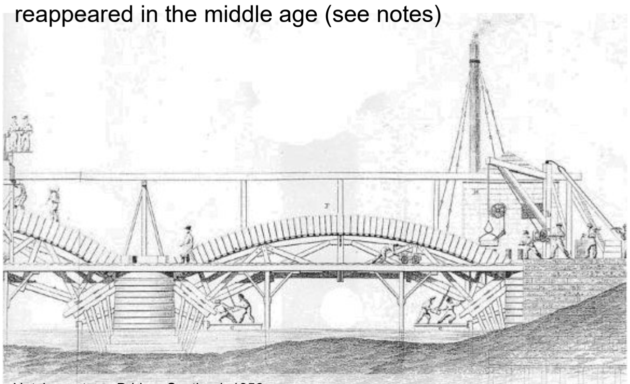
Photo: Falsework / centring of the Gmündertobelbrücke, Stein-Teufen AR, Switzerland, Emil Mörsch (1908). clamped arch, span 79 m, f/L = 1/3. One of the first major reinforced concrete arch bridges without hinges. Photos © www.e-pics.ethz.ch

Arch bridges – Erection methods: General remarks and centrings

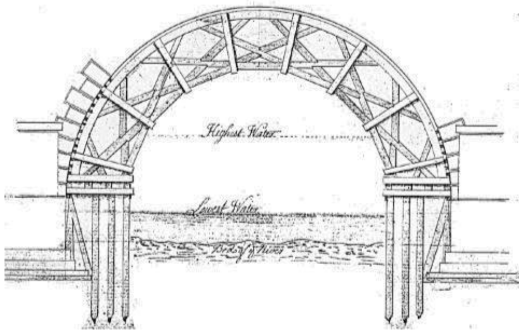
Stone arches

- For centuries, stone arches have been erected on timber centrings (= arch or dome falsework)
- Information on Roman arch bridges, and more so their centrings, is scarce (Vitruvius gives some information)
- The practice of building stone bridges died out in Europe with the collapse of the Roman empire and only reappeared in the middle age (see notes)

First Westminster Bridge, England, 1750, Charles Leblye



Hutchesontown Bridge, Scotland, 1856



Illustrations on right side: First Westminster Bridge, Swiss Engineer Charles Lebelye, 15 spans of ca. 17 m (1750, replaced 1862). Painting by Canaletto (with the Lord Mayor's Procession on the Thames), 1747. Drawing of James King’s centring for an arch of Westminster Bridge (1739). Left side: Decentering of Hutchesontown Bridge in Glasgow (1856).

Painting © Yale Center for British Art. Illustrations Taken from Peter Cross-Ruskin, “Centres for Large Span Masonry Arch Bridges in Britain to 1833”, 2nd International Congress on Construction History, Queens' College, Cambridge University, 2006.

Quotation from Cross-Rudkin: *Arch bridges have been built in Britain possibly from Roman times, when some significant structures along Hadrian's Wall are suggested (Bidwell & Holbrook 1989). Engineering drawings of these early structures do not survive, though the ten volumes on architecture by Marcus Vitruvius (translated into French by Fleury and English by Morgan) contain descriptions of bridgeworks. By definition, the temporary works have been removed, so apart from the information given in Vitruvius it is only possible to suggest construction techniques by detailed study of the remaining bridges themselves. […] It is not clear why the practice of building stone bridges died out in Europe with the collapse of the Roman Empire, or why they should have reappeared in several countries at more or less the same time. […] In Britain this renaissance dates from at least the late 11th century (Harrison 2004, p. 110). Almost all of the 'vernacular' bridges of the midlands and south of England over the next 600 years are of moderate span, the first one having a span in excess of 50 feet being built at Lewes in 1727. However in the north of England structures of this span appear from the 1350s and in Scotland a century later. By the middle of the 16th century a few spans had reached 100 feet, as much as any remaining Roman bridge. From then to 1738 only the Great Bridge at Blenheim and the Causey Arch in County Durham were of similar span. In the next 110 years only 22 bridges with spans greater than 100 feet were built, but the largest, Grosvenor Bridge at Chester (built in 1827-33), spanned 200 feet and was for thirty years the largest in the world.*

Arch bridges – Erection methods: General remarks and centrings

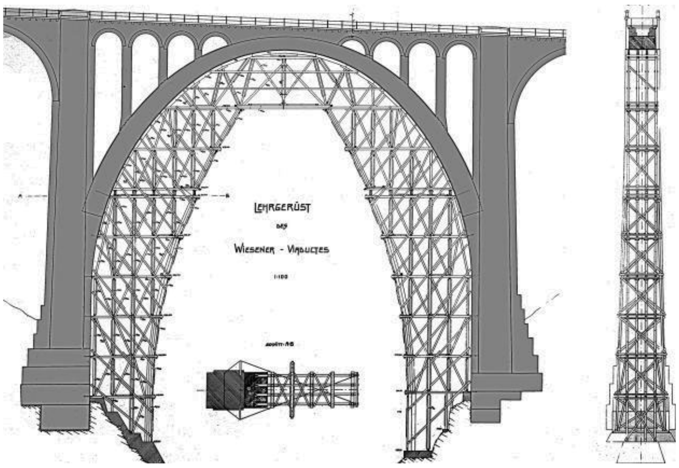
Pflanzgarten Viaduct in construction, Switzerland, 1908

Photo: Construction of the Pflanzgarten Viaduct (RhB Line Wiesen-Filisur), 1908. Photo © Archiv RhB.

Note the symmetrical erection of the arch rib (gaps near the quarter points closed last).

Arch bridges – Erection methods: General remarks and centrings

- Though inherently inefficient for larges spans (see previous slides), this method was used for the first concrete arch bridges, that were indeed “concrete stone” arch bridges, using concrete as inexpensive stone surrogate.



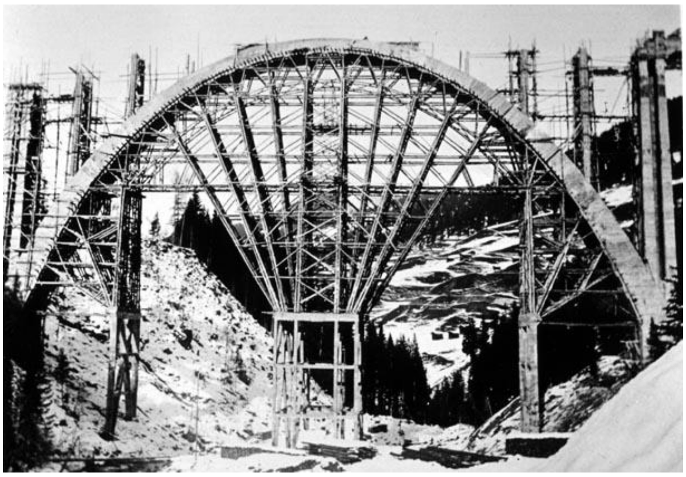
l = 55 m
f / l = 1 / 1.6
Wiesener Viaduct, Switzerland, 1909, F. Hennings / Froté Westermann & Cie

Photos: Wiesener Viadukt, Rhätische Bahn, F. Hennings / Froté Westermann & Cie (1909). Concrete stone deck arch railway bridge. Length 210 m, arch span 55 m, height 62 m. Centring by Richard Coray.

Photo of bridge © www.bahnbilder.ch, David Gubler / Photo and illustration of falsework © www.e-pics.ethz.ch.

Arch bridges – Erection methods: General remarks and centrings

- Centrings, often using timber, were also used for the first reinforced concrete arch bridges.
- In many cases, the falsework was as attractive, if not even more appealing, than the final structure



Langwieser Viaduct, Switzerland, 1914, H. Schürch / Ed. Züblin & Cie

Photos: Langwieser Viadukt, Rhätische Bahn, H. Schürch / Ed. Züblin & Cie. (1914). First major reinforced concrete railway bridge. Length 284 m, deck arch, span 100 m, height 62 m. Centring by Richard Coray.

Arch bridges – Erection methods: General remarks and centrings

- Timber centrings can also be used for arch bridges crossing water. They can be assembled on shore (where the centring can easily be supported) and then floated in as tied arch.
- The most prominent example is Freyssinet's Pont de Plougastel (Pont Albert-Louppe) crossing the bay of Brest, see photos.
- "Wind deviation" devices (see photo below) were mounted on Freyssinet's iconic bridge after the construction of a modern cable-stayed bridge nearby, to protect the latter from turbulence – a disgrace.

Plougastel Bridge, France, 1930, Eugène Freyssinet

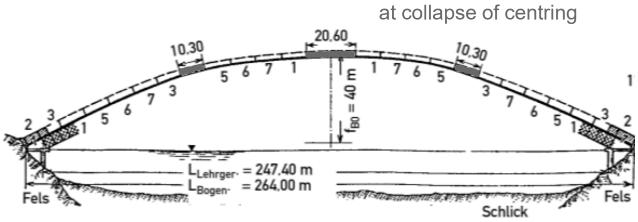
Photos: Pont de Plougastel (Pont Albert-Louppe), Bretagne, Eugène Freyssinet (1930). Three arches with 186 m span each, total length 888 m. Falsework floated in, used three times for the three deck arches that were cast sequentially.

Photos: Floating in of the falsework for the Pont Albert-Louppe, Plougastel, Bretagne, 1929 copied from W. Lorenz „Brücken und Brückenbauer – Haltungen zum Konstruieren, Jahrbuch 1998 der Braunschweigischen Wissenschaftlichen Gesellschaft, p. 105-132. Finished bridge © Wikipedis

Arch bridges – Erection methods: General remarks and centrings

- Large-span timber falsework arches need to be designed and detailed as meticulously as final structures.
- While there were no problems in the Plougastel bridge, the similar falsework of the Sandö Bridge – though with a substantially longer span (record concrete arch span at the time) – collapsed on the 31.8.1939. Eighteen construction workers died.
- The bridge was then finally built on a massive falsework with intermediate shoring.

missing parts of arch slab
at collapse of centring



Photos: Sandö Bridge across Ångermanälven river, Lunde-Sandö, Sweden (1943). Deck arch. span 264 m (record concrete arch span at the time), f/L = 1/6.3, total length 810 m. Falsework collapsed in 1939 (potential failure cause: lateral buckling of nailed timber flanges).

Photos and illustrations: Falsework illustration and photo of first falswork adapted from M. Herzog, „Der Einsturz des hölzernen Lehrgerüstbogens der Sandöbrücke im Rückblick,“ Bautechnik 75, Heft 7, 1998, pp. 450. Second falsework © Björn Åesson, Understanding Bridge Collapses. Finished bridge © keibr, Wikimedia Commons.

Arch bridges – Erection methods: General remarks and centrings

- The Gladesville Bridge in Sydney (main span 305) succeeded The Sandö Bride in 1964 as longest span concrete arch bridge.
- While looking similar, the Gladesville Bridge is more slender and featured several innovative construction methods, with a high degree of prefabrication, resulting in a highly efficient construction process (see notes).
- The bridge was designed mainly by T. Gee, a young British engineer (born 1934), and was the last major project in which E. Freyssinet was personally involved.

Gladesville Bridge , Sydney, Australia, T. Gee (Maunsell) / E. Freyssinet

Gladesville Bridge across Parramatta river, Sydney, Australia (1964). Deck arch, span 305 m (record concrete arch span at the time), f/L = 1/7.4, total length 579 m. Design by Tony Gee, Maunsell & Partners, with consulting by Eugène Freyssinet.

Highly efficient construction process using precast segmental box elements (floated in, lifted to the arch crown and lowered into position on rails along the arch falsework, which was supported on piles). The same falsework was used for the four parallel arch ribs. Each arch rib was lifted off the formwork after completion by means of inflatable gaskets (hydraulic flat jacks subsequently injected with cementitious grout), such that the falsework could be launched transversely and used for erecting the next arch rib. The four arch ribs were finally connected by transverse prestressing. Prefabricated elements were also used for the piers, the spandrel columns and the deck (multi-girder open cross-section).

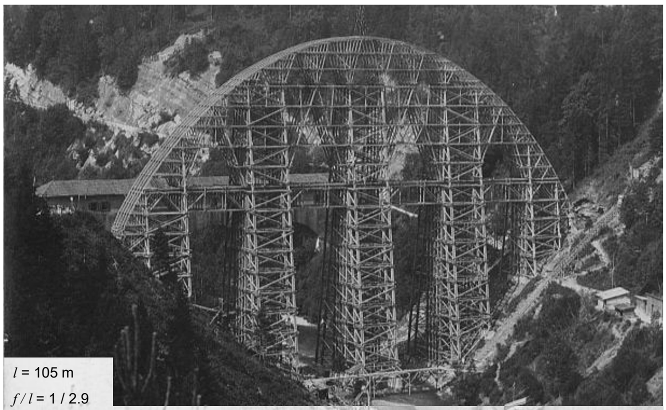
Photos: Construction stages © Transport for NSW see link below. Finished bridge: kfm, 2022.

Further reading and historic video of bridge construction:

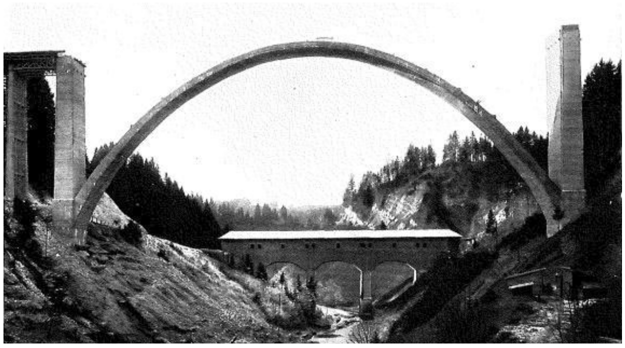
https://roads-waterways.transport.nsw.gov.au/about/environment/protecting-heritage/gladesville-bridge-50th-anniversary.html#Photogallery

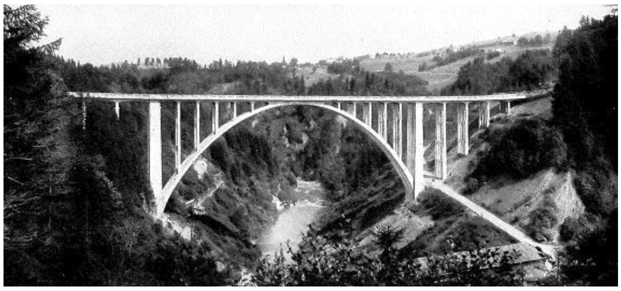
Arch bridges – Erection methods: General remarks and centrings

- Most of the prominent early concrete arch bridges were built using remarkable timber centrings.
- This and the following slides show three further extraordinary Swiss examples (Hundwilertobel Bridge, Salginatobel Bridge, Gueroz Bridge).



Hundwilertobel Bridge, Switzerland, 1925, A. Schläpfer, Ed. Züblin & Cie



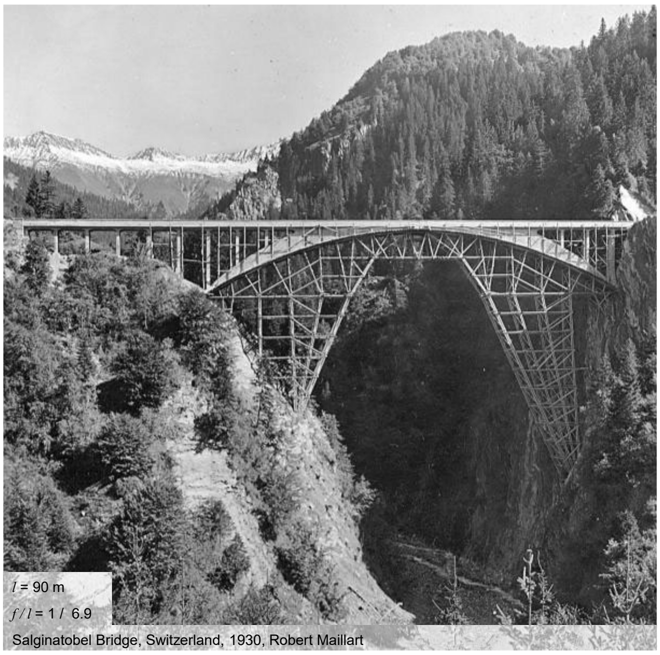


Photos: Hundwilertobelbrücke, A. Schläpfer, Ed. Züblin & Cie 1925, replaced 1992). Reinforced concrete deck arch bridge, arch span 105 m (3rd longest concrete arch span workdwide at time of erection), f/L = 1/2.9, 74 m above ground.

Photo of centring, left side © www.e-pics.ethz.ch. Photos of arch and bridge taken from M. Ros, Versuche und Erfahrungen an ausgeführten Eisenbeton-Bauwerken in der Schweiz, EMPA Bericht No. 99, Beilage zum XXVI. Jahresbericht des Vereins schweizerischer Zement-, Kalk- und Gips-Fabrikanten, 1937.

Arch bridges – Erection methods: General remarks and centrings

- These centrings were already expensive at the time, but still competitive with other construction methods due to the relatively low labour cost compared to materials, particularly steel.
- Richard Coray designed many of these centrings, whose erection was often challenging.



Salginatobel Bridge, Switzerland, 1930, Robert Maillart

Photos: Salginatobelbrücke, Robert Maillart (1930). Reinforced concrete deck arch bridge, span 133 m. Centring by Richard Coray.

Photos https://www.atlasofplaces.com/architecture/salginatobelbruecke/

Arch bridges – Erection methods: General remarks and centrings

- Centrings remained the preferred construction method of many designers for reinforced concrete arches until the 1940s, although alternative erection methods existed already (Melan system, see behind).
  - → Consequently, only few reinforced concrete arches with spans above 80, and only a handful above 100 m were built (see notes).

Gueuroz Bridge, Switzerland, 1934, Alexandre Sarrasin

Photos: Pont de Gueuroz, Vernayaz, Alexandre Sarrasin (1934). Reinforced concrete deck arch bridge, span 99 m. Centring by Richard Coray.

According to Heinrich Spangenberg (H. Spangenberg, «Weitgespannte Wölbbrücken», Report of the 2nd International Congress for Bridge- and Structural Engineering, 1929, International de Construction des Ponts et Charpentes, only 35 reinforced concrete arches with spans above 80 m, and as few as seven with spans above 100 m existed worldwide in 1929, in chronological order:

	Bridge	Span	*f / L*
-	Tiber Bridge, Rome (1911)	100.0 m	1 / 10 (!)
-	Langwieser Viadukt, Chur-Arosa (1914)	100.0 m	1 / 2.38
-	Cappelen Bridge, Minneapolis (1923)	121.9 m	1 / 4.45
-	Seine Bridge, St. Pierre-du-Vauvray (1923)	131.8 m	1 / 5.27
-	Hundwilertobel Bridge, Appenzell (1925)	105.0 m	1 / 2.92
-	Tweed Bridge, Berwick UK (1928)	110.0 m	1 / 7.92
-	Caille Bridge, Cruseilles (1928)	139.8 m	1 / 5.2

Arch bridges – Erection methods: General remarks and centrings

- Economy remained a problem of concrete arches cast on centrings, despite progress in construction and analysis methods such as casting of the arches in rings (similar to the erection of stone arches in rings, e.g. in the Soliser Viadukt).
- In the Tara bridge (aka Đurđevića-Tara Bridge), the arch was cast in three rings, enabling a lighter centring (centring by R. Coray).

Tara Bridge, Montenegro, 1940, Mijat S. Trojanović

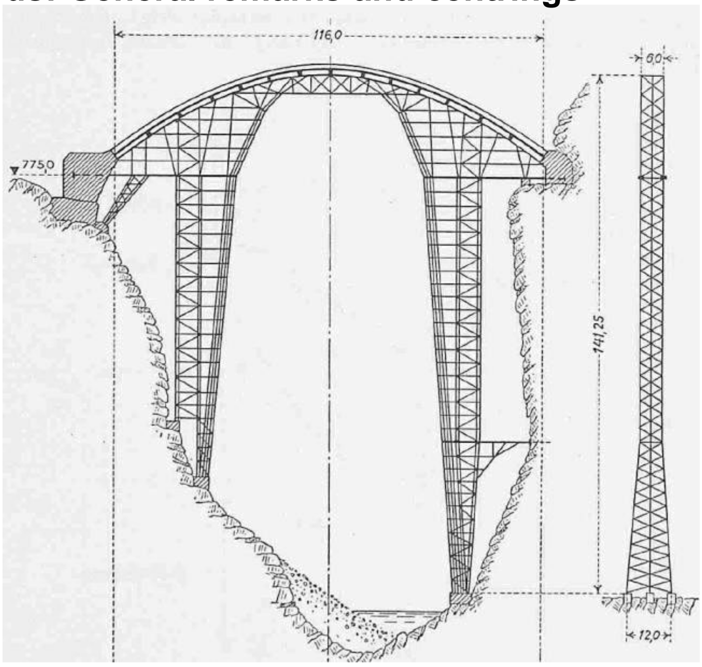


Illustration and photo: Tara Bridge (aka Đurđevića-Tara Bridge), Žabljak, Yugoslavia (now Montenegro), Mijat S. Trojanović (1940). Concrete arch, main span 116 m, 140 m above ground. Falsework by R. Coray.

Drawing: © R. Coray, “Vom Bau der Strassenbrücke über die Tara in Jugoslavien,“*Schweizerische Bauzeitung,* Band 117/118, 1941, pp. 260-261

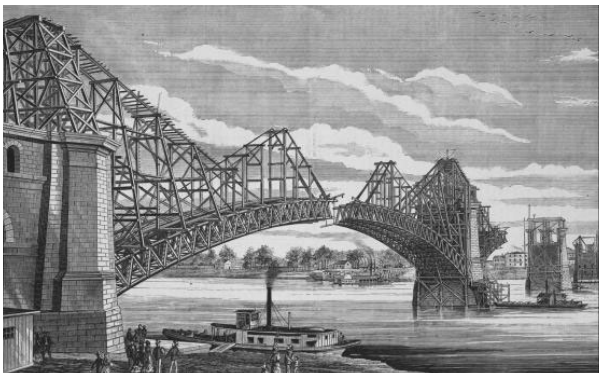
Photo © M. Durcatova, Shutterstock

Arch bridges

Erection methods – Cantilever-constructed steel arches

Arch bridges – Erection methods: Cantilever-constructed steel arches

- On the other hand, for almost 150 years, steel truss arch bridges have been built by cantilevering, either with or without temporary supports or stays.
- Typically, they were designed as two- or three-hinged arches to minimise restraint
- The first, prominent example is the Eads Bridge across the Mississippi, built by cantilevering (with temporary towers and stays) as early as 1874, with three spans above 150 m.



Eads Bridge, USA, 1874, James Eads

Illustration and photo: Eads Bridge across Mississippi, St. Louis – East St. Louis, James Eads (1874). First cantilever constructed iron/steel truss deck arch bridge (with temporary towers and stays), main spans 153.1+158.6+153.1 m (502+520+502 ft, record arch span at the time), width 14 m. Subway train First pneumatic caisson foundation in the U.S.

Illustration: © Linda Hall Library od Science, Engineering and Technology, reproduced in J. Talbot: The Eads Bridge A Revolution in Engineering. Modern Steel Construction, AISC, March 2011. Photo: © kbh3rd, Wikimedia Commons

Arch bridges – Erection methods: Cantilever-constructed steel arches

- In truss arches built by cantilevering without backstays, the arch abutment is clamped during construction, and only free to rotate after closure of the arch. Hence, the upper truss chords
  - are fully utilised in construction (tension chords)
  - receive little load in the final configuration (they primarily help stabilizing the arch from buckling)
- This is most obvious at the bridge ends, where forces during cantilevering are highest, but once the arch is closed, the top chords are virtually (completely in two- or three-hinged arches) stress free
  → such arches are inherently uneconomical and, in this respect, lack logic of form.
- Using temporary towers and stays during cantilevering as in the Garabit Viaduct, the arch can be hinged at its abutments from the beginning, yielding a much more consistent design in the final configuration.

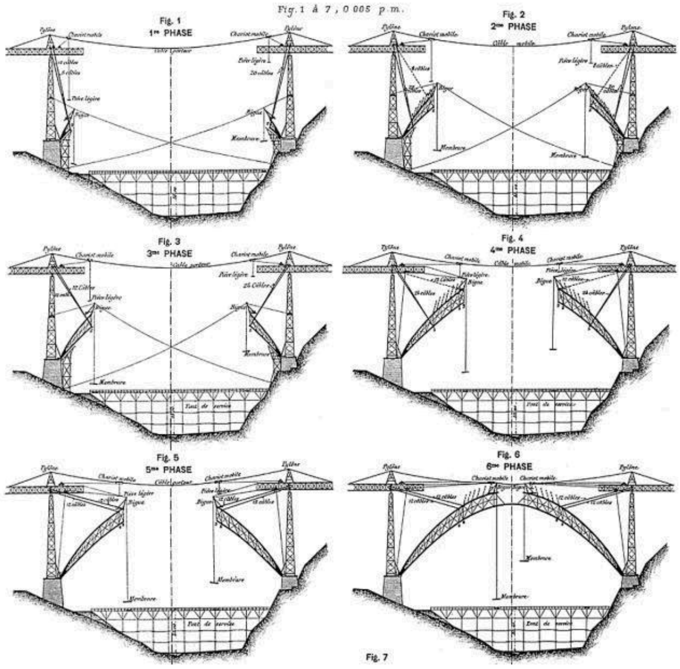
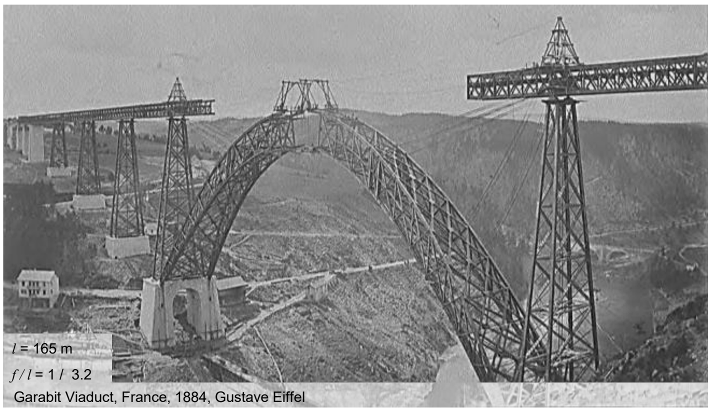


Illustration: Erection of the Garabit Viaduct, Gustave Eiffel (1884). Steel truss deck arch, main span 165 m, total length 565 m, 122 m above ground.

Illustration © Gustave Eiffel, Mémoire sur le Viaduc de Garabit, Paris: Librairie Polytechnique, Baudry et Cie, Editeurs, 1889 (taken from K.E. Kurrer: Geschichte der Baustatik. 2. Auflage, Ernst&Sohn, 2016).

Arch bridges – Erection methods: Cantilever-constructed steel arches

- If the arch abutments are hinged from the beginning of construction, the structural safety during erection fully relies on the temporary towers and stays
- While this appears more economical, it is certainly less robust. In the following years, steel truss arches were thus frequently cantilevered starting with a clamped arch (converted to a hinge after closure) combined with temporary towers and stays.



Garabit Viaduct, France, 1884, Gustave Eiffel

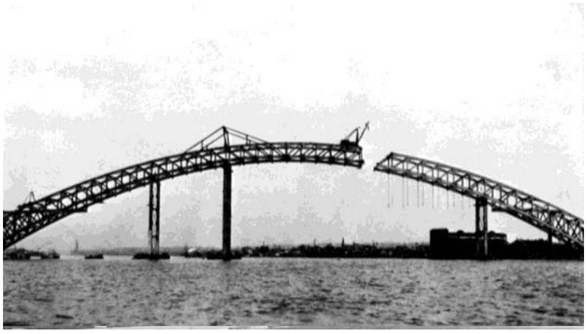
LE VIADUC DE GARABIT.

Illustration: Erection of the Garabit Viaduct, Gustave Eiffel (1884). Steel truss deck arch, main span 165 m, total length 565 m, 122 m above ground.

Photo of finished bridge © Patrick Giraud, Wikimedia Commons. left side © Gallicia digital library, Erection process photo right side © G. Eiffel, Notice sur le Viaduc du Garabit (près Saint-Flour, ligne de Marvejols a Neussargues), Imprimérie administrative & des chemins de fer de Paul Dupont, 1888

Arch bridges – Erection methods: Cantilever-constructed steel arches

- Among the many cantilever-constructed truss arch bridges worldwide, there are several iconic structures.
- The Bayonne Bridge, across the Kill van Kull strait, designed by Swiss engineer Othmar Ammann and his team, set a new arch span record of 511 m when it opened in 1930 (top right photo), that held until 1977.
- In order to increase navigational clearance, the deck was raised by about 20 m in 2017, under full traffic during construction – an extraordinary achievement (bottom photos)



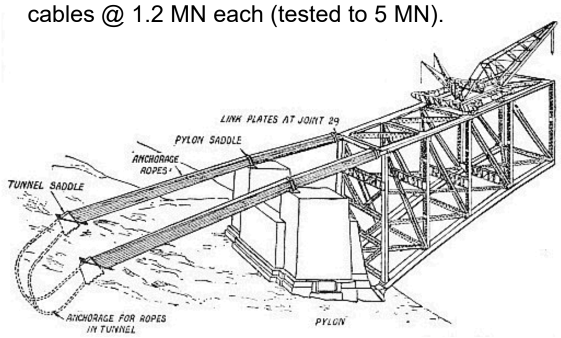
Bayonne Bridge, USA, 1931, Othmar Ammann

Photos: Bayonne Bridge, Staten Island, Othmar Ammann (1931). Cantilever constructed (with temporary piers) two-hinge steel truss through arch, arch span 511 m (record arch span at the time, currently the 5th longest arch bridge in the world), width 30.5 m, total height 99 m. Deck raised by ca. 20 m in 2017 to increase navigational clearance, construction under traffic.

© top photo Jim.Henderson, wikimedia commons. © double deck Arnold Reinhold, wikimedia commons, © construction 1931 Americanbridge.net

Arch bridges – Erection methods: Cantilever-constructed steel arches

- The Sydney Harbour Bridge, with a slightly smaller span of 503 m, is another, perhaps even more iconic steel truss arch bridge.
- While temporary supports in the Kill van Kulll were used in the former, the Sydney Harbour Bridge was built by cantilevering without temporary towers nor stays.
- In turn, massive temporary steel support cables running in tunnels were used during construction (128 cables @ 1.2 MN each (tested to 5 MN).



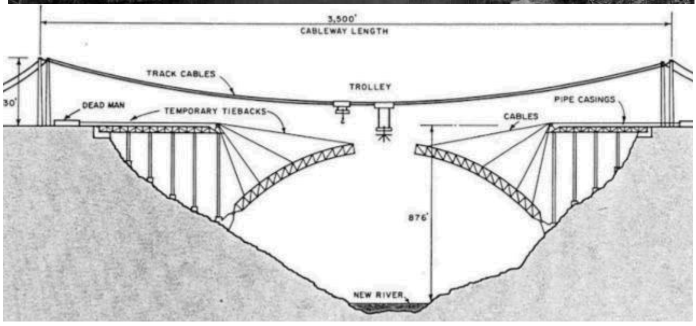
Sydney Harbour Bridge, Australia, 1932, R. Freeman (Sir Douglas Fox and Partners) / Dorman, Long & Co / Sir John Burnet and Partner

Photos: Sydney Harbour Bridge, R. Freeman (Sir Douglas Fox and Partners) / Dorman, Long & Co / Sir John Burnet and Partner, (1932). Cantilever constructed two-hinge steel truss through arch, arch span 503 m (currently still the 7th longest arch bridge in the world), width 49 m, total height 134 m.

Photo on left side (support cables): © https://railwaywondersoftheworld.com/sydney-harbour.html and https://sydney-harbour-bridge.nesa.nsw.edu.au/engineering-studies/support-cables.php. (information on cable forces). Photos on right side: top © National Museum Australia. bottom © Wikipedia.

Arch bridges – Erection methods: Cantilever-constructed steel arches

- The New River Gorge Bridge, West Virginia, set a new arch span record (518 m) in 1977, that held until 2012.
- While the Bayonne Bridge and the Sydney Harbour Bridge are through arches – though the full arch thrust is resisted by the foundations –, the New River Gorge Bridge is a deck arch.
- This enabled using stays extending from the deck above the abutment (figure), similar as in the Garabit viaduct, and building the arch hinged at abutments.
- Other than in Garabit, the arch segments were transported via a cableway system (Seilkran).



New River Gorge Bridge, USA, 1977, C. Knudsen, American Bridge Co

Photos: New River Gorge Bridge, Fayetteville, West Virginia, C. Knudsen, American Bridge Co. (1977). Cantilever constructed two-hinge weathering steel truss deck arch, arch span 518.2 m, total height 174 m.

Photos and illustrations: bottom © National Park Service. Top Wikipedia.

Arch bridges – Erection methods: Cantilever-constructed steel arches

- Steel truss arches are still being built today, see e.g. the bridge illustrated on this slide (New Burro Creek Bridge, 2007), cantilevered using temporary diagonals similar as in recent concrete arches, see behind).
- However, mainly due to the relatively high cost of steel as a compression member, they have become less competitive compared to other typologies:
  - → Cable-stayed bridges are more economical than tied or through arches in most cases, particularly for very large spans
  - → Concrete arch bridges have become more economical for medium-large spans by the development of erection methods that are much more efficient than centrings
  - → Recently, steel-concrete arch bridges have become economical for even longer spans and are frequently used, particularly in China

New Burro Creek Canyon Bridge, USA, 2006, Arizona Department of Transportation Bridge Group

Illustration and photo: New Burro Creek Canyon Bridge, Arizona Department of Transportation (2006). Weathering steel truss deck arch, main span 219 m. Cantilever construction using temporary diagonals and ties at deck level.

Top photo © AISC / NSBA. Bottom Photo © Eric Sakovski, highestbridges.com

Arch bridges

Erection methods – The Melan System and related methods

Arch bridges – Erection methods: The Melan System and related methods

- The erection of efficient arch bridges can be greatly facilitated by the combined use of steel and concrete.
- Already in 1892, Josef Melan patented his Melan System, which used steel profiles as "rigid reinforcement" – essentially a composite construction system (see notes). Applying this system to arch bridges consists of the following:
  - → erecting a steel arch (steel truss, bracings provided to ensure stability against buckling)
  - → fixing a (timber) formwork to the steel arch
  - → casting the concrete around the steel profiles
- Melan himself did not design many structures, and many engineers at the time had concerns about the combined action of steel profiles and concrete. Composite action was not well understood, and shear connectors unknown.
- Heinrich Spangenberg resolved the concerns regarding different stress states in steel and concrete by ballasting the steel arch with gravel and removing the latter in the sections where the concrete was cast (System Melan-Spangenberg).
- The Echelsbacher Brücke (illustrations) was the longest span arch built using this system.

Echelsbacher Bridge, Germany, 1930, Heinrich Spangenberg

Josef Melan, Professor in Brno, Vienna and Prague, was the father of Ernst Melan (known e.g through his work on initial stress states, concluding that determining the stress state in a structure is useless). The Melan System was competing with Hennebique's system and others at the time, but rather than reinforcing bars as the Hennebique System, used steel profiles as "rigid reinforcement". While the system was primarily intended for floor slabs, it could also be used for bridges.

Photos: Echelsbacher Brücke, Ammerschlucht, H. Spangenberg, Germany (1930). Melan-Spangenberg system arch, span 130 m. © © F. Düll, R. Gerhardt, „Die Echelsbacher Brücke," Ernst&Sohn, Berlin, 1931 (top copied from H. Eggemann, K.-E. Kurrer, "On the International Propagation of the Melan Arch System since 1892", 3rd International Congress on Construction History, 2009, bottom from K. Goj, M. Hennecke, "Restoration of the Echelsbacher Bridge in Germany," *Engineering History and Heritage*, Vol.170, Issue EH3, pp. 152-161).

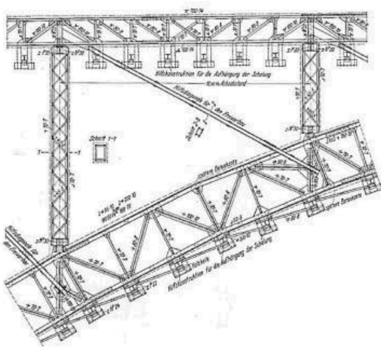
The Echelsbacher Bridge was replaced by a new concrete arch bridge in 2017-2021, maintaining the historic arch (construction heritage) yer without any load-bearing function apart from carrying its own weight.

Animated photos © Dr. Schütz Ingenieure (https://drschuetz-ingenieure.de/main/showproject.php?&id=122&subid=122&proj_id=3232&gruppe=Br%C3%BCckenbau)

Arch bridges – Erection methods: The Melan System and related methods

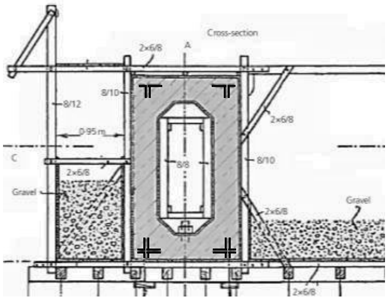
- However, the Melan-Spangenberg system complicated erection and undermined the economical advantages of the Melan System
  - → many, if not most "Melan arch bridges" were built using conventional falsework
  - → Often, Melan System trusses were supported on towers / shoring, see photos of Pont des Planches

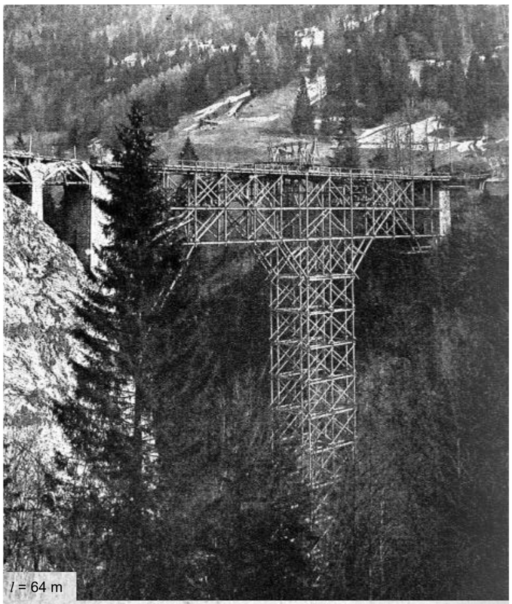
Echelsbacher Brücke: Steel truss



Echelsbacher Brücke: Arch section and formwork

yellow: steel truss / blue: gravel





Planches Bridge, Switzerland, 1913, Louis-François de Vallière

Photo: Pont des Planches, Grande Eau, Vaud, L.F. de Vallière (1913). Melan system deck arch bridge, span 63.6m, height 60 m. Built using timber falsework (the latter re-used for the Pont du Vanel 5 km downstream).

Photo © M. Ros, Der Bau von Gerüsten und Hochbauten aus Holz in der Schweiz, Beilage zum Diskussionsbericht Nr. 5 der EMPA «SIA Normen für Holzbauten», 1925

Illustrations: Echelsbacher Brücke, Ammerschlucht, H. Spangenberg, Germany (1930). Melan-Spangenberg system arch, span 130 m.

© F. Düll, R. Gerhardt, „Die Echelsbacher Brücke," Ernst&Sohn, Berlin, 1931 (copied from K. Goj, M. Hennecke, "Restoration of the Echelsbacher Bridge in Germany," *Engineering History and Heritage*, Vol.170, Issue EH3, pp. 152-161).

Animated photo ©

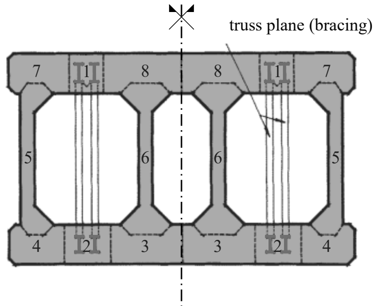
Arch bridges – Erection methods: The Melan System and related methods

- The Spanish engineer and entrepreneur José Eugenio Ribera optimised the Melan System (double trusses providing more stiffness) and patented the modified system himself in 1902.
- Ribera was very successful with this system in Spain, building several hundred bridges his patent.
- Fritz von Emperger, a scholar of Melan, was similarly successive with the original Melan System in the U.S. (Melan Arch. Constr. Company).
- The Melan-Ribera System was refined to perfection by Eduardo Torroja in the Viaducto Martín Gil (Río Esla, embalse de Ricobayo), by subdividing the concrete section in several parts, successively increasing the strength and adding more weight. This way, the arch with 210 m span could be built using a surprisingly light steel truss (less than 500 kg/m, according to L.M. Viartola, for the 4.5 m deep concrete arch, see notes).

Martín Gil Viaduct, Spain, 1942, Martin Gil / Eduardo Torroja

Arch section

(casting sequence)



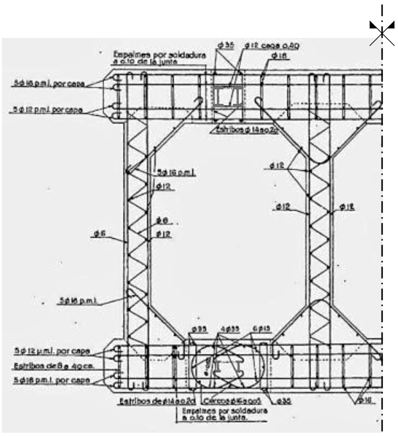
Ilustration and photo: Viaducto Martín Gil, Embalse de Ricobayo (río Esla), Zamora, Spain, Martin Gil y Eduardo Torroja (1942). Railway viaduct with arch main span, total length 479 m, deck arch, span 209.8 m, f/L = 1/3.3. Construction of the reinforced concrete arch designed by M. Gil was interrupted due to the Spanish civil war. E. Torroja took over the Project after the war, changing the arch design and erection method to the Ribera System, essentially corresponding to the Melan System). World's longest concrete arch bridge at time of completion.

Photo © Luis Cortés Zacarías, Wikimedia commons. Illustration adopted from Archivo Torroja, CEHOPU-CEDEX

Reference steel weight: L.M. Viartola, «Construcción de puentes arco,» Revista de Obras Públicas, Febrero 2005, pp. 23-36.

Arch bridges – Erection methods: The Melan System and related methods

- By subdividing the cross-section in several stages, both in cross-section as well as along the arch axis, bending moments during erection and buckling risk could be minimised.
- While this was economical at the time, such a refined subdivision of the section would be excessively expensive today (high labour cost)



Half arch section with reinforcement

Photos: Viaducto Martín Gil, Embalse de Ricobayo (río Esla), Zamora, Spain, Martin Gil y Eduardo Torroja (1942). Railway viaduct with arch main span, total length 479 m, deck arch, span 209.8 m, f/L = 1/3.3. Construction of the reinforced concrete arch designed by M. Gil was interrupted due to the Spanish civil war. E. Torroja took over the Project after the war, changing the arch design and erection method to the Ribera System, essentially corresponding to the Melan System). World’s longest concrete arch bridge at time of completion.

Top photo © Archivo Torroja, CEHOPU-CEDEX. Bottom photo © Luis Cortés Zacarías, Wikimedia commons. Entire Viaduct © railzamora.es

Arch bridges – Erection methods: The Melan System and related methods

- In spite of the success of Ribera and Emperger, designers like Maillart did thus not use these systems, partly due to the mentioned concerns about the bond between steel and concrete (in fact, delamination has been observed in some early Melan arches), partly due to other reasons (rivalry, nationalism, …).
- During and after World War II, due to the scarcity of steel, the building systems with rigid reinforcement (Melan, Ribera, and others) disappeared.
- For example, the elegant arches of Ch. Menn (Tamina, Nanin e Casciella) were built on timber falsework, just like arches centuries earlier.
- Due to the increasing Labour cost, this was already very costly at the time, and would be excessively expensive today.

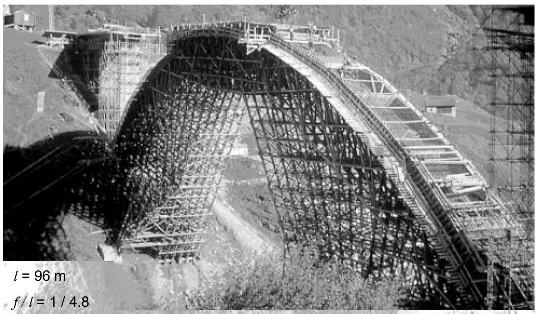
Rhein bridge, Switzerland, 1962, Christian Menn

Photos: Centring and finished Rheinbrücke Tamins, Christian Menn (1962). Concrete deck arch bridge, span 158 m.

Photos © P. Marti, O. Monsch, B. Schilling. Ingenieur-Betonbau.

Arch bridges – Erection methods: The Melan System and related methods

- Actually, it appears that the Melan System, and its potential economical benefits, had faded into oblivion (or it was still regarded as inferior due to the concerns about steel-concrete connection).
- For example, in his seminal book *Prestressed Concrete Bridges*, Ch. Menn – doubtlessly a leading arch bridge designer of his time – briefly mentioned the Melan system and Emperger's applications to arches in the historical overview, but
  - → throughout the entire section of arch bridges implicitly presumed casting on centring
  - → merely referred to different ways of casting the arch to minimise the load to be carried by the centring
- In slender slab arches, which are very elegant in the final configuration (and therefore preferred by Ch. Menn), the centring needs to carry not only the weight of the arch, but – to avoid instability – also a significant portion of the column and deck girder weights, requiring heavy and expensive centrings.



l = 96 m

f / l = 1 / 4.8

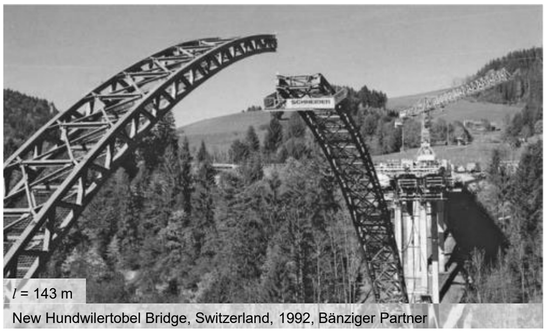
Cascella Bridge, Switzerland, 1968, Christian Menn

Photos: Centring and finished Ponte Cascella, Christian Menn (1968). Concrete deck arch bridge, span 96m, total length173 m

Photos © P. Marti, O. Monsch, B. Schilling. Ingenieur-Betonbau.

Arch bridges – Erection methods: The Melan System and related methods

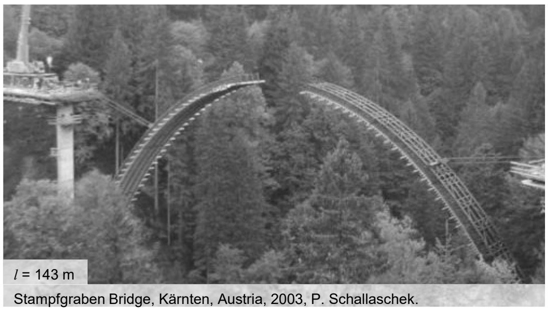
- Some designers did, however, use the Melan System. This and the next slide show two examples of Swiss and Austrian applications, where the steel trusses were assembled upright and rotated subsequently around the arch abutments (as previously used in erecting large arch centrings, e.g. for the Pont de Longeray, 1943).
- Although the clients and engineers involved in the projects shown on this slide were convinced that the system had many advantages and anticipated a more frequent use in the future, very few arch bridges were built in Europe using the Melan System over the past decades.



l = 143 m

New Hundwilertobel Bridge, Switzerland, 1992, Bänziger Partner

Rotation of centering for the Longeray arch bridge



l = 143 m

Stampfgraben Bridge, Kärnten, Austria, 2003, P. Schallaschek.

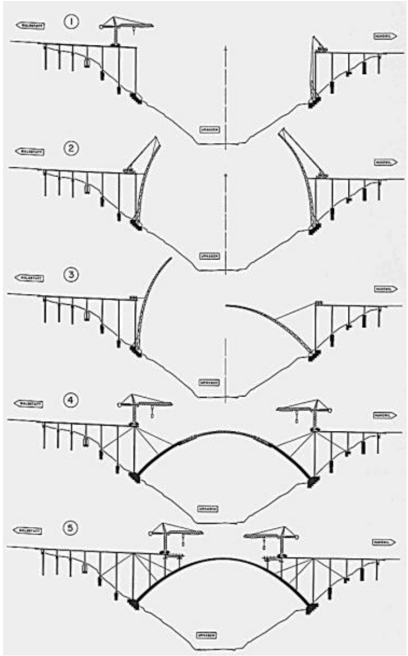
Photos: Melan System arches; Steel half arches assembled upright (with formwork in Stampfgraben) and subsequently rotated around arch abutments until closure, controlled by stays.

- Neue Hundwilertobelbrücke, Hundwil/Waldstatt, Bänziger Partner (1992). Deck arch, span 143 m. Geometry of arch regulated by stays. Photo © Tec21

- Stampfgraben Bridge, Kärnten, P. Schallaschek (2003). Deck arch, span 135 m. Photo © H. Eggemann, K.-E. Kurrer, “On the International Propagation of the Melan Arch System since 1892”, 3rd International Congress on Construction History, 2009.

Reference Viaduc de Longeray: Marcel Prade, *Ponts & Viaducs au XIXe Siècle*. Brissaud, 1988.

Arch bridges – Erection methods: The Melan System and related methods



l = 143 m

New Hundwilertobel Bridge, Switzerland, 1992, Bänziger Partner

Neue Hundwilertobelbrücke, Hundwil/Waldstatt, Bänziger Partner (1992). Deck arch, span 143 m. Geometry of arch regulated by stays.

Photos and figure © A. Köppel, R. Walser. «Hundwilertobelbrücke.» Schweizer Ingenieur und Architekt Nr. 11, 14. März 1991

Arch bridges

Erection methods – Vertical assembly and rotation

Arch bridges – Erection methods: Vertical assembly and rotation

- The vertical assembly of arches, with subsequent rotation to closure, has also been used but for entire arch halves.
- In steel arches, tieback forces are moderate thanks to the reduced weight, as in the Viaducto de Alconétar (2006).

Alconetar Arch Bridge, Spain, 2006, J.A. Llombart

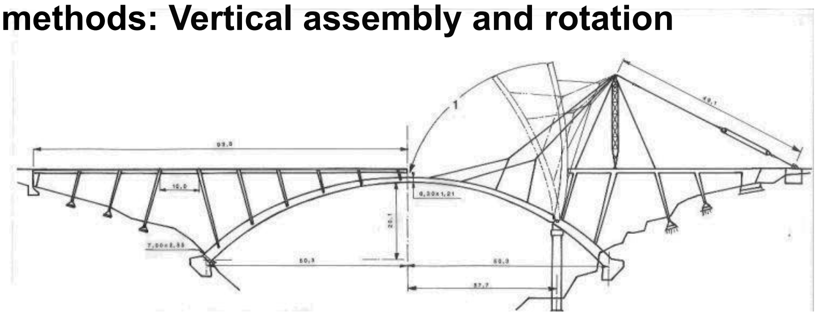





Photos: Arco de Alconetar, Embalse de Alcántara, Cáceres, Spain, J.A. Llombart (2006). Weathering twin steel arch bridges, deck arches, span 220 m, length 400 m. Half arches assembled upright and subsequently rotated around abutment hinges.

Arch bridges – Erection methods: Vertical assembly and rotation

- Much higher tieback forces are required in concrete arches, due to the higher weight.
- Nonetheless, Riccardo Morandi used this method already in the 1950s, first in a footbridge (Vagli Sotto, Garfagnana) and then in the Paul Sauer Bridge over the Storms River, South Africa (1956, span 120 m, rotated arch halves 37 m each).



Paul Sauer Bridge, South Africa, 1956, Riccardo Morandi

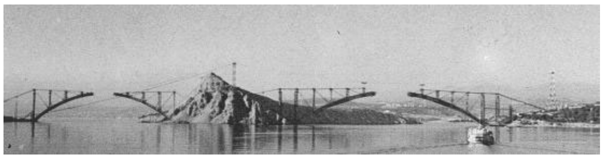
Photos: Paul Sauer Bridge over the Storms River, N2 Garden route from Port Elizabeth to Cape Town, South Africa, Riccardo Morandi (1956). Concrete deck arch bridge, span 100 m, 120 m above river. Half arches built upright and subsequently rotated around provisional concrete hinges at springing lines.

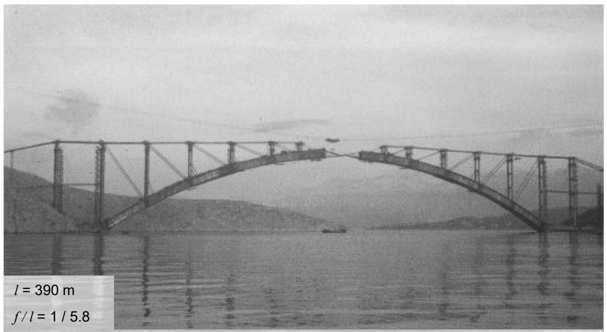
Arch bridges

Erection methods – Cantilever-constructed concrete arches

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- Rather than Melan System arches, the following construction methods have been frequently used for medium-large span concrete arches in Europe in the last decades
  → cantilevering using temporary stays and, in longer spans, towers (“stayed arch cantilevering”)
  → cantilevering of deck and arch as a truss, with temporary diagonals (“deck-and-arch truss cantilevering”, sometimes using temporary cables running parallel to the deck and temporary spandrel columns)
- In the following, deck and arch truss cantilevering is described first. Stayed arch cantilevering was used earlier and is more frequently used today. It is also used in the modern CFST method, and therefore outlined afterwards.
- The first large-span deck-and-arch truss cantilevered concrete arches known to the authors are the Krk bridges (spans of 244 and 390 m), designed by Ilija Stojadinović.
- The longer of the two bridges was the record span for concrete arch bridges until 1997; accounting for the underwater part, it would have held this record even longer.





Krk Arch Bridges, Croatia, 1980, Ilija Stojadinović

Photos: Krk arch bridges, Ilija Stojadinović (1980). Concrete deck arch bridges, spans 390 m / 244 m, f/l = 1/5.8 and 1/ 4.5

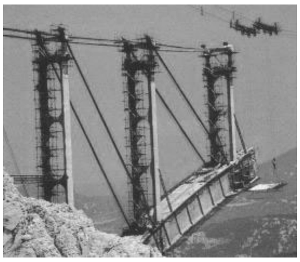
Photos courtesy of B. Stojadinovic.

Further reading: L. Savor, J. Bleiziffer, «Long Span Arch Bridges of Europe,» Long arch bridges, *Proceedings,* 2008, pp. 171-180.

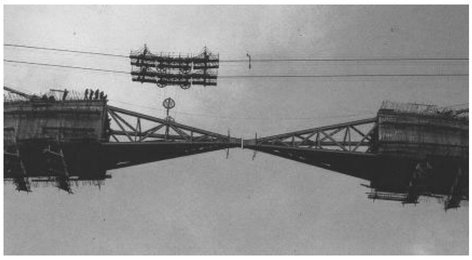
Arch bridges – Erection methods: Cantilever-constructed concrete arches

- In the Krk bridges, temporary cables running parallel to the deck were used, rather than activating the deck in tension, and temporary spandrel columns were also used during cantilevering
- The arch was built in stages, connecting the precast elements by in-situ joint casting:

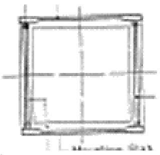
arch cantilevering (temporary cables, diagonals + columns)



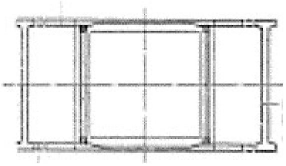
midspan closure (jacks regulating arch thrust = geometry installed until 1985)



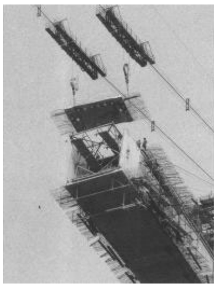
Arch basic section (cantilevered)

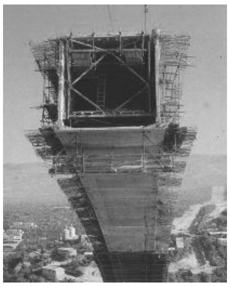


Arch final section (outer ribs added after arch closure)



assembly of arch basic section (cantilevered part)





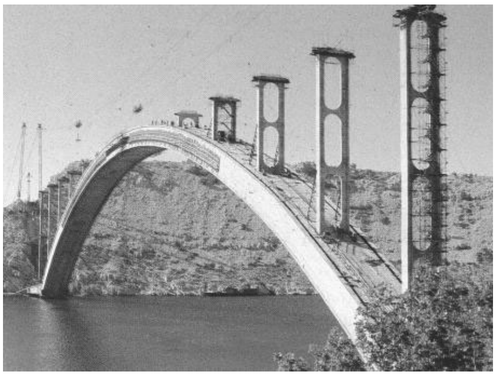
hoisting of outer arch ribs

Krk arch bridges, Ilija Stojadinović (1980). Concrete deck arch bridges, spans 390 m / 244 m, f/l = 1/5.8 and 1/ 4.5

Photos and drawings courtesy of B. Stojadinovic.

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- In the Krk bridges, temporary cables running parallel to the deck were used, rather than activating the deck in tension, and temporary spandrel columns were also used during cantilevering
- Precast elements were also used for the deck girder, resulting in a very efficient erection



spandrel column

spandrel column with temporary diagonal

deck erection (precast girders)

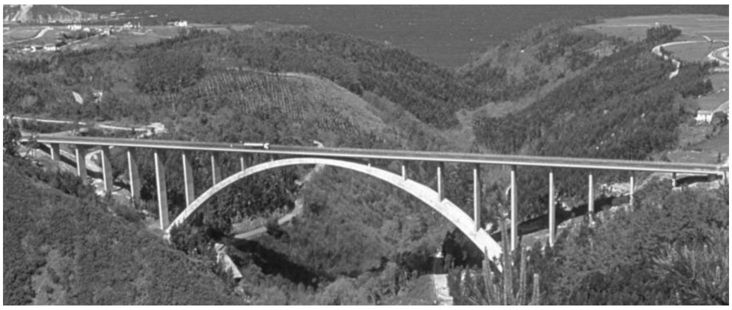
Krk arch bridges, Ilija Stojadinović (1980). Concrete deck arch bridges, spans 390 m / 244 m, f/l = 1/5.8 and 1/ 4.5

Photos and drawings courtesy of B. Stojadinovic.

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- The Arco de la Regenta (Puente Pintor Fierros) was also built using deck-and-arch cantilevering, in this case using the steel-concrete composite deck as tension chord.
- This bridge was opened in 1996 and widened from two to four lanes (12 → 22 m width) in 2008, under traffic, without substantial strengthening need on arch nor foundations: These had already been designed in 1996 to enable a later widening.

Regenta Arch Bridge, Spain, 1996, Asturias. J.J. Arenas



Arco de la Regenta (Puente pintor Fierros), near Cudillero, Asturias. J.J. Arenas (1996, widened to 4 lanes in 2008). Concrete hollow section arch with steel-concrete composite deck, deck arch, span 194 m, length 380 m, 100 m above ground.

Photos © Arenas y Asociados /Luis Miravalles / Flickr / Antonio Navarro Manso

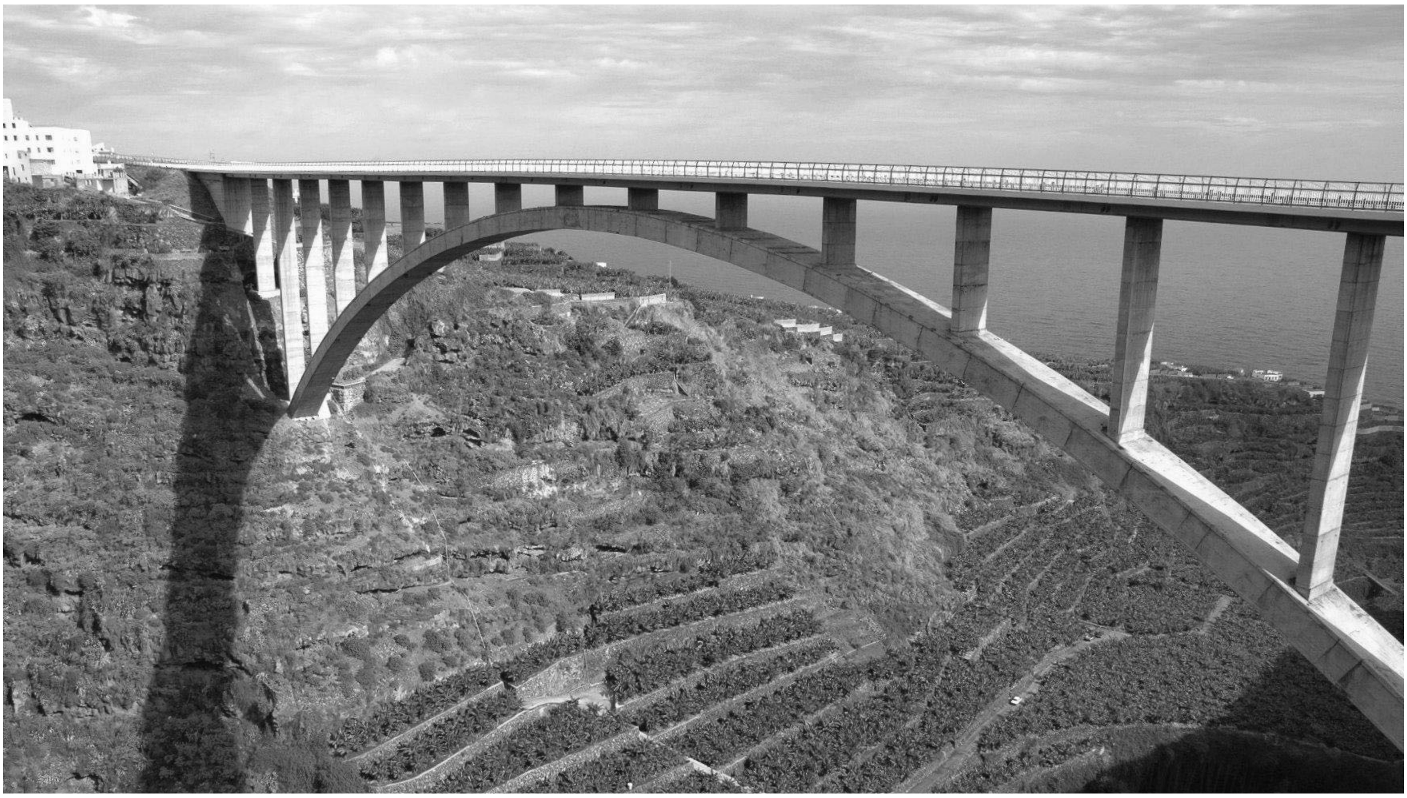
Arch bridges – Erection methods: Cantilever-constructed concrete arches

- The Arco de los Tilos is one of the longest span concrete arches built in the past decades by deck-and-arch truss cantilevering.
- As in the Arco de la Regenta, the steel-concrete composite deck was used as tension chord.

Tilos Bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

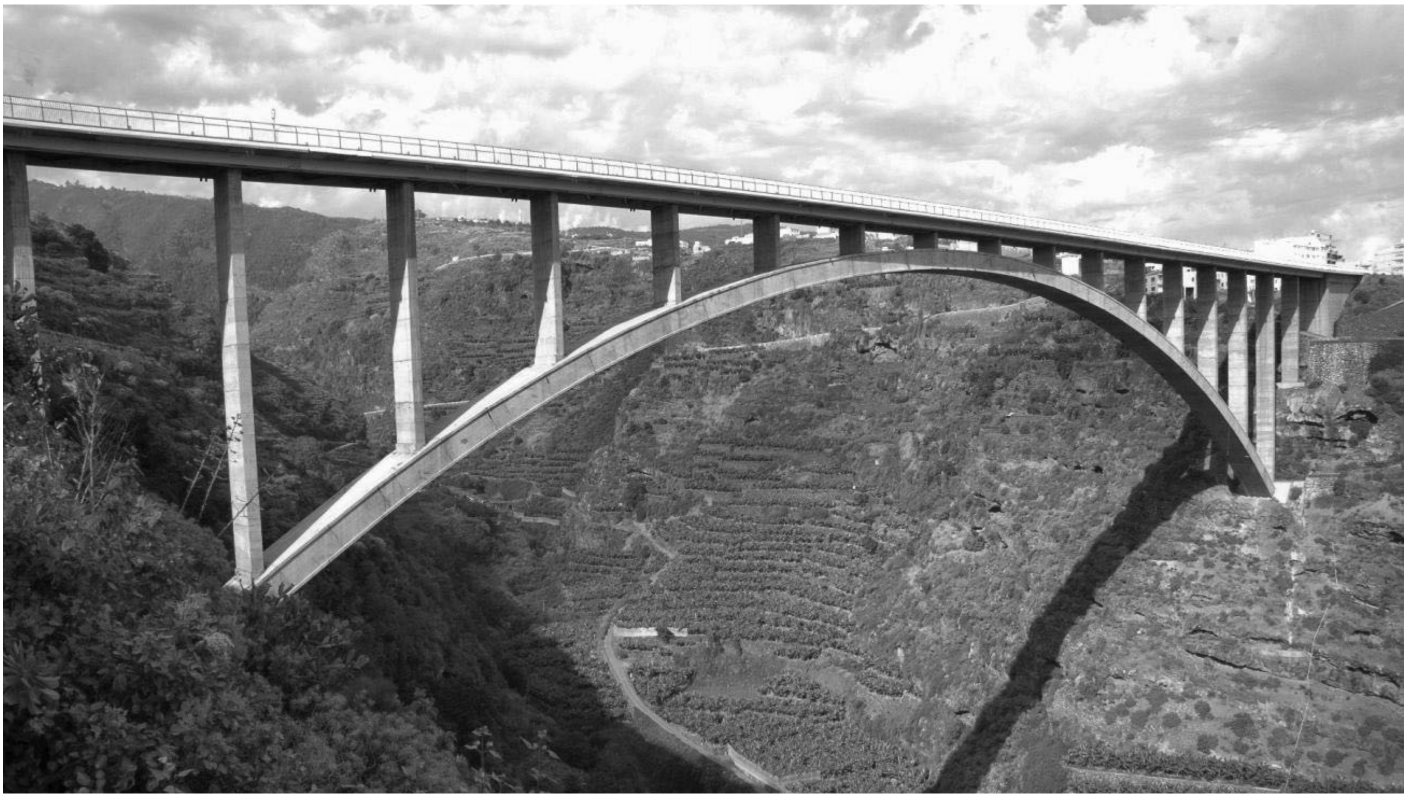
Arco de los Tilos, S. Pérez Fadón and J.E. Herrero Beneitez, San Andrés y Sauces, Isla de La Palma, Canarias (2004). Concrete hollow section arch with steel-concrete composite deck, deck arch, span 255 m, length 353 m, 150 m above ground.

Photos: left and top right: http://arquitectur.blogspot.com/2018/01/puente-de-los-tilos-la-palma-islas.html; bottom right: Wikipedia https://de.wikipedia.org/wiki/Datei:Puente_de_los_Tilos.jpg



Tilos bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Photos: https://www.flickr.com/photos/13311129@N00/2717729836/ © Lutz Hirschmann

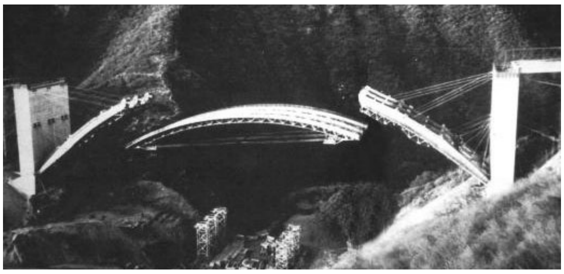


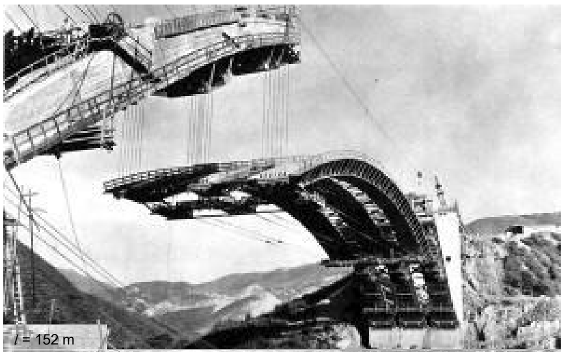
Tilos bridge, Spain, 2004. S. Pérez-Fadón Martínez and J.E. Herrero Benítez

Photos: https://www.flickr.com/photos/lutzmann/2717729818/in/photostream/ © Lutz Hirschmann

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- Stayed arch cantilevering was used earlier than deck-and-arch cantilevering and is more frequently used today. It is also used in the modern CFST method described at the end of this chapter.
- While stayed arch cantilevering had been used in steel bridges much earlier, the first known application of stayed concrete arch cantilevering are the three arch viaducts of the Caracas-La Guaira motorway in Venezuela, designed by E. Freyssinet / J. Muller and built by Campenon Bernard.
- Rather than cantilevering the entire arch, the middle part was built on an 80 m long falsework suspended from the arch cantilevers. This has the advantage that flat, inefficient stays can be avoided without the need for towers.





La Guaira Viaduct, Venezuela, 1952/1953, E. Freyssinet / Jean Muller

Photos: One of the three Viaducts in the Caracas-La Guaira Mororway, Venezuela, E. Freyssinet / Jean Muller (1952/53). Three concrete deck arch bridges, spans 152 / 146 / 138 m. Stayed cantilevering of outer parts of arches, completed by casting on midspan falsework (80 m length) suspended from the previously erected, stayed arch parts.

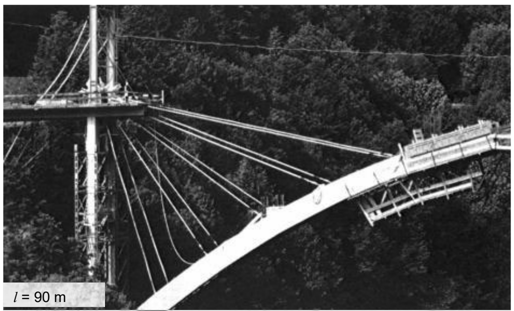
Top photo: © J. Muller, «La conception des ponts, » Culture Technique No. 26, 1992, pp. 271-281.

Bottom Photo http://efreyssinet-association.com/

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- A similar erection method as in the Caracas-La Guaira arches was used for the outer parts of the falsework of the Ponte da Arrábida (span 270 m), see photos on right side .
- Today, stayed cantilevering of the entire arch is more frequent, see bottom photo (Ponte Val Crotta in Ticino, span 90 m).
- Commonly, the arch is cast in situ, using formwork travellers similar to those used for cantilever-constructed concrete girders
- Alternatively, precast segmental cantilevering is also used.

Arrábida Bridge, Portugal, 1963, Edgar Cardoso



Val Crotta Bridge, Switzerland, 1985, L. Brenni and G. Dazio

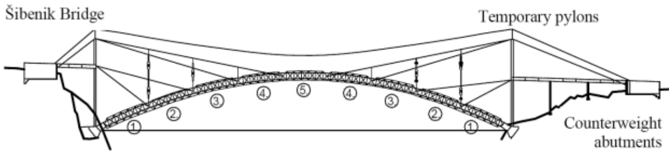
Photos: Right side Falsework installation of the Ponte da Arrábida, Porto – Vila Nova de Gaia, Edgar Cardoso (1963). Concrete arch bridge, main span 270 m (record span for concrete arches at the time), total length 493 m, f/L = 1/5.2. Twin hollow box concrete arches, concrete deck with open cross-section (grillage). Entire arch falsework used twice (moved transversely after casting the first arch to cast second one).

Bottom left Val Crotta Bridge, Ticino, L. Brenni and G. Dazio (1985). Concrete arch bridge, deck arch, span 90 m, built by stayed cantilevering.

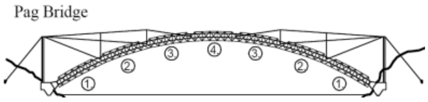
Photos top © http://portoarc.blogspot.com/2013/04/28-ribeiras-e-pontes-iii.html. Bottom: L. Brenni, G. Dazio. «Brücke über das Val Crotta,» Prestressed Concrete in Switzerland 1982-1986, fip Swiss Group, 1986.

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- In the deck-and-arch truss cantilevering method, high tieback forces are required, limiting the field of application in terms of span and soil conditions for anchorage of temporary backstays.
- In stayed arch cantilevering, equally high stayback tie forces result if no towers are used. The tieback forces can be substantially reduced by using temporary towers, similar as used when cantilevering large span steel truss arches
- If temporary towers are used in stayed arch cantilevering is an economical decision: The extra cost for the towers needs to be compensated by the reduced stay forces and backstay anchorage cost. Usually, towers are economical for large span arches.
- The slide shows different choices for tower heights adopted in two arch bridges designed by Ilija Stojadinovic: The Šibenik arch bridge (span 246 m, high towers) and the Pag arch bridge (span 193 m, low towers).



Šibenik Bridge, Croatia, 1966. Ilija Stojadinović



Pag Bridge, Croatia, 1968. Ilija Stojadinović

Photos: Šibenik (top) and Pag (bottom) arch bridges, Ilija Stojadinović (1966/1968). Spans 246 and 193 m, f/l = 1/8 and 1/7. Concrete arch bridges built by stayed arch cantilevering. Arches cast in situ, deck using precast girders. Variable tower height to optimise economy.

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- The Viaducto de Almonte, whose arch was built cantilevered using towers and stays, is one of the world's longest – and most elegant – concrete arches, and the longest span high speed train arch bridge worldwide.
- More details, see presentation of guest speaker Guillermo Capellán.

Almonte Viaduct, Spain, 2016, Arenas & Asociados

Photos: Viaducto de Almonte, Arenas & Asociados (J.J. Arenas, G. Capellán, M. Sacristán), High Speed Line Madrid-Extremadura-Portugal, Cáceres, Spain (2016). High speed train concrete deck arch bridge, main span 384 m, total length 996 m, f/L = 1/5.7. Hollow box high strength concrete arch, prestressed concrete box girder.

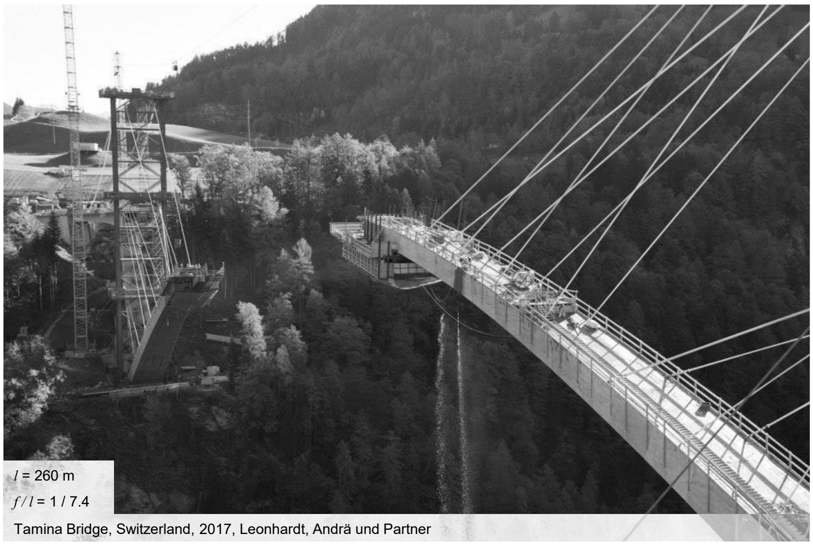
Photos © Arenas & Asociados.

Photos: Viaducto de Almonte, Arenas & Asociados (J.J. Arenas, G. Capellán, M. Sacristán), High Speed Line Madrid-Extremadura-portugal, Cáceres, Spain (2016). High speed train concrete deck arch bridge, main span 384 m, total length 996 m, f/L = 1/5.7. Hollow box high strength concrete arch, prestressed concrete box girder.

Photo © Arenas & Asociados.

Arch bridges – Erection methods: Cantilever-constructed concrete arches

- The Tamina Bridge is another recent example of a large span concrete arch cantilevered using towers and stays



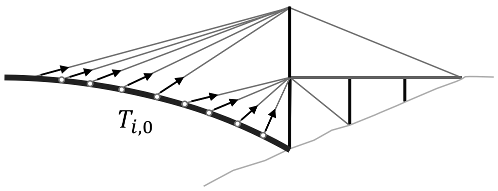
Tamina Bridge, Switzerland, 2017, Leonhardt, Andrä und Partner

Tamina Bridge, Pfäfers-Valens, Leonhardt Andrä und Partner (with dsp Ingenieure + Planer und Smoltczyk&Partner), deck arch, span 260 m, f/L = 1/7.4, total length 475 m.

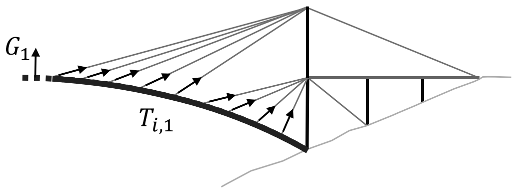
Photos © Meichtry und Widmer (construction engineering for contractor).

Arch bridges – Erection methods: Cantilever-constructed concrete arches

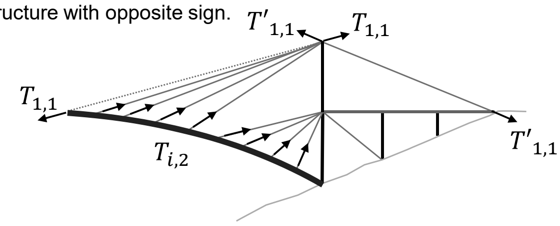
0. Final stage of half arch: Half arch modelled with hinges at all intersection points (arch-ties) except in the last tie close to the crown. This arrangement gives the tension forces $T_{i,0}$ of the ties in the last construction phase. Cable preload is chosen such that the correct arch geometry is obtained.



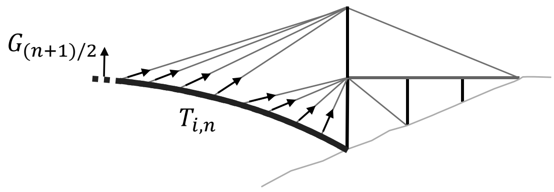
1. Disassembling the structure from the final stage of the half arch: Half arch without hinges. The last segment is removed and its self-weight is applied to the remaining structure with opposite sign.



2. Disassembling the structure from the previous step: Half arch without last segment, without hinges. The last stay cable is removed and the tension forces $T_{1,1}$ and $T'_{1,1}$ (cable forces in corresponding cables after applying the negative self-weight G_1 in stage 1) are applied to the structure with opposite sign.



...n. Disassembling the structure from an intermediate stage of the half arch: Gradually shorter part of half arch without hinges. The same procedure (steps 1-2) is used to obtain the forces in each stage until the half arch is completely disassembled.



The calculation of the internal forces in the arch during construction can be determined by disassembling the structure, starting from the final stage of the half arch, i.e. from the final configuration and removing the structure in the opposite direction as it is built.

Hinges in the final stage are introduced to ensure that the arch carries (almost) pure compression in this state.

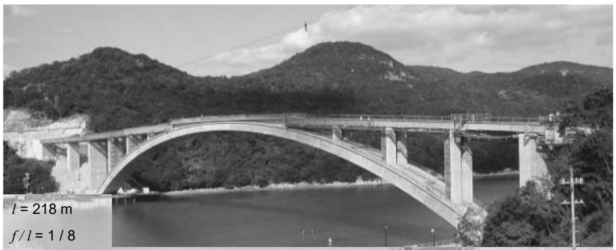
Tamina bridge: erection

Arch bridges

Erection methods – Evolution of the Melan System

Arch bridges – Erection methods: Evolution of the Melan System

- In Asia, arch erection methods inspired by the Melan System have been much more successful ofer the past decades.
- In Japan, more than 20 arch bridges have been built since 1970 using partial Melan System solutions (according to Eggemann and Kurrer, see notes and photos on this slide: Kashirajima Bridge, span 218 m).
  → erecting parts near abutments conventionally by arch cantilevering (stayed or trussed)
  → lifting in steel girders for the Melan System midspan part
- In Japan and particularly in China, many long span arch bridges have been, and are being erected using hollow steel profiles, filled with concrete after closure. The steel profiles thus serve as combined falsework and reinforcement.
- This method, evidently similar to the Melan System (though only recognised by the Japanese), is known as “concrete lapping with pre-erected composite” (CLCA) in Japan, and as “Concrete filled steel tube arches” (CFST) in China.
- The CFST Method is described on the following slides.



Kashirajima Bridge, Japan, 2002, Chodai Co. Ltd.

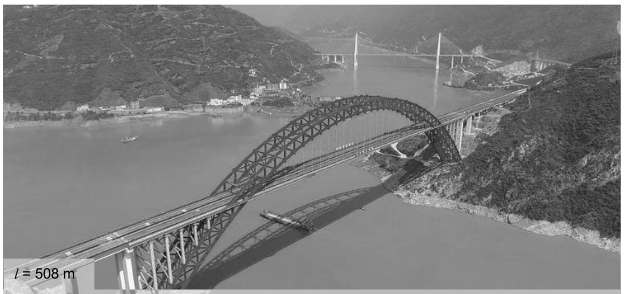
Photos: Kashirajima Bridge, Seto Inland Sea, Okayama, Japan (2002). Partial Melan System deck arch, span 218 m, f/L = 1/8. Concrete arch (box girder) cantilevered with stays from abutments, steel box of middle part (130.4 m) using Melan System lifted in with floating crane. Steel box of idle part encased with concrete (steel serving as inner formwork) after closure.

Photos © Dywydag Systems, //www.dywidag-formties.com/

Source recommended for further reading: H. Eggemann, K.-E. Kurrer, “On the International Propagation of the Melan Arch System since 1892”, 3rd International Congress on Construction History, 2009.

Arch bridges – Erection methods: Evolution of the Melan System

- In CFST arch bridges, hollow section steel arches are erected by stayed cantilevering and subsequently grouted with concrete, forming a steel-concrete composite arch.
- In China, more than 400 CFST arch bridges have been built (≥ 12 with L > 300 m, ≥ 4 with L > 400 m). This slide shows a recent example (Xiangxi Yangtze River Bridge, span 508 m (2019).

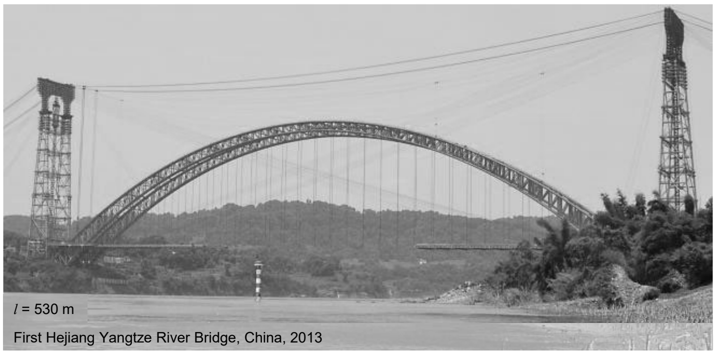


Xiangxi Yangtze River Bridge, China, 2019

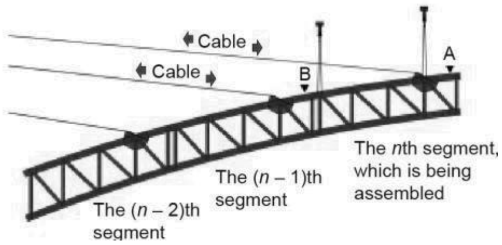
Photos: Xiangxi Yangtze River Bridge, CFST arch bridge, span 508 m, height 240 m © E. Sakowski, www.highestbridges.com

Arch bridges – Erection methods: Evolution of the Melan System

- Currently, the maximum span of a CFST arch bridge is 530 m (First Hejiang Yangtze River Bridge, aka Bosideng Bridge, 2013, see photos).
- Much research has been carried out in China to optimise this type of structures, e.g.
  … adjusting stay forces during grouting to minimise bending moments
  … grout properties and vacuum grouting etc.
  … composite action of tubes and concrete
  … etc.



First Hejiang Yangtze River Bridge, China, 2013



Photos and illustrations: First Hejiang Yangtze River Bridge (aka Bosideng Bridge), Sichuan (2013). CFST through arch bridge, main span 530 m, total length 831 m. Currently the world's longest span CFST bridge, and the 3rd longest arch bridge overall (two steel truss arch bridges have longer spans: Chaotianmen 552 m, Lupu 550 m).

Source and further reading: J. Zheng, J, Wang, "Concrete-Filled Steel Tube Arch Bridges in China," Bridge Engineering Review paper, *Engineering*, No, 4 (2018), pp. 143-155.

Photos top © Wikipedia. Remaining photos Zheng, J, Wang, "Concrete-Filled Steel Tube Arch Bridges in China," Bridge Engineering Review paper, *Engineering*, No, 4 (2018), pp. 143-155.

First Hejiang Yangtze River Bridge (aka Bosideng Bridge), Sichuan (2013). CFST through arch bridge, main span 530 m, total length 831 m. World's longest span CFST bridge, and the 4rd longest arch bridge overall (the Tian'e Longtan concrete arch bridge, and two steel truss arch bridges have longer spans: Tian'e Longtan 600 m, Chaotianmen 552 m, Lupu 550 m).

Source and further reading: J. Zheng, J, Wang, "Concrete-Filled Steel Tube Arch Bridges in China," Bridge Engineering Review paper, *Engineering*, No, 4 (2018), pp. 143-155.

Photo © megaconstrucciones.net

Arch bridges – Erection methods: Evolution of the Melan System

- A further development of CFST bridges consists in arches made of a CFST composite steel skeleton encased by concrete – even closer to the concept of the original Melan System – are being built, mainly also in China ("CFST reinforced concrete arches").
- A recent example is the Yunnan–Guangxi Railway Nanpan River Bridge (aka Nanpanjiang Railway Bridge Qiubei, see photos).

l = 416 m
f/l = 1 / 4.2
Yunnan–Guangxi Railway Nanpan River Bridge, China, 2016

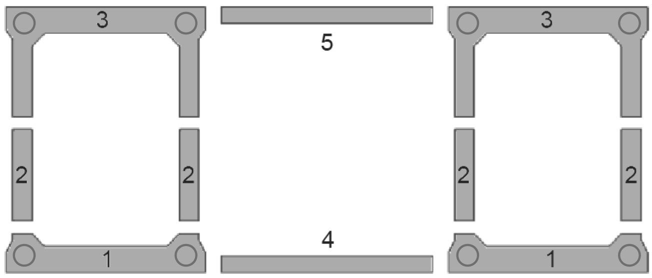
Photos: Yunnan–Guangxi Railway Nanpan River Bridge (aka Nanpanjiang Railway Bridge Qiubei), CFST reinforced concrete deck arch bridge, span 416 m, f/L = 1/4.2, total length 852 m.

Photos © Erik Sakowski / highestbridges.com

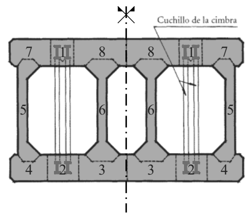
Arch bridges – Erection methods: Evolution of the Melan System

- The similarity of the cross-section of the Yunnan–Guangxi Railway Nanpan River Bridge to Torroja's solution for the Viaducto Martín Gil is striking– albeit at a much larger scale (figures on right side):
  - → Viaducto Martín Gil:
    Span 192 m, f/L = 1/3.3, h_{arch} = 4.5 m
  - → Nanpan River Bridge:
    Span 416 m, f/L = 1/4.2, $h_{arch} \approx$ 9 m (steel tubes = 8 m)
- CFST reinforced concrete arches have clear advantages in terms of durability and maintenance (no coating)
- Furthermore, they are very efficient and economical:
  - → high contribution of inexpensive concrete
  - → avoidance of buckling issues by gradually increasing inertia and load carried by the arch
  - → minimisation of bending moments during casting by optimising casting sequence along arch span, and actively controlling stay forces
- Spans up to 700…800 m appear economically feasible in China according to Zheng and Wang (source see note).

Yunnan–Guangxi Railway Nanpan River Bridge:
Cross-section and casting sequence (size steel tubes approximate)



Comparison with Viaducto Martín Gil:
Cross-section and casting sequence
(≈ same scale as above)

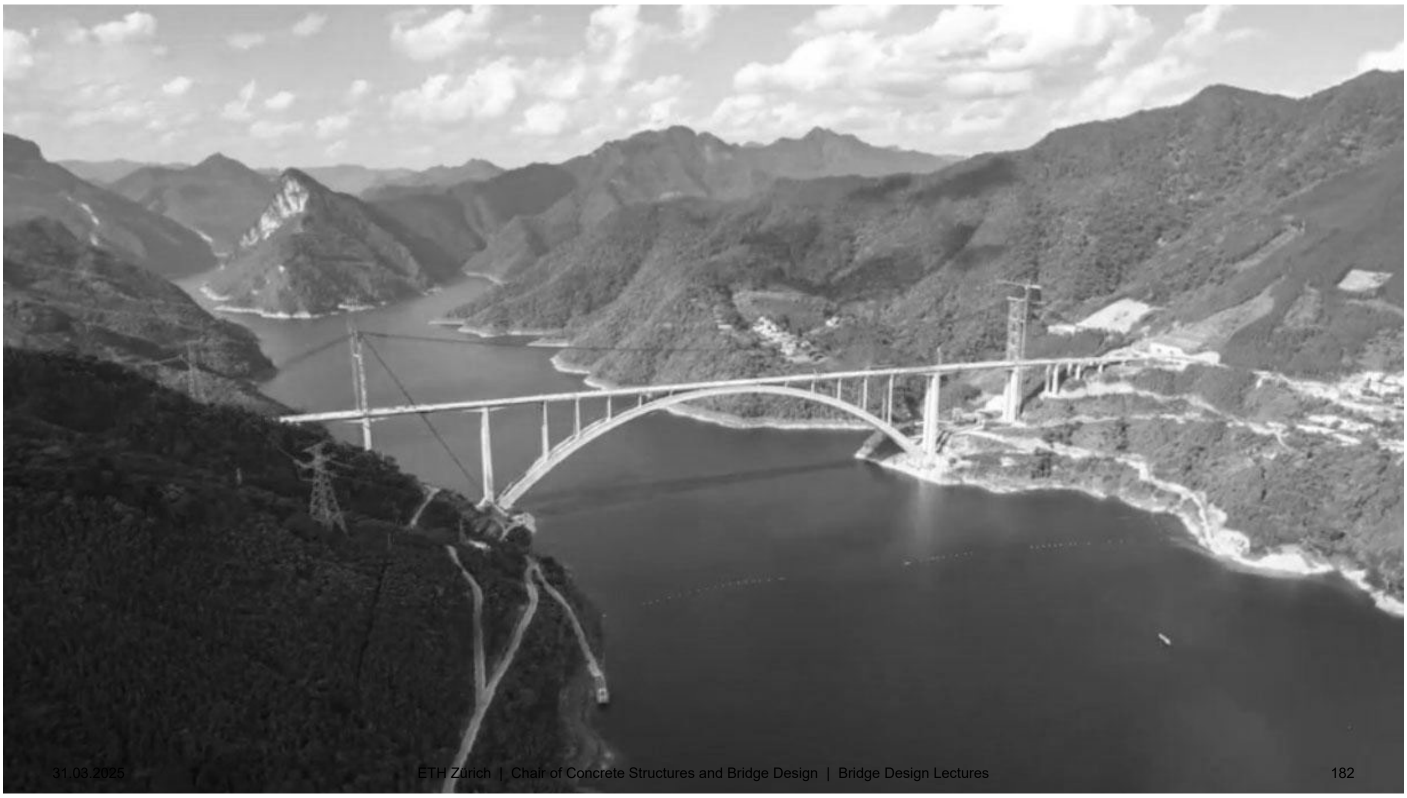


Yunnan–Guangxi Railway Nanpan River Bridge: Source and further reading: J. Zheng, J, Wang, "Concrete-Filled Steel Tube Arch Bridges in China," Bridge Engineering Review paper, *Engineering*, No, 4 (2018), pp. 143-155.

Viaducto martin Gil: Illustration adopted from Archivo Torroja, CEHOPU-CEDEX

Yunnan–Guangxi Railway Nanpan River Bridge (aka Nanpanjiang Railway Bridge Qiubei), CFST reinforced concrete deck arch bridge, span 416 m, f/L = 1/4.2, total length 852 m.

Photos © Erik Sakowski / highestbridges.com



Tian'e Longtan Bridge, Guangxi (2024). Concrete arch bridge (encased CSFT arch), currently the longest span arch bridge in the world. Main span 600.0 m, rise 125 m (f/L=1/4.8), total length of main bridge 760 m. 140 m above reservoir level, 290 m above valley ground.

Source and photo © www.highestbridges.com

Arch bridges

Erection methods – Final remarks

Arch bridges – Erection methods: Final remarks

- In many arch bridges, the deflection caused by the axial deformation of the arch – causing significant bending moments, see structural behaviour – is compensated at closure by applying a controlled axial force at the crown by means of hydraulic jacks.
- Throughout the history of arch bridges, there has been a debate whether such an "opening of the crown" is useful or even required, as there are pros and cons:
  → helps actively controlling the geometry
  → helps removing the formwork and falsework in concrete arches (if the jacking force corresponds to the arch thrust under dead load, the arch lifts off the formwork)
  → in tied arches, it may eliminate the need for hanger re-tensioning
  → causes extra cost and complicates the erection process
  → in concrete arches, most of the effect is lost due to creep
- Essentially, whether such an operation is carried out is a decision of the designer. In any case, the design has to consider the corresponding internal actions.

Tercer Milenio Bridge, Spain, 2008, Juan José Arenas

Photos: Puende del Tercer Milenio,. Zaragoza, J.J. Arenas (). Opening of the arch at the crown, 120 MN jacking force. Photos © Arenas & Asociados.

Arch bridges – Erection methods: Final remarks

- Short span steel arch bridges are usually lifted in, where possible with temporary shoring.
- The slides show two examples, with and without shoring.

Tardis Bridge, Switzerland, 2013, dsp Ingenieure + Planer

Pontones Bridge, Spain, 2005, Arenas & Asociados

Left: Tardis bridge, Mastrils-Landquart, Switzerland, dsp Ingenieure + Planer (2003). Steel through arch with steel-concrete composite deck, span 85 m, length 100 m. Photo © dsp Ingenieure + Planer.

Right: Puente sobre el río Pontones, Cta. Hoznayo-Villaverde, Cantabria, Spain, Arenas & Asociados (2005). Steel tied arch with steel-concrete composite deck, span 60 m, f/L = 1/8. Photo © Arenas & Asociados.

Arch bridges – Erection methods: Final remarks

- Tied arch bridges, being “externally” simply supported, can be launched longitudinally or transversally like girder bridges.
- The Brücke Bernstrasse (Fürst Laffranchi / IUB) in Oftringen was first launched longitudinally over the SBB tracks, subsequently carrying the traffic in this position while the old bridge was demolished. Finally, it was launched transversely into its final position.

SBB Bridge Oftringen, Switzerland, 2018, Fürst Laffranchi Ingenieure GmbH / IUB Engineering

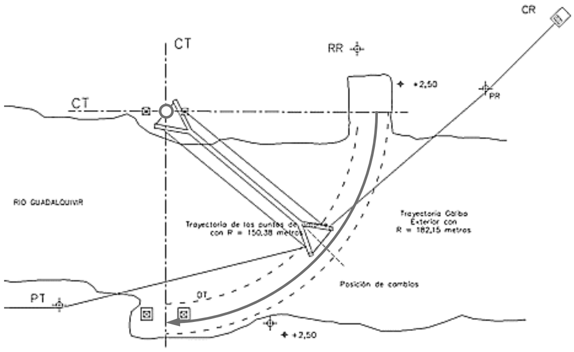
Brücke über SBB, Bernstrasse Oftringen, Fürst Laffranchi Ingenieure GmbH / IUB Engineering (2018). Steel tied arch bridge with steel-concrete composite deck, span 36 m. Replacing an existing bridge with minimum traffic interruption.

Steel structure and inner part of concrete deck (weight 360 t) were built on a temporary dam (top right) and then incrementally launched longitudinally over railway lines. Subsequently, the bridge deck was completed and traffic deviated over the new bridge, such that the existing bridge could be demolished and the abutments of the new bridge be built (left). Finally, the new bridge (now weighing 1400 t) was transversely launched into its final position (bottom right), during a 36 hour traffic closure.

Photos © Fürst Laffranchi (top right) / IUB Engineering (left) / Hebag (launching contractor, bottom right)

Arch bridges – Erection methods: Final remarks

- Tied arch bridges crossing water can be built on shore, using conventional construction methods (shoring, access for cranes, …) and floated into their final position (similar to the Plougastel and Sandö bridge falsework commented earlier).
- The Barqueta Bridge in Sevilla was built on one riverbank and rotated 90° in plan across the river Guadalquivir into its final position.



Barqueta Bridge, Spain, 1992, J.J. Arenas and M. Pantaleón

Puente de la Barqueta, Sevilla, J.J. Arenas and M. Pantaleón (1992). Steel tied arch bridge with triangular portal frames and orthotropic deck. Span 168 m. Built on shore and rotated over the Guadalquivir river (Meandro de Ranillas) into final position. Weight

Photos © Arenas y Asociados.