Cable-Stayed Bridges

(Schrägseilbrücken)

The contents of this Chapter, authored by George Klonaris, are largely based on the lecturer's tenure with the eminent bridge design firms T.Y. Lin International (5 yrs) and COWI North America (formerly Buckland & Taylor) (6 yrs). Experience and knowledge gained on the analysis, design and construction of cable-stayed bridges through formal training and on-the-job mentoring is reflected herein.

Special acknowledgements go to the following individuals:

David Goodyear, PE, SE, PEng, NAE (form. Senior Vice President & Chief Bridge Engineer at TYLI)

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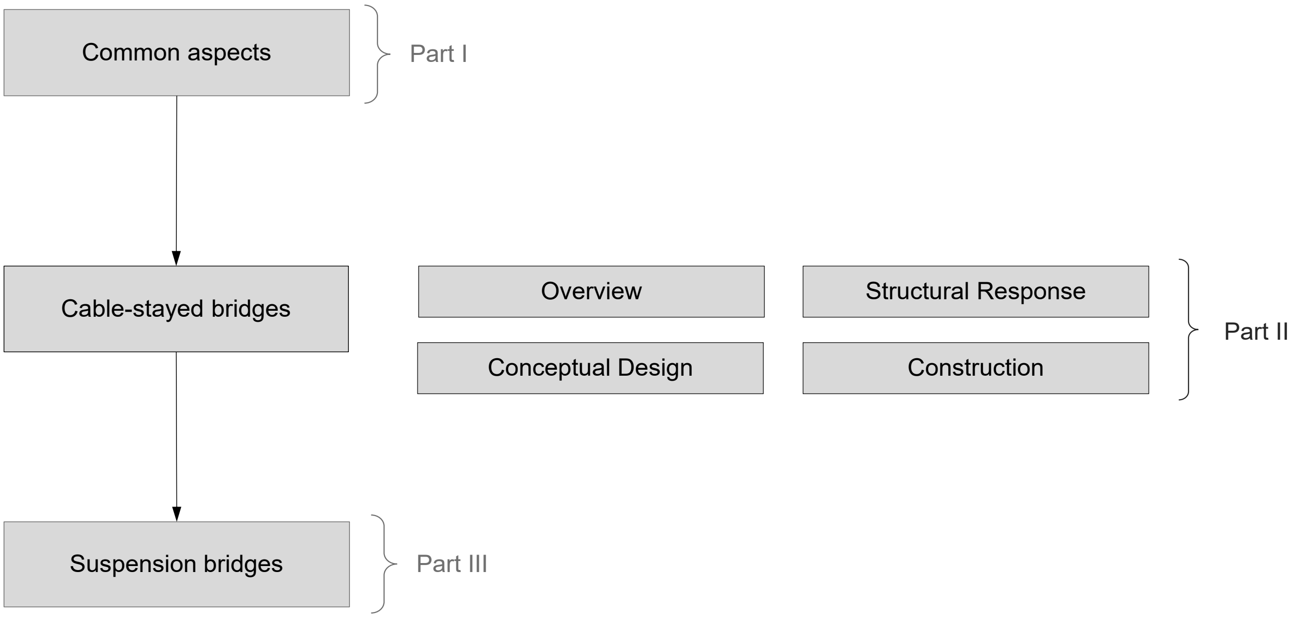
Dusan Radojevic, PhD, PEng (Vice President, Bridge Sector Manager at TYLI, form. at COWI)

Andrew Griezic, PhD, PEng, PE (Principal Bridge Engineer, Associate VP at TYLI, form. at COWI)



Recommended References:

Podolny, W. & Scalzi, J.B. (1986), “Construction and Design of Cable-Stayed Bridges“, Wiley.

Walther, R., Houriet, B., Isler, W., Moïa, P. & Klein, J.F. (1999), “Cable-Stayed Bridges,” 2^{nd} Edition, Thomas Telford.

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

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Setra (2002), Cable Stays – Recommendations of French international commission on Prestressing

PTI (2018), DC45.1-18: Recommendations for Stay Cable Design, Testing, and Installation, Post-Tensioning Institute.

fib Bulletin 89 (2019): Acceptance of cable systems using prestressing strands (Recommendation) [replaced Bulletin 30].

Why study cable-supported bridges?

- Basic knowledge of the fundamental behaviour and construction methods of all bridge typologies is required at the conceptual phase
- For engineers seeking to specialise in long-span bridges → starting point…
- For engineers indirectly involved in long-span bridges, e.g. as Owner, Prime consultant → develop a common language and understanding of the key issues involving long-span bridges

Learning objectives:

- What is the fundamental behaviour of cable-stayed bridges?
- What are the main geometric features of cable-stayed bridges and which design requirements determine their form?
- When is a cable-stayed bridge the appropriate typology and how does it compare with competing typologies?
- What are some of the particularities of cable-stayed bridges?
- What are the main considerations with respect to constructibility?

Cable-supported bridges

Cable-stayed bridges – Overview

Evolution of bridge state-of-the-art case study: The Forth Bridges

The case of the Forth Bridges illustrates the progression of the state-of-the-art of the bridge technology during the last century. The Forth Rail Bridge had the longest cantilever span when opened and continues to be the world's second-longest cantilever span. It was also the first major structure in Britain to be constructed of steel. The Forth Road Bridge was the fourth longest suspension bridge in world (main span = 1006 m), behind the Mackinac Bridge (1158 m), the Golden Gate Bridge (1280 m) and the Verrazzano-Narrows Bridge (1298 m). The Queensferry Crossing is the longest triple-tower cable-stayed bridge in the world (total length = 2700 m).

It is interesting to observe that the construction duration for the three bridges (8 yrs, 6 yrs & 6 yrs, respectively) has not been reduced dramatically due to the technological developments, as might have been expected. However, the advances in construction safety are obvious as demonstrated by the recorded loss of life (73, 7 & 1 lives lost, respectively).

Photo Credit: https://www.heliair.com/wp-content/uploads/2019/02/Three-Bridges-Tour-Scotland-Helicopter-Flight.jpg

Reference: https://www.theforthbridges.org/queensferry-crossing/

Further reading:

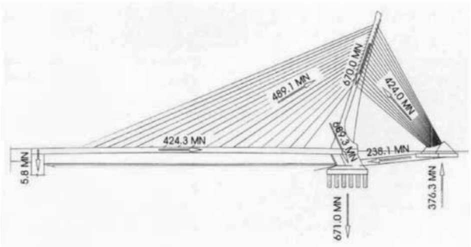
https://e-mosty.cz/wp-content/uploads/2016/06/e-mosty12017QueensferryCrossing.ForthRoadandRailwayBridges.March2017.pdf

Cable-supported bridges

Cable-stayed bridges – Overview
Definition and Classification

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
  - → Span Arrangement:
    - Single Span
    - Two Span
    - Three Span (standard)
    - Multi Span



Lérez River Bridge in Pontevedra, Spain, 1995. Carlos Fernandez Casado, S.L.

This example of a single-span, earth-anchored cable-stayed bridge, although not representative of the most common span arrangement for cable-stayed bridges, helps to illustrate their main function: Applied vertical loads on the cable-supported span are primarily (for the case of closely-spaced cables) resisted through inclined tension along the stay cables, while the horizontal component of the stay cables tension is balanced by axial compression in the deck-girder system. The axial tension in the stay cables is transferred to the tower where it is resolved in compression in the tower and tension in the backstays, which are in turn anchored to the ground. The efficiency of the cable-stayed bridge stems from the fact that all members (girder, tower, stay cables) are carrying loads primarily through axial (normal) forces and only minimal bending.

Photo Credit:

https://www.cfcsl.com/en/portfolio/lerez-bridge-pontevedra-spain-1995/

Illustration & Further reading:

Leonardo Fernández Troyano (Dr Eng.), Javier Manterola Armisén (Dr Eng.) & Miguel A. Astiz Suárez (Dr Eng.) (1998) The Inclined Towers of the Ebro and Lérez Bridges, Structural Engineering International, 8:4, 258-260, DOI: 10.2749/101686698780488776

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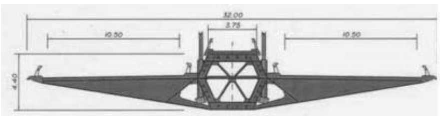

Alamillo Bridge, Sevilla, Spain, 1992. Santiago Calatrava

In contrast to the Lérez River Bridge (previous slide), where the function of the bridge is evident to the observer, the Alamillo Bridge, although visually impressive, lacks logic of form, i.e., transparency as to its function. The lack of backstays to stabilize the tower makes it difficult to determine whether the tower is supporting the girder against sagging or whether the girder is supporting the tower against toppling over. In lieu of backstays, the tower has to rely on its self-weight to balance the tension from the stay cables. Given that the tower self-weight is constant, while the applied vertical loads on the deck, and therefore the tension in the stay cables, are variable, the resultant compression force introduced to the tower at the cable anchorages will generally not be collinear with the axis of the tower, thereby resulting in bending moments at the base of the tower, thus reducing the structural efficiency of the system.

Furthermore, while one of the main advantages of cable-stays bridges with respect to the construction sequence is that the superstructure can be incrementally erected while supported by the stay cables without the need for falsework, this was not the case for the Alamillo Bridge. While the original erection scheme assumed that sections of the tower and superstructure could be progressively cantilevered and balance each other via the corresponding connecting stay cable, this would have required simultaneous procurement of the tower and superstructure segments, with the potential for significant delays if perfect coordination could not be achieved. For this reason, the contractor opted to decouple the procurement of the tower from that of the superstructure, by erecting the superstructure on falsework, thus negating the main erection advantage of cable-stayed bridges.

Photo Credit:

https://calatrava.com/projects/alamillo-bridge-cartuja-viaduct-seville.html

Further reading: J.J. Orr (2008). “A critical analysis of Santiago Calatrava’s Puente del Alamillo, Seville” Proceedings of Bridge Engineering 2 Conference, 16 April 2008, University of Bath, UK

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l = 230 m

h = 115 m (h / (2l) = 1 / 4.0)

d = 3.3 m (d / (2l) = 1 / 139)

Haiwen Bridge, China, 2019

The symmetric two-span configuration is not very common, but can be an appropriate solution to meet specific site constraints. It is generally advantageous to opt for an asymmetric span layout, as this results in a stiffer structure (see behind).

Photo Credit:

http://en.people.cn/n3/2019/0304/c90000-9552401.html

Cable-supported bridges – Cable-Stayed Bridges: Overview

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l = 471 m, l_1 = 198 m (l_1 / l = 0.42)
h = 118 m (h / l = 1 / 4.0)
d = 2.7 m (d / l = 1 / 174)

Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

The three span arrangement with two towers flanked by two anchor piers is the standard cable-stayed bridge configuration. The back spans are proportioned so that they are less than half of the main span. This allows for pre-tensioning the backstays and stiffening the overall structure. Applied vertical loads on the main span are primarily (for the case of closely-spaced cables) resisted through inclined tension along the stay cables, while the horizontal component of the stay cables tension is balanced by axial compression in the deck-girder system. The axial tension in the stay cables is transferred to the tower where it is resolved in compression in the tower and tension in the backstays, which are in turn anchored to the anchor pier. The back-stay forces are transmitted to the anchor pier through special uplift bearings/tie-down devices. To reduce or eliminate the magnitude of tensile axial forces transmitted to the anchor piers, counter-weights may be placed near the end of the back-span. The counter-weight solution is not recommended for regions with high seismicity.

Photo Credit:

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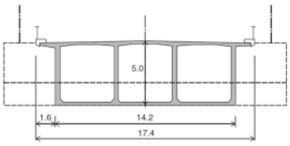

Lake Maracaibo Bridge (Puente General-Rafael-Urdaneta), Venezuela, 1962. Riccardo Morandi

Span arrangements that include more than three spans, and correspondingly more than two towers, are classified as multi span. The interior spans and towers lack the advantage of being stabilised by backstays and anchor piers. Therefore, alternative measures must be taken to stiffen the structure. The approach taken in the Lake Maracaibo Bridge was to use very stiff towers that can resist unbalanced loading of the interior spans.

Note that the Lake Maracaibo Bridge represents the first generation of cable-stayed bridges where the stay cables were supporting the superstructure at a few discrete locations, essentially replacing piers.

Photo Credit:

https://de.wikipedia.org/wiki/General-Rafael-Urdaneta-Br%C3%BCcke

Illustration Credit:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

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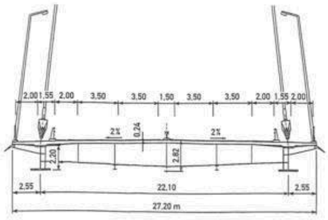

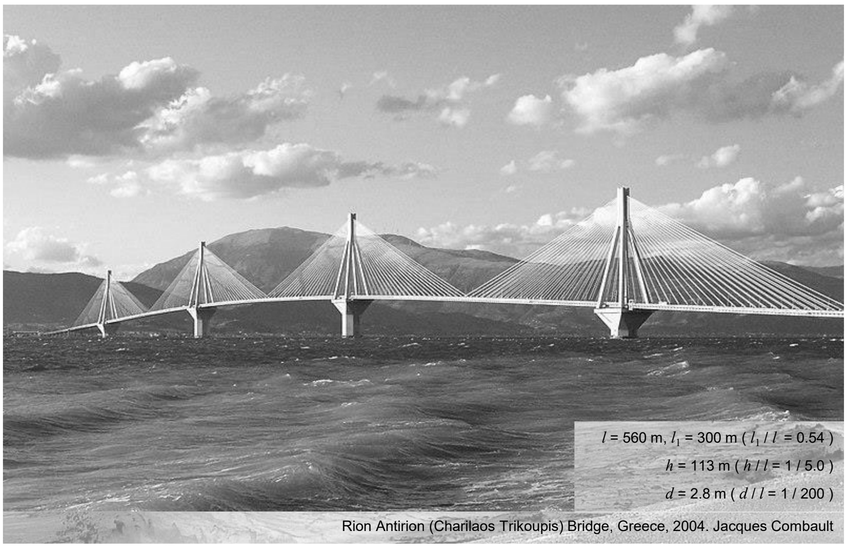

Rion Antirion (Charilaos Trikoupis) Bridge, Greece, 2004. Jacques Combault

Similarly to the Lake Maracaibo Bridge, the Rion Antirion Bridge uses the stiff tower approach, in this case combined with closely-spaced stay cables.

Photo Credit:

https://en.wikipedia.org/wiki/File:Rio-Antirio_bridge_cropped.jpg

Illustration Credit:

Svensson, H. (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn.

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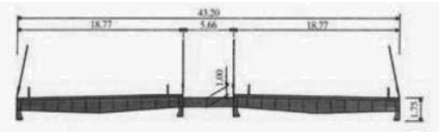

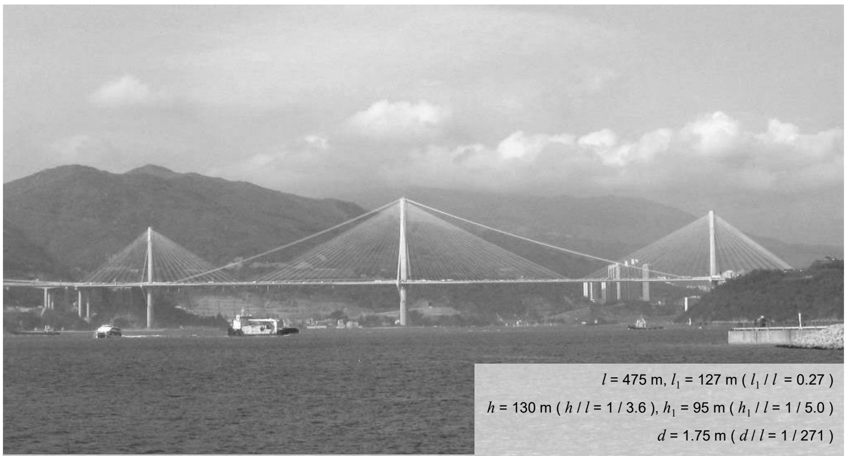

Ting Kau Bridge, Hong Kong, 1997. Sclaich Bergermann Partner

A unique approach was used to stabilise the interior tower of the Ting Kau Bridge, with the use of special-purpose stay cables that connect the top of the interior tower to the point where the superstructure intersects with the exterior towers.

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Illustration Credit:

Holger Svensson (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn, Berlin

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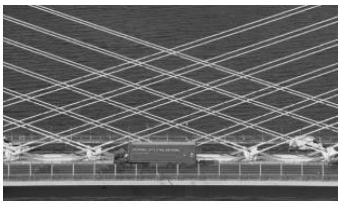

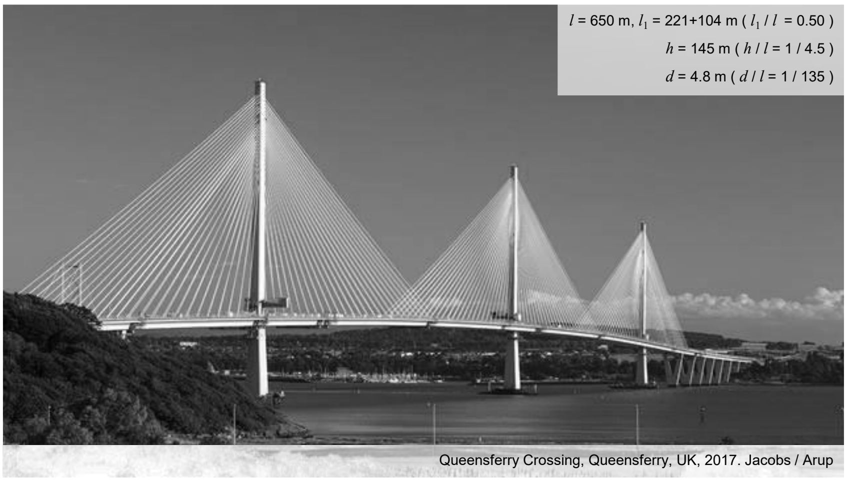

Queensferry Crossing, Queensferry, UK, 2017. Jacobs / Arup

In the case of the Queensferry Crossing, the structure is stiffened by overlapping the main span stay cables. One disadvantage of this approach is that a wider bridge deck is required to accommodate the the anchorages of the overlapping stay cables.

Photo Credits:

Left: https://www.theforthbridges.org/queensferry-crossing/

Right: https://uk.ramboll.com/projects/ruk/queensferry-crossing-northern-europes-largest

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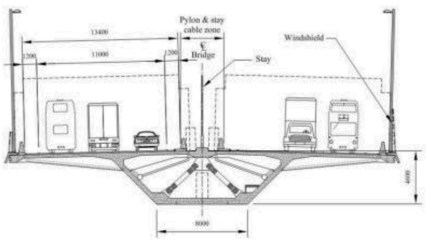


Mersey Gateway Bridge, Cheshire, UK, 2017. COWI / FHECOR

Finally, in the case of the Mersey Gateway Bridge, the spans are proportioned so that the interior tower is shorter than the ones stabilised by backstays, thus reducing the tributary span for the interior tower and its slenderness (compared to the exterior towers).

Photo Credits:

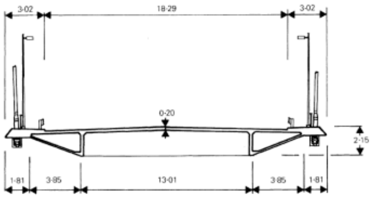
https://www.cowi.com/solutions/infrastructure/mersey-gateway-bridge-united-kingdom

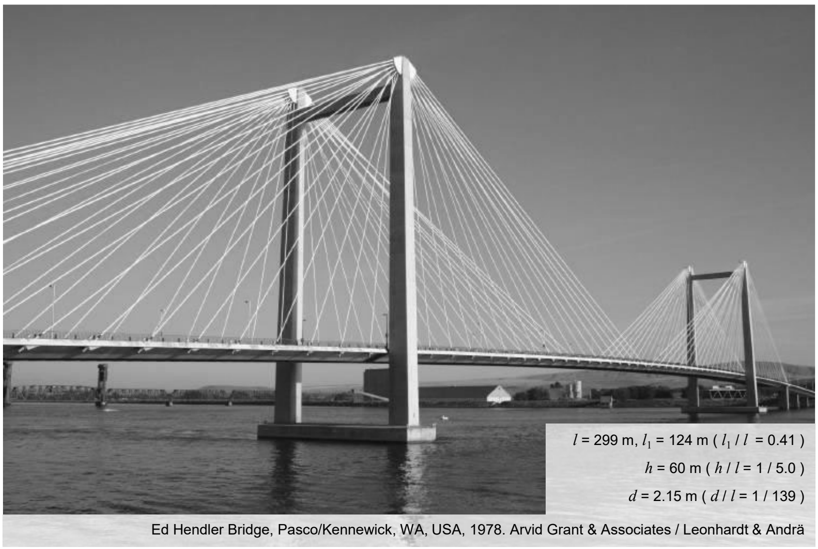
Illustration Credit:

Sanders P, Brennan G, Wood H, Banks J & Romo-Martin J (2019) “Design and Construction of Mersey Gateway Bridge, U.K”, Structures Congress 2019 : Bridges, Nonbuilding and Special Structures, and Nonstructural Components

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
  - → Stay Cable Arrangement:
    - Fan
    - Harp
    - Hybrid (Semi-Fan)





Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä

The fan arrangement is theoretically the most efficient because the average stay inclination is maximised. However, anchoring the stays at the top of the tower can be quite challenging. To mediate this challenge, the top of the tower may feature proprietary saddle devices, where the stays run continuous through the towers and are anchored only at the deck level (see guest lecture by Max Meyer on types of stay cable anchorages). There are however certain issues with the use of saddles, the most important being fretting fatigue. Other issues include the potential for slipping of the stays at the saddle location and complications during erection.

Photo Credits:

https://www.bridgemeister.com/pic.php?pid=1774

https://bridgehunter.com/photos/24/37/243702-L.jpg

Illustration Credit:

Rene Walther (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford

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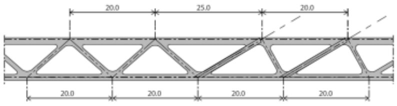

Øresund Bridge, Copenhagen, Denmark, 2000. COWI

The harp arrangement is favoured by architects due to the clean aesthetics. However, it is the least economical system because all stay cables have a relatively flat inclination. In addition, the shorter lower stays are significantly stiffer compared to the longer upper stays and can attract very high forces, e.g. in the case of high seismic forces (in the longitudinal direction) combined with a floating deck at the tower.

Photo Credits:

Left: Holger Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Right: By Jorchr - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=51733078

Illustration Credit:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

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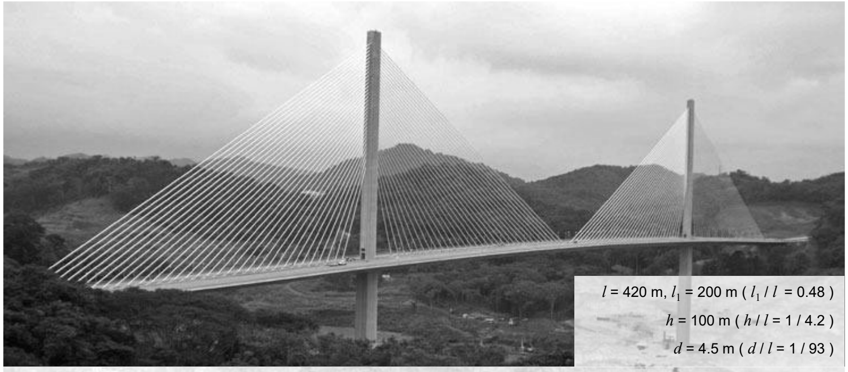

Puente Centerario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP

The semi-fan arrangement has become the most prevalent system because it tends to be the most economical.

Photo Credit:

https://www.tylin.com/en/projects/panama_canal_second_crossing

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
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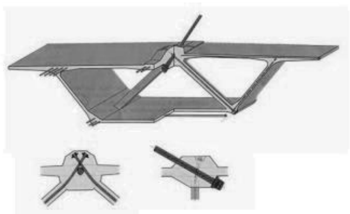
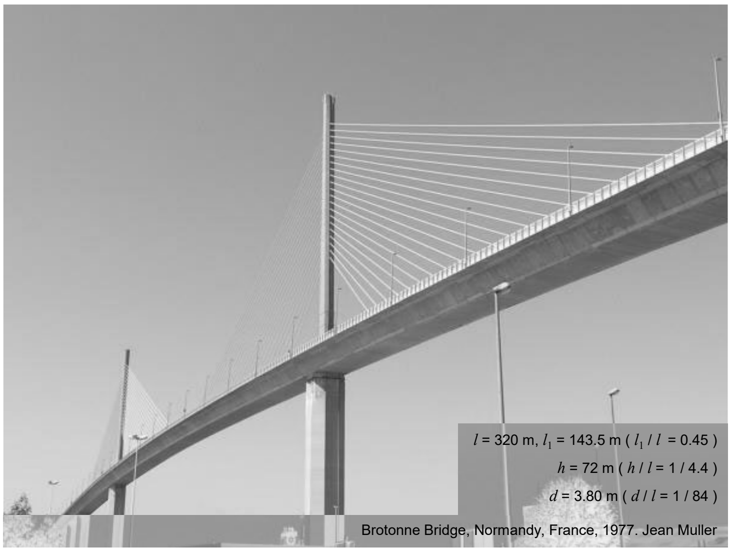
    - Single Plane
    - Two Vertical Planes
    - Two Inclined Planes
    - Multiple Vertical Planes
    - Multiple Inclined Planes





Brotonne Bridge, Normandy, France, 1977. Jean Muller

Single plane arrangements result in clean aesthetics, are possible for narrow to medium width decks, and are combined with box girders (torsional rigidity provided by the closed section is required to resist eccentric loading). They are typically supported by single towers (pictured). Inverted "Y" towers are also common (see behind).

Photo Credit:

https://structurae.net/en/structures/brotonne-bridge

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Rene Walther (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford.

Svensson, H. (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn.

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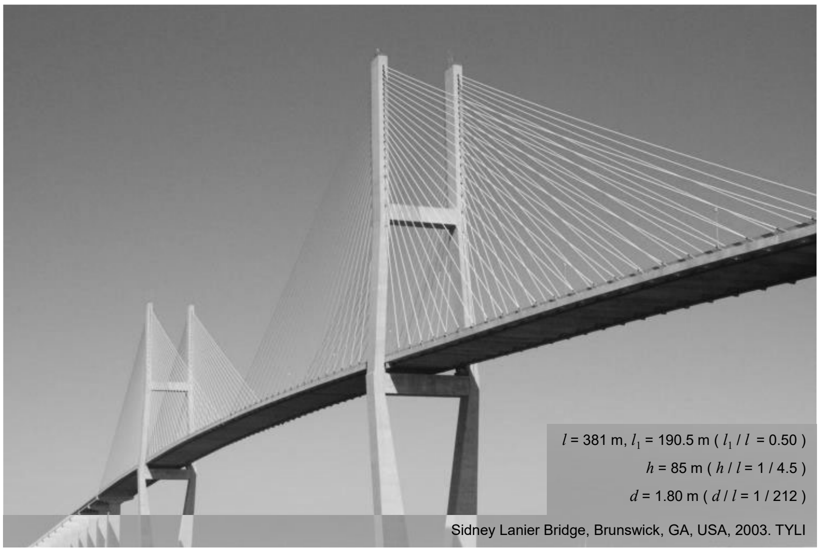

Two vertical planes arrangements are typically combined with open cross-section superstructures. Box girders are also sometimes used but are less convincing in appearance, unless slender and streamlined. They are typically combined with "H" towers (pictured).

Photo Credit:

https://commons.wikimedia.org/wiki/File:Sidney_Lanier_Bridge.jpg

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    - Multiple Vertical Planes
    - Multiple Inclined Planes

Tatara Bridge, Hiroshima, Japan, 1999. Honshu-Shikoku Bridge Authority

Inclined planes are used in combination with “A”, Diamond or Inverted “Y” towers (see behind) in order to improve the aerodynamic performance of very long spans.

Photo Credit:

https://structurae.net/en/structures/tatara-bridge

Illustration Credit:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

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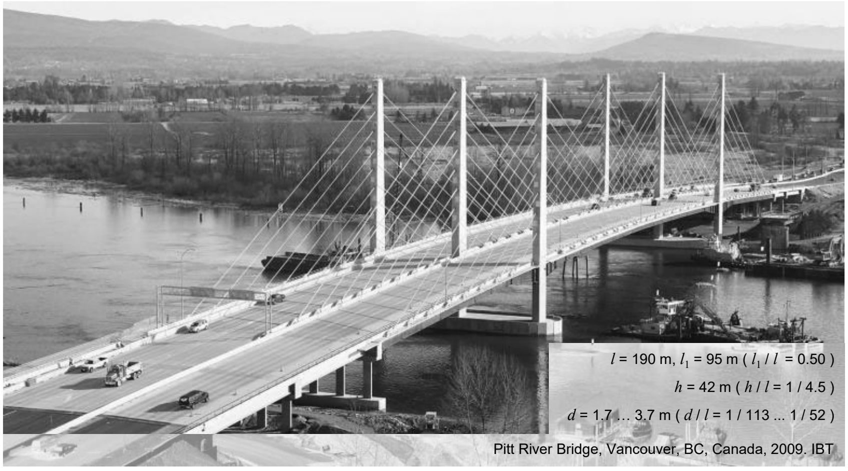

l = 190 m, l_1 = 95 m (l_1 / l = 0.50)

h = 42 m (h / l = 1 / 4.5)

d = 1.7 ... 3.7 m (d / l = 1 / 113 ... 1 / 52)

Pitt River Bridge, Vancouver, BC, Canada, 2009. IBT

For very wide decks, it becomes more efficient to add a plane of cables, rather than relying on the deck to span transversely between two cable planes. Harp cable arrangements (pictured) are often preferred in the case of multiple cable planes to improve transparency from every viewing angle.

Note that the use of vertical cable planes and "H" towers results in wide foundation elements (see next slide for alternative).

Photo Credit:

https://www.systraibt.com/en-projet/pitt-river-bridge

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Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT

Multiple inclined plane arrangements combined with a single tower can help to minimise the foundation footprint. The Port Mann Bridge had the widest deck in the world when it opened, with 10 lanes of traffic.

Photo Credit:

https://www.tylin.com/en/projects/port_mann_bridgehighway_1_project (Thomas Heinser Studio)

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
  - → Tower Configuration:
    - Single Tower
    - “H” Tower
    - “A” Tower
    - Diamond Tower
    - Double Diamond Tower
    - Inverted “Y” Tower

Sunshine Skyway Bridge, Tampa, FL, USA, 1987. Figg & Muller

Single towers are the simplest form of tower, are typically supporting a single plane of cables, but can also support two or more inclined planes.

A disadvantage of single towers is that they interfere with the flow of traffic and hence result in wider decks (pictured) or require splitting of the deck (see previous slide).

Photo Credit:

ttps://de.wikipedia.org/wiki/Sunshine_Skyway_Bridge#/media/Datei:Sunshine_Skyway_on_the_Tampa_Bay.jpg

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Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

JJ Audubon Bridge, LA, USA, 2011. Buckland & Taylor, Ltd.

"H" tower is a term that is loosely used to describe towers which feature two vertical (or approximately vertical) legs connected by one or more cross-beams to form a frame in the transverse direction. The number of cross-beams should be kept to a minimum (or altogether eliminated if possible) as they are expensive to form. The number and location of the cross-beams depends on the total height of the tower and the elevation of the deck. "H" towers support two vertical (or approximately vertical) cable planes. In order to result in vertical cable planes, the tower legs may need to be slightly deviated at the deck level to allow for the superstructure to pass through (pictured left).

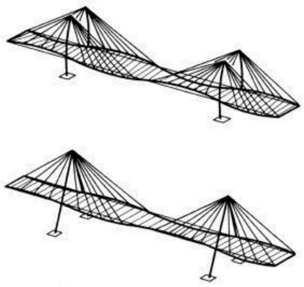
Photo Credits:

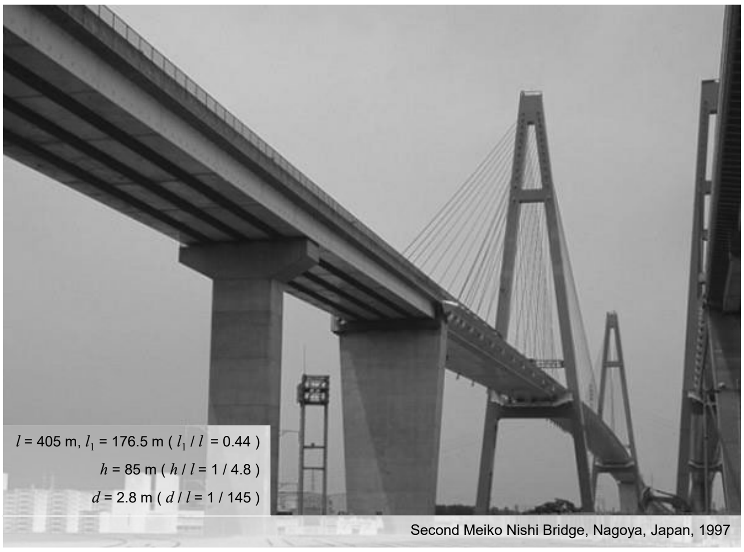
Left: https://commons.wikimedia.org/wiki/File:Sidney_Lanier_Bridge.jpg

Right: https://www.touchstonearchitecture.com/audubon-bridge

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
  - → Tower Configuration:
    - Single Tower
    - "H" Tower
    - "A" Tower
    - Diamond Tower
    - Double Diamond Tower
    - Inverted "Y" Tower





Second Meiko Nishi Bridge, Nagoya, Japan, 1997

In the case of "H" towers, the flexural and torsional modes of the superstructure have similar frequencies (dictated by the tower stiffness). The use of "A" towers helps to separate the flexural and torsional modes, while they also increase the overall stiffness of the system. This is because the two edges of the deck cannot oscillate vertically independent of each other (as in the case of "H" towers), given that the cables are connected at the top of the "A" tower. Therefore, "A" towers (or Diamond, or Inverted "Y") are required beyond a certain span length to improve the aerodynamic stability of the deck.

Note that "A" towers are theoretically most efficient when combined with the fan cable arrangement so that all cables meet at a common node at the top of the tower. For the more practical semi-fan cable arrangement, an inverted "Y" tower is often used instead (see behind).

Photo Credit:

https://structurae.net/en/structures/second-meiko-nishi-bridge

Illustrations Credit:

Rene Walther (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Overview

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Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

“A” towers result in very wide foundation footprints. In order to mitigate this, diamond towers can be used instead. A strong horizontal tie, typically located below the deck level, is required to resolve the deviating compression forces in the inclined tower legs.

Photo Credit:

Cable-supported bridges – Cable-Stayed Bridges: Overview

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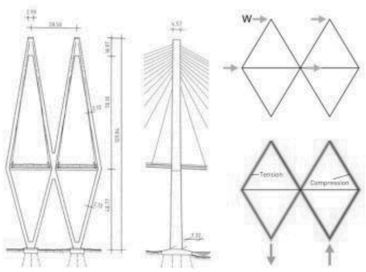

Fred Hartman Bridge, Baytown, TX, USA, 1995. LAP / URS

A special case of diamond towers in the case of very wide decks is the double diamond configuration (pictured). It offers the advantage of an efficient wind resisting mechanism in the transverse direction.

Special attention must be paid in the erection analysis of such tower systems, especially if the erection of the two independent decks is not performed concurrently. Controlling the geometry, stresses and foundation settlements can be a challenge in the case of a transversely asymmetric erection sequence.

Photo Credit:

By United States Coast Guard, PA2 James Dillard - U.S. Coast Guard Visual Information Gallery. U.S. Coast Guard Visual Information Gallery Home, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3499375

Illustrations Credit:

Svensson (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Overview

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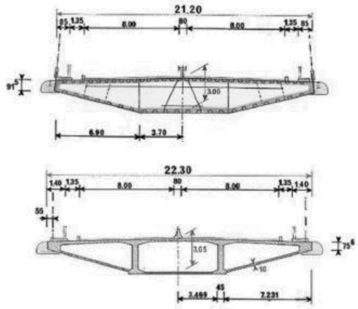
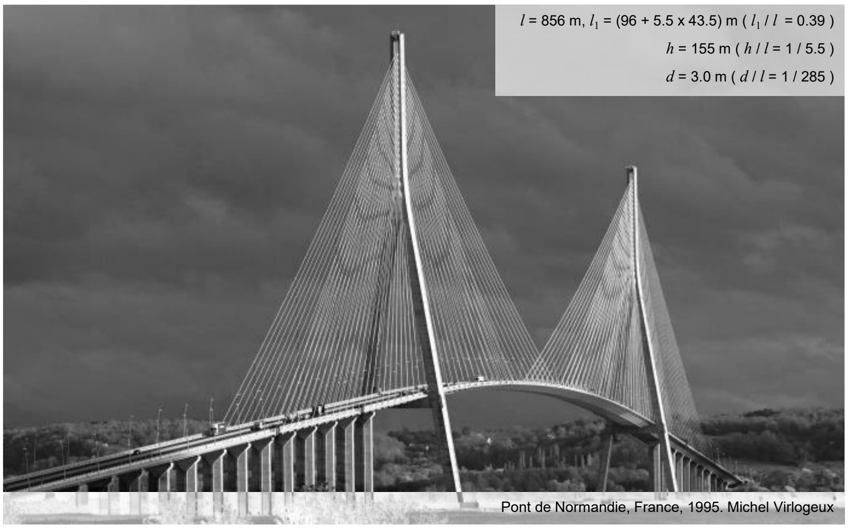
    - Inverted “Y” Tower





Inverted “Y” towers offer the same advantages as “A” towers, with the added benefit that in the case of the commonly used semi-fan cable arrangement, both cable planes are anchored to the tower along the same vertical axis, further enhancing the torsional stiffness and aerodynamic stability of the deck.

Photo Credit:

https://www.bouygues-construction.com/en/press/news/pont-de-normandie-still-standing-tall

Illustrations Credit:

Svensson, H. (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn.

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
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    - Inverted "Y" Tower

As in the case of girder bridges, the substructure elements (tower in this case) offer the opportunity to enhance the aesthetic appearance of cable-stayed bridges, often with minimal impact on total construction cost. However, it is also possible to result in structures that appear contrived where the form does not follow function.

Photo Credits:

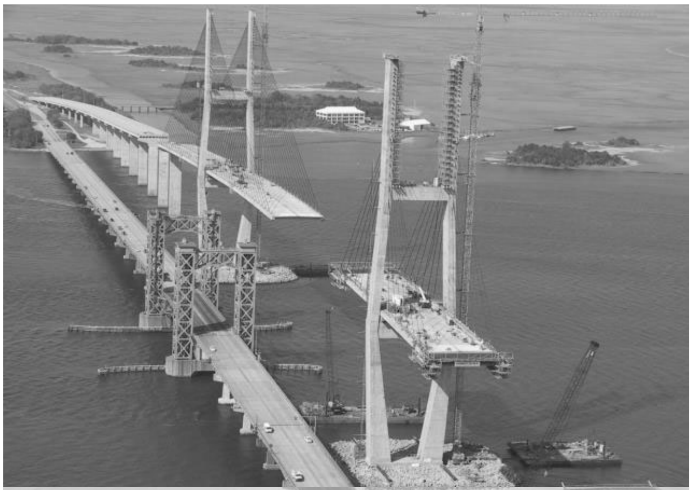
Top Left: https://www.tylin.com/en/projects/twin_river_bridge

Bottom Left: https://www.tylin.com/en/projects/sanhao_bridge

Right: https://www.arup.com/perspectives/publications/the-arup-journal/section/the-arup-journal-2019-issue-1

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
  - → Girder Type:
    - Flexible
      - Concrete Edge Girder
      - Steel / Composite Edge Girder
      - Hybrid: Concrete Edge Girder + Steel Floor Beams
    - Stiff
      - Concrete Box
      - Steel Box (Orthotropic)
      - Truss



Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

Flexible girder systems originated in Germany. Emphasis is placed on the axial loading of the stay cables and away from the bending strength of the girder (axial loading is more efficient than bending).

Stays supporting flexible girder systems typically exhibit higher fatigue stresses than in the case of stiff girder systems.

Photo Credit:

ttps://upload.wikimedia.org/wikipedia/commons/a/ab/SidneyLanierBridgeConstruction.jpg

Cable-supported bridges – Cable-Stayed Bridges: Overview

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      - Truss


Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT

Composite girder systems typically feature precast deck slabs that have cured sufficiently to allow the majority of shrinkage strains to occur unrestrained.

In the case of a CIP deck slab, the shrinkage takes place after the slab has been made composite with the steel girders. Due to the high degree of indeterminacy provided by the closely spaced stays the shrinkage strains cannot be accommodated in the same way as for a conventional girder bridge, resulting in crack control issues.

Photo Credit:

https://www.flatironcorp.com/project/port-mann-bridge-highway-1/

Cable-supported bridges – Cable-Stayed Bridges: Overview

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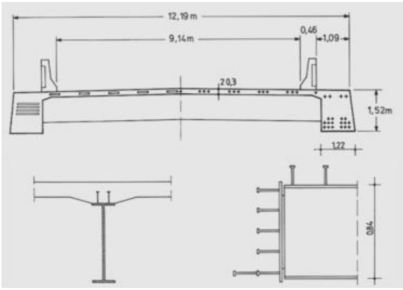

East Huntington Bridge, WV, USA, 1985. Arvid Grant / LAP

Hybrid systems offer the possibility to use concrete edge girders to carry the compression forces and light weight steel floor beams (acting compositely with the deck) to carry the traffic loads transversely to the edge girders.

Photo Credit:

https://bridgehunter.com/wv/cabell/6A215/

Illustration Credit:

Svensson, H. (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn.

Cable-supported bridges – Cable-Stayed Bridges: Overview

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      - Concrete Box
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      - Truss

Brotonne Bridge, Normandy, France, 1977. Jean Muller

Box girder systems originated in France. The main advantage is that the box girder can be combined with a single plane of stay cables due to its torsional rigidity. It can also be an economical solution if the same cross-section is used for the approach structures (cost of formwork and equipment is amortised over a longer length).

Photo Credit:

Left: https://www.bridgetech-world.com/blogs/the-bridge-club/twin-box-girders-for-precast-segmental-cable-stayed-bridges

Right: https://structurae.net/en/structures/brotonne-bridge

Cable-supported bridges – Cable-Stayed Bridges: Overview

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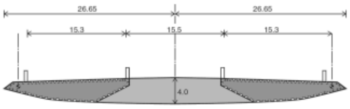

Stonecutters Bridge, Hong Kong, 2009. Arup / COWI

Typically used for spans longer than 600 m, where savings in weight and a streamlined cross-section is required.

Photo Credit:

https://www.bdonline.co.uk/wa-100/building-bridges-within-the-construction-industry/5010315.article

Illustration Credit:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:
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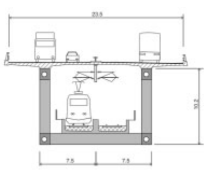
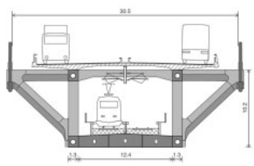
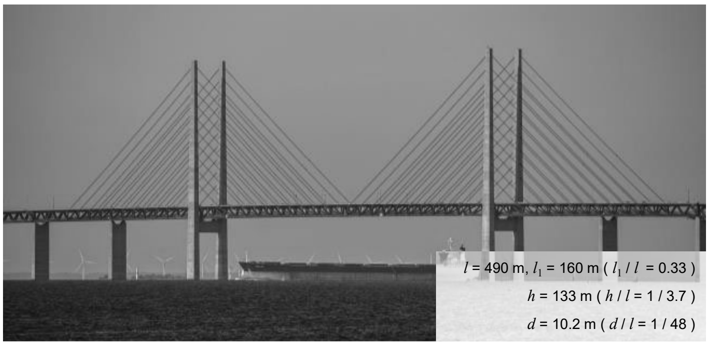






Øresund Bridge, Copenhagen, Denmark, 2000. COWI

Commonly used in the case of railway bridges and/or where double-deck systems are employed.

Photo Credits:

Top: By Jorchr - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=51733078

Bottom: https://en.wikipedia.org/wiki/%C3%98resund_Bridge

Illustrations Credit:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley.

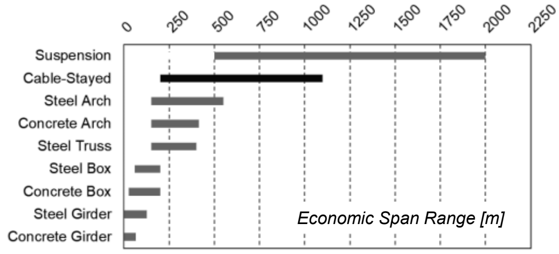
Cable-supported bridges

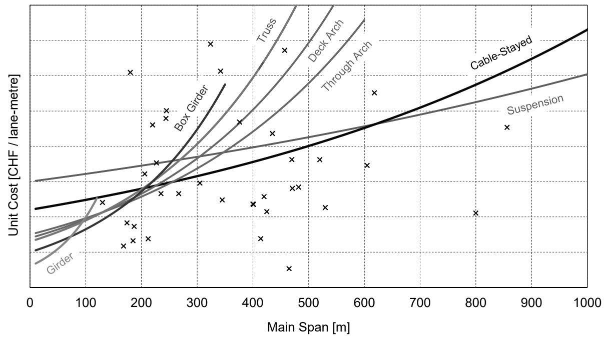
Cable-stayed bridges – Conceptual Design

Reference: The structure and content of this section is partially adapted from an in-house training course by Don Bergman (Vice President and Major Projects Director) at COWI North America in 2017.

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 … 1100 m)
  - → For very long spans (> 500 m) the only other alternative are suspension bridges
  - → For medium to long spans (200 … 500 m) there are several competing typologies, typically at a higher unit cost though
  - → For short to medium spans (< 200 m) girder bridges are usually more economical than cable-stayed bridges
  - → The area where the curves intersect (~ 200 m) is of great interest

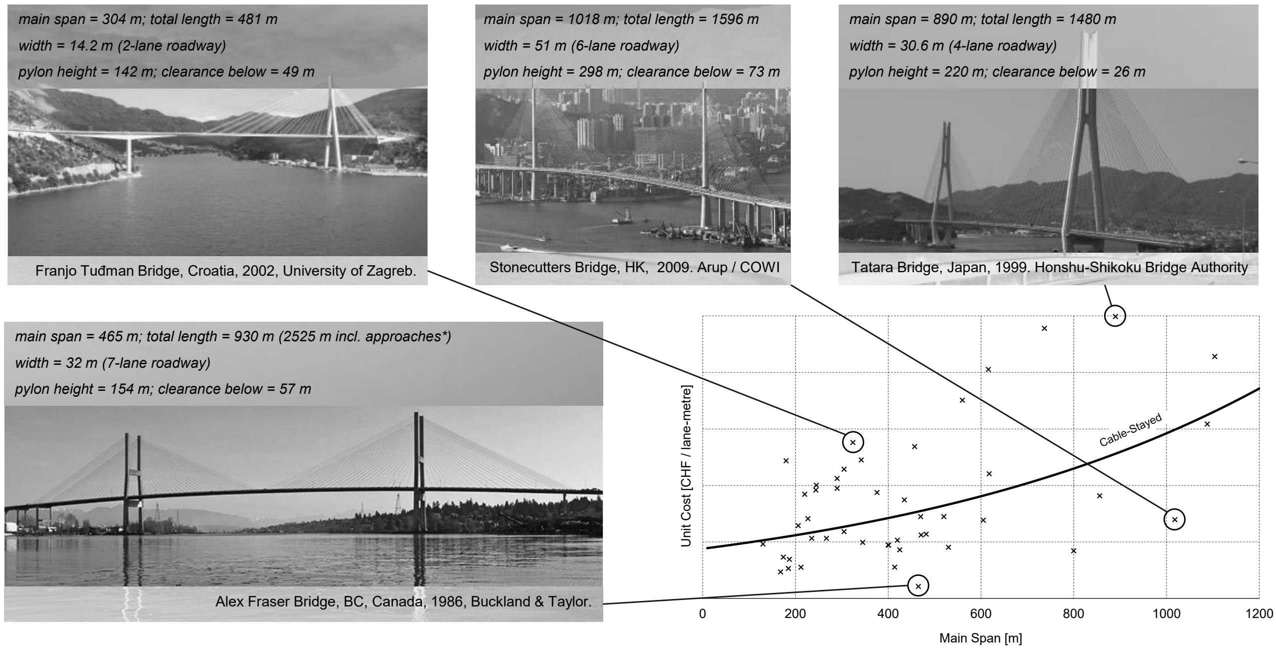




When referring to “Unit Cost vs. Main Span” curves to make an initial assessment on the most economical typology for a certain main span, it is important to keep in mind the wide scatter of data that is commonly associated with these “best-fit” curves. The figure above shows the data points used to create the curve for the cable-stayed bridges. The scatter may be attributed to several factors, including unique site conditions (e.g. high seismicity and/or extreme wind loading, foundations in open water and/or poor soil conditions, exposure to large vessel traffic and thus extreme collision forces), regional material and labour costs, and aesthetics-related choices.

Reference: http://hotrails.net/2014/09/an-empirical-rough-order-of-magnitude-cost-function-for-bridge-structures/

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design



04.04.2023 ETH Zürich | Chair of Concrete Structures and Bridge Design | Bridge Design Lectures 39

References:

Franjo Tuđman Bridge:

https://en.wikipedia.org/wiki/Franjo_Tu%C4%91man_Bridge_(Dubrovnik) (Photo)
https://structurae.net/en/structures/franjo-tudjman-bridge

Alex Fraser Bridge:

https://www.tylin.com/en/projects/alex_fraser_bridge (Photo)
https://structurae.net/de/bauwerke/alex-fraser-bruecke
https://en.wikipedia.org/wiki/Alex_Fraser_Bridge

* Unit cost includes approaches

Tatara Bridge:

https://structurae.net/en/structures/tatara-bridge (Photo)

Stonecutters Bridge:

https://commons.wikimedia.org/wiki/File:Stonecutters%27_Bridge2.jpg (Photo)
https://en.wikipedia.org/wiki/Stonecutters_Bridge
https://structurae.net/en/structures/stonecutters-bridge

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 … 1100 m)
  - → For very long spans (> 500 m) the only other alternative are suspension bridges
  - → Main disadvantages of suspension bridges vs. cable-stayed bridges are:
    - Construction time: Suspension cable spinning is a lengthy process (even if PPWS are used), while erection of stay-cables is faster and concurrent with deck erection
    - Earth anchorages of suspension cables are massive, while the horizontal component of stay-cable forces is resisted by the deck.
    - Cable quantity: Suspension bridges generally require more cable than cable-stayed bridges.
    - Aerodynamic stability & stiffness: Suspension bridges require decks with higher flexural and torsional stiffness than cable-stayed bridges.

Photo: Suspension cable installation: daelim.co.kr

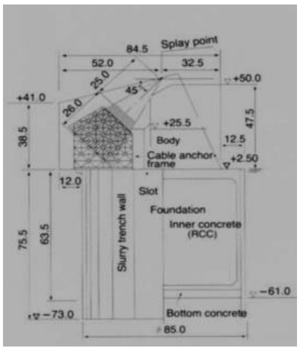
References:

Leonhardt F (1978). "Cable-Stayed Bridges for Long Spans", Reprint of an address given in Australia during November 1978, Printed by Lithocraft Graphics, South Melbourne.

Aschrafi M (1998). "Comparative investigations of suspension bridges and cable-stayed bridges for spans exceeding 1000 m", IABSE reports, Volume 79.

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

Suspension cable anchorage construction (Akashi Kaikyo Bridge):



This example of the suspension cable anchorage of the Akashi Kaikyo Bridge (Japan, 1998 – main span = 1991 m) illustrates the scale and scope of the construction process. It should also be noted, that the main construction steps involved in suspension bridges are sequential (i.e. construction of cable anchorages and towers, spinning of suspension cables, installation of hangers, erection of deck and stiffening girder), requiring each step to be completed before the next step commences, thus stretching the construction schedule. In contrast, erection of cable-stayed bridges is more incremental and certain construction steps (e.g. erection of stay cables and girder-deck system) are performed in parallel.

Illustration & Photo Credits:

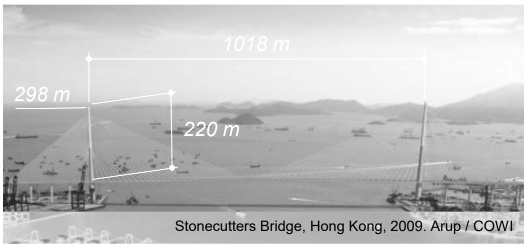
http://www.ams.ir/jozavat/Shegeftiha/Chapter2/Akashi-Kaikyo-Bridge.pdf

https://en.wikiarquitectura.com/building/akashi-kaikyo-bridge/#puente-akashi-constr-7

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  → Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 … 1100 m)
  → For very long spans (> 500 m) the only other alternative are suspension bridges

  → Suspension bridges become more economical for spans > 1000 m because:
    - High towers are required to ensure the stiffness of the cables (axially loaded flat cables are very inefficient, see static analysis of cables)
    - The high towers and the size of the associated stay cable fan generate very high wind loads
    - Vibration control of long stay cables becomes challenging



Stonecutters Bridge, Hong Kong, 2009. Arup / COWI

25 de Abril (Tagus River) Bridge, Lisbon, Portugal, 1966. Steinman, Boynton, Gronquist & Birdsall

Another disadvantage of cable-stayed bridges compared to suspension bridges relates to the potential for future deck replacement. In the case of suspension bridges, the deck system is mainly serving a functional role (i.e. providing the riding surface for vehicles) but it is not required to provide stability to the main load-carrying elements (suspension cable, towers, earth anchorages). Thus, it is possible to replace the deck system to extend its service life and/or modify its function. Such examples of deck replacement include:

Lions Gate Bridge, Vancouver, Canada (1938, deck replaced in 2001, main span = 473 m):

- First time deck of a major suspension bridge has been replaced.
- Replacement was facilitated by night-time and weekend closures where old sections of the deck were lowered to barges and new ones were lifted into place.
- Replacement allowed for moving pedestrian walkways to the outside of the hanger planes and widening of the road lanes from 3.0 m to 3.6 m.

Angus L. Macdonald Bridge, Halifax, Canada (1955, deck replaced in 2017, main span = 441 m):

- Similar replacement methods as for the Lions Gate Bridge (COWI was the principal designer for the deck replacement of both bridges).
- Hangers were also replaced (became longer) because the new stiffening trusses were relocated from above to below the deck level.

References:

https://en.wikipedia.org/wiki/Lions_Gate_Bridge

https://en.wikipedia.org/wiki/Angus_L._Macdonald_Bridge

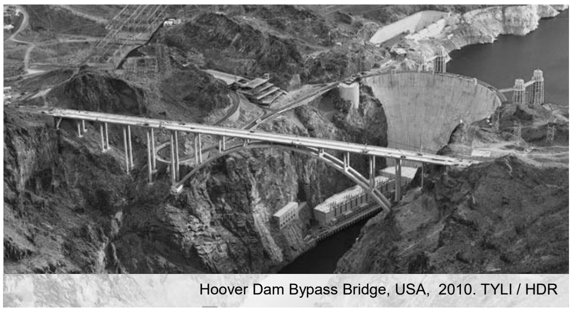
Photo Credits:

http://bestbridge.net/Asia_en/stonecutters-bridge.phtml

https://commons.wikimedia.org/wiki/File:25_De_Abril_Bridge_(45711364404).jpg

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  → Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 … 1100 m)
  → For medium to long spans (200 … 500 m) there are several competing typologies:
    - Cantilever truss / Arch truss bridges: High life-cycle costs, spans up to 550 m
    - Concrete true arch bridges: Require specific ground conditions to resist thrusts, spans up to 450 m
    - Steel/CFST true arch bridges: High life-cycle costs, spans up to 600 m
    - Tied-arch bridges: Perceived lack of redundancy, spans up to 550 m
    - Concrete girder bridges: spans up to 300 m
    - Steel girder bridges: spans up to 300 m


Hoover Dam Bypass Bridge, USA, 2010. TYLI / HDR

(Continued from previous slide):

In contrast to suspension bridges (and thrust arches like the one shown above), in a cable-stayed bridge the girder-deck system is essential to the structural stability of the bridge, as it anchors the stay cables. While this function of the girder-deck system contributes to the overall efficiency and economy of cable-stayed bridges, it also means that future replacement is practically impossible or extremely challenging at best. Concepts involving installation of temporary framing systems that can transfer (bypass) the deck thrust while section of the deck is being replaced have been proposed as part of Maintenance and Operation manuals of new cable-stayed bridges, however execution of such concepts has not been attempted to date. As the stock of cable-stayed bridges becomes older in the decades to come and maintenance needs increase, this disadvantage will perhaps become more relevant.

The bottom photo of the Hoover Dam Bypass Bridge illustrates the advantage of cable-stayed bridges over arch bridges with respect to the erection process. Arch bridges often require temporary stays and towers to construct the arch ribs, essentially constructing a temporary cable-stayed bridge in the process. In the case of cable-stayed bridges, the permanent structural members (towers & stay cables) are also part of the superstructure erection method, thus requiring significantly fewer temporary works.

Photo credit:

https://www.tylin.com/en/projects/hoover_dam_bypass_bridge, Jamey Stillings Photography

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
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  - → For medium to long spans (200 … 500 m) there are several competing typologies:
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    - Concrete true arch bridges: Require specific ground conditions to resist thrusts, spans up to 450 m
    - Steel/CFST true arch bridges: High life-cycle costs, spans up to 575 m
    - Tied-arch bridges: Perceived lack of redundancy, spans up to 550 m
    - Concrete girder bridges: spans up to 300 m
    - Steel girder bridges: spans up to 300 m


Bugrinsky Bridge, Russia, 2014. Albert Koshkin / Sibmost

Network tied-arch bridges are a competing alternative to cable-stayed bridges at the lower end of the economic span range of cable-stayed bridges (200 … 300 m). Tied arches are especially appropriate in the case of river crossings, where typically the soil conditions would not allow for thrust arches. The main disadvantage of network tied-arch bridges is that, while they are very efficient in their final configuration, they require substantial temporary works during erection. This is particularly an issue when clearances, e.g. a navigation channel, need to be maintained during erection. In such a case, cable-stayed bridges have the advantage due to their cantilevered construction method, unless it possible to construct the tied arch off-site and then float into place [see for instance Lake Champlain Bridge, NY, USA (2011) and Wellsburg Bridge, WV, USA (2023)].

Arch Float-In References:

Lake Champlain Bridge construction time lapse:
https://www.youtube.com/watch?v=r5KSCqtcjq4&ab_channel=EarthCam

Wellsburg Bridge construction time lapse:
https://www.youtube.com/watch?v=eQCbIEgPt6A&ab_channel=Mammoet

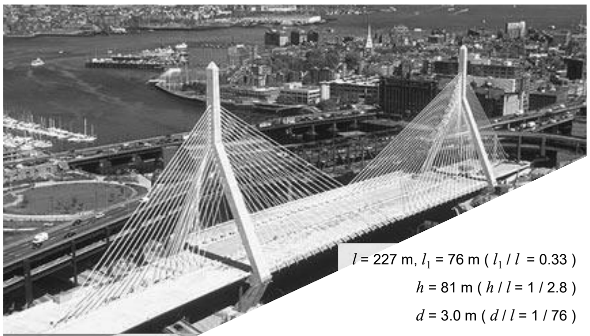
Photo credits:

Top: By Alexey Salmin - Own work, CC BY-SA 4.0,
https://commons.wikimedia.org/w/index.php?curid=42656129

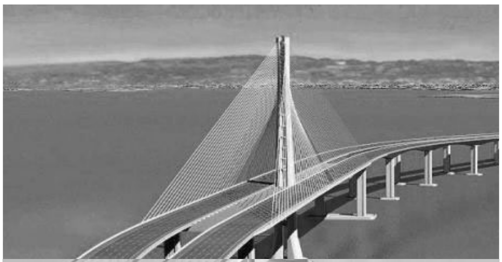
Bottom: https://bashny.net/t/en/263521

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Based on economic criteria alone cable-stayed bridges could be the preferred typology for spans in the 200 … 1100 m range.
  - → However, for aesthetic reasons (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.



Leonard P. Zakim Bunker Hill Memorial Bridge, Boston, USA, 2003. FIGG / HNTB


San Francisco – Oakland Bay Bridge: Cable-Stayed Alternative


San Francisco – Oakland Bay Bridge, USA, 2013. TYLI

The main span of the new San Francisco – Oakland Bay Bridge (pictured bottom right) is an example where the owner (with public input) opted for a self-anchored suspension bridge to match the aesthetics of the neighbouring existing Bay Bridge and the Golden Gate Bridge (both suspension bridges built in the 1930's). A cable-stayed bridge (rendered top right) would have been much more economical.

The Zakim Bridge (pictured bottom left) was conceived as a signature span, part of a mega project (the most expensive highway project in the US) built mostly during the 1990's in Boston, MA. Officially named the Central Artery/Tunnel Project, commonly known as the Big Dig, it mainly involved rerouting of an interstate highway below ground through the city centre. The Zakim Bridge has become an icon of the city and is often used as a backdrop to establish location. With a relatively modest main span of 227 m, a cable-stayed bridge was perhaps not the most economical solution, a fact that is accentuated by the presence of the adjacent Leverett Circle Connector Bridge, which features a more conventional steel box girder solution crossing a similar span.

Rendering of SFOBB Cable-Stayed Alternative:

David Goodyear & John Sun (2003), "New Developments in Cable-Stayed Bridge Design, San Francisco," Structural Engineering International 1/2003

Photo Credits:

Left: http://wfrjr.com/data/bridge/Boston/LeonardZakim.html (Leonard P. Zakim Bunker Hill Memorial Bridge, Main Span = 227 m)

Right: https://www.bayareafastrak.org/en/home/index.shtml

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Based on economic criteria alone cable-stayed bridges could be the preferred typology for spans in the 200 … 1100 m range.
  - → However, for aesthetic reasons (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.
  - → Also, height restrictions (e.g. due to proximity to an airport) may preclude the relatively tall towers required for a cable-stayed bridge. An extradosed bridge could be a viable alternative in this case (spans up to 270 m).

Rose Fitzgerald Kennedy Bridge, Ireland, 2020. Arup / Carlos Fernandez Casado SL.

Ibi Gawa Bridge, Japan, 2001. CTI Engineering Co. Ltd.

Extradosed bridges can be a competitive alternative to girder and cable-stayed bridges for main spans in the 150-250 m range, particularly when clearance constraints below and above the deck level do not allow for the girder depth that would be required for a girder bridge and the tower height that would be required for a cable-stayed bridge.

Photo Credit:

Top: By An Dearthoir - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=86362713 (Rose Fitzgerald Kennedy Bridge, Main Span = 230 m)

Bottom: https://structurae.net/en/structures/ibi-gawa-bridge (Ibi Gawa Bridge, Main Span = 271.5 m)

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Based on economic criteria alone cable-stayed bridges could be the preferred typology for spans in the 200 … 1100 m range.
  - → However, for aesthetic reasons (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.
  - → Also, height restrictions (e.g. due to proximity to an airport) may preclude the relatively tall towers required for a cable-stayed bridge. An extradosed bridge could be a viable alternative in this case (spans up to 270 m).
  - → Conversely, a cable-stayed bridge could be selected for spans shorter than 200 m when a signature bridge is desired.
    - Increased cost for towers and cables must be accepted
    - Inherent complexities of this typology are still present even for relatively short spans

Esplanade Riel, Winnipeg, Canada, 2003. Buckland & Taylor Ltd.

Photo Credit:

https://structurae.net/en/structures/esplanade-riel (Esplanade Riel, Main Span = 106 m)

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

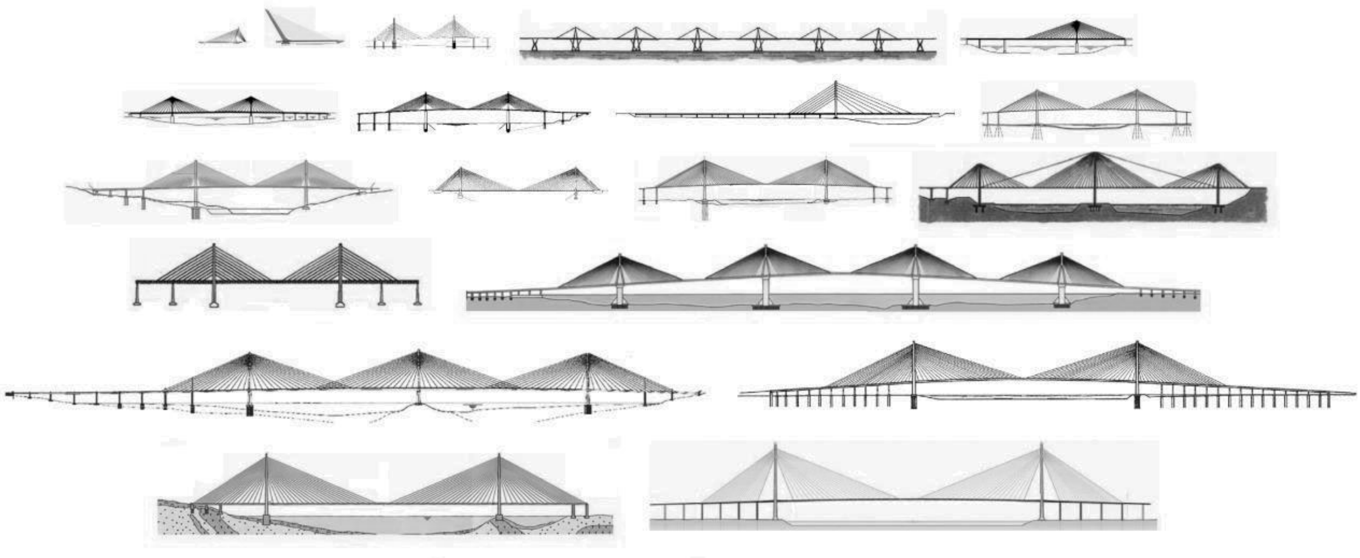


Illustration Credits:

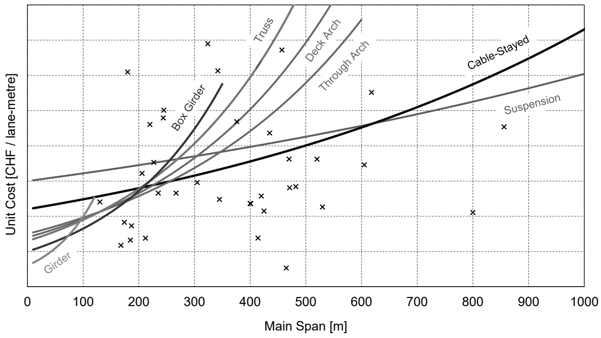
Walther, R., Houriet, B., Isler, W., Moïa, P. & Klein, J.F. (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford.

Svensson, H. (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn.

https://www.cfcsl.com/en/portfolio/lerez-bridge-pontevedra-spain-1995/

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  - → Unit costs for cable-stayed bridges vary considerably:
    - Due to wide range of spans
    - Due to special conditions associated with mega-projects
    - Due to aesthetics-related choices
  - → In order to achieve an economic design, we must understand the economics of cable-stayed bridge construction:
    - What constitutes the "base case" design?
    - What are the features requiring a premium over the "base case" and when/how these should be added?



Seri Wawasan Bridge, Putrajaya, Malaysia, 2003. PJSI

Photo Credit:

By Gryffindor - Own work This panoramic image was created with Autostitch (stitched images may differ from reality)., CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=2987051

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:
  → "Base Case" Cable-Stayed Bridge:
    - Minimalist solution: nothing can be taken away
    - Aesthetically pleasing if carefully executed
  → Basic features of design concept:
    - Symmetry about mid-span and centreline
    - Closely spaced stay cables
    - Two vertical towers, two anchor piers (three spans)
    - Semi-fan stay cable arrangement in vertical plane(s)

- Open cross-section: edge girder & floor beam (composite or concrete)
- Two cable planes
- H-tower

- Closed cross-section: box girder (concrete)
- One cable plane
- Single tower


Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI


Puente Centerario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP

Photo Credits:

Top: https://structurae.net/en/structures/sidney-lanier-bridge

Bottom: https://www.tylin.com/en/projects/panama_canal_second_crossing

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Planning and bridge concept selection:

  Enhancements to the “base case” design resulting to a cost premium may be required due to:

  → Wind (aerodynamic) effects:
  - Tower: “A” or Inverted “Y”
  - Girder: Streamlined box cross-section

  → Seismic effects:
  - Increased strength and/or ductility demands (more complicated detailing)
  - Special devices: Lock-up-devices, energy dissipating dampers, tuned-mass dampers

  → Hardening:
  - Important structures often require an Accident and Terrorist Vulnerability Assessment (ATVA)
  - Protection of stay cables against fire, blast, cutting charges, etc.

  → Aesthetic requirements

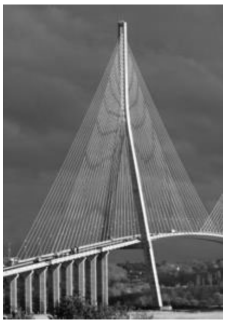
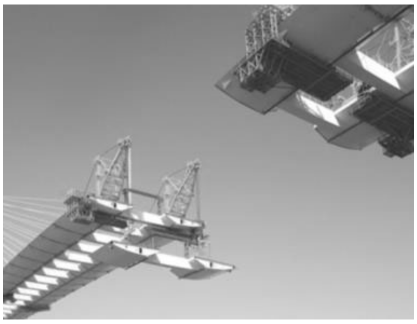



Photo Credits:

Top left: https://www.bdonline.co.uk/wa-100/building-bridges-within-the-construction-industry/5010315.article

Top right: https://www.bouygues-construction.com/en/press/news/pont-de-normandie-still-standing-tall

Bottom left: https://www.fipindustriale.it/index.php?area=108&menu=99&page=302&lingua=1&idsession=95687544

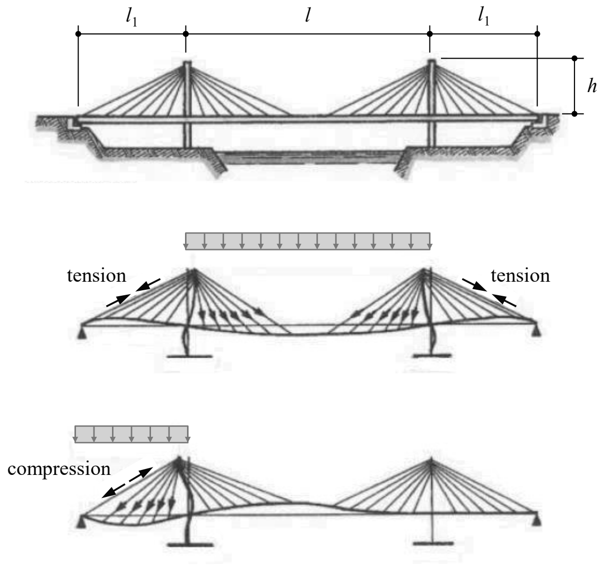
Bottom Right: http://www.freyssinet.com/freyssinet/wfreyssinet_en.nsf/0/53574A4D01DC20F2C12584190037E403/$file/BRIDGE%2095.PDF

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Basic proportions of cable-stayed bridges:

  The geometry of cable-stayed bridges is determined by the following ratios:

  → Side spans (l_1) to main span (l) ratio:
  - Backstays govern the stiffness of the bridge and are subject to significant stress reversals
  - l_1 / l ratio determines the fatigue stress range in the backstays and demands for tie-down devices / counterweights at anchor piers



Illustrations Credit:

Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

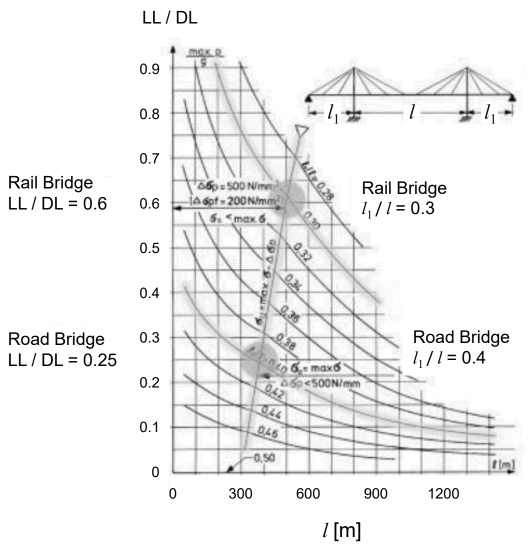
- Basic proportions of cable-stayed bridges:

  The geometry of cable-stayed bridges is determined by the following ratios:

  → Side spans (l_1) to main span (l) ratio:
  - Backstays govern the stiffness of the bridge and are subject to significant stress reversals
  - l_1 / l ratio determines the fatigue stress range in the backstays and demands for tie-down devices / counterweights at anchor piers
  - Optimum l_1 / l ratio depends on LL / DL ratio:
    - Road bridges, l_1 / l = 0.4 … 0.5
    - Rail bridges, l_1 / l = 0.3 … 0.4

  → Tower height (h) to main span (l) ratio:
  - Controlled by flattest stay: optimum angle ≈ 23 deg (inclination ca. 40%)
  - Optimum h / l ratio ≈ 1/5 (compare to 1/10 for suspension bridges)

Recommended side span / main span ratios [Svensson 2012]



A side span to main span ratio of less than 0.5 allows for tensioning of the backstays and results in a stiffer structure.

Shortening the side spans reduces the total cable-supported length and can therefore result in savings (assuming that conventional girder approach spans are more economical) but results in higher tie-down demands and complicated connection details at the anchor piers.

The fatigue stress range in the backstays increases with increasing l_1/l ratio, while the effective cable stiffness decreases. Therefore, side spans for rail bridges are typically shorter than for road bridges to reduce the fatigue stresses in the backstay cables.

Illustrations Credit:

Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- Design Development:
  - → Project Specific Design Criteria:

    Long-span, cable-supported bridges are typically not fully covered by the provisions of standard bridge codes. Topics that may require development of project-specific criteria (→ service criteria agreement) may include:

    - Load combinations
    - Serviceability requirements, e.g. deflection limits
    - Wind loading / Aerodynamic vibrations
    - Stay cable systems acceptance criteria
    - Progressive collapse requirements (e.g. accidental cable loss)
  - → Guideline documents for stay cable design, testing and installation have been developed to supplement the standard bridge codes

Guideline Documents:

PTI (2018), DC45.1-18: Recommendations for Stay Cable Design, Testing, and Installation, Post-Tensioning Institute.

Setra (2002), Cable Stays – Recommendations of French international commission on Prestressing

fib Bulletin 89 (2019): Acceptance of cable systems using prestressing strands (Recommendation) [replaced Bulleting 30].

Cable-supported bridges

Cable-stayed bridges – Structural Response

Reference: The structure and content of this section is partially adapted from an in-house training course by Dr. Armin Schemmann (Senior Bridge Specialist) at COWI North America in 2017.

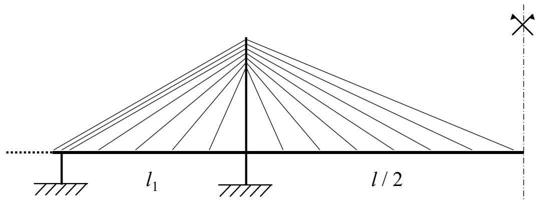
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

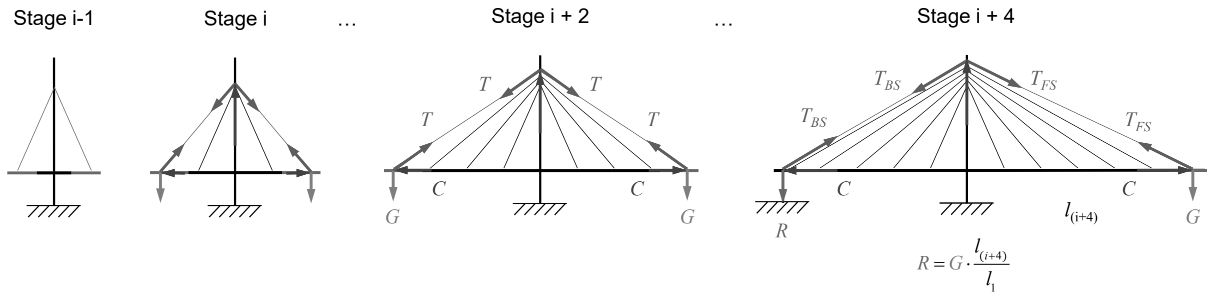
- Basic load-carrying mechanism of a cable-stayed bridge:

  → Response to Dead Load:

  Stay cables:

  - Each stay cable can be assumed to support a tributary length of the girder
  - Backstays are the exception: they are used to resist the unbalanced load in the main span





During the erection stages when girder and deck segments are installed symmetrically about the tower, the stay cable forces (and corresponding compressive forces in the superstructure) can be calculated by considering force equilibrium at the deck level (see illustrated Stages i and i+2).

After the back span “lands” on the anchor pier and segments are only added on the main span side, the forestay cable forces may still be estimated by considering force equilibrium at the deck level. However, the corresponding backstay cable force should now be calculated by considering horizontal equilibrium at the top of the tower. Once the backstay force has been determined, the uplift force resisted by tie-downs/counterweights at the anchor pier can be calculated by force equilibrium at the deck level (see illustrated Stage i+4).

Refer to Chapter 9.1 – Common Aspects, Static analysis of Cables, Axial stiffness of laterally loaded cables for details on the non-linear (geometric) behaviour of stay cables.

Current FEA software such as SOFiSTiK, RM Bridge, and LARSA 4D feature cable elements that are able to model the non-linear response of stay cables. Note that a non-linear analysis must be performed in order to take advantage of the cable element capabilities. Such an analysis is required for modelling the erection stages in order to obtain deformation and stress results of sufficient accuracy to control geometry and stresses during construction.

Analysis of the completed bridge under transient loading can be performed with sufficient accuracy by superposition of linear analyses, where cables are treated as chorded (truss) elements with an idealised modulus of elasticity (see Chapter 9.1).

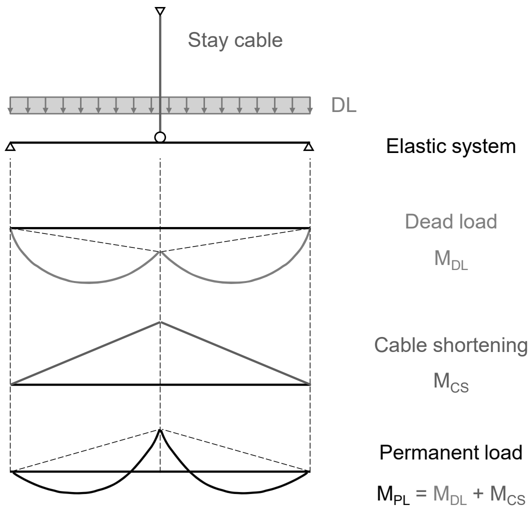
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Basic load-carrying mechanism of a cable-stayed bridge:

  → Response to Dead Load:

  Stay cables:
  - Each stay cable can be assumed to support a tributary length of the girder
  - Backstays are the exception: they are used to resist the unbalanced load in the main span

  Girder:
  - DL application on the elastic system results in significant deflections and corresponding moments
  - Appropriate cable shortenings are required to restore the girder to the target profile and moment diagram



Considering the simple case of a propped beam, it can be seen how the final bending moment diagram under permanent loads can be adjusted by imposing appropriate cable shortening.

Illustrations Credit:

Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Basic load-carrying mechanism of a cable-stayed bridge:

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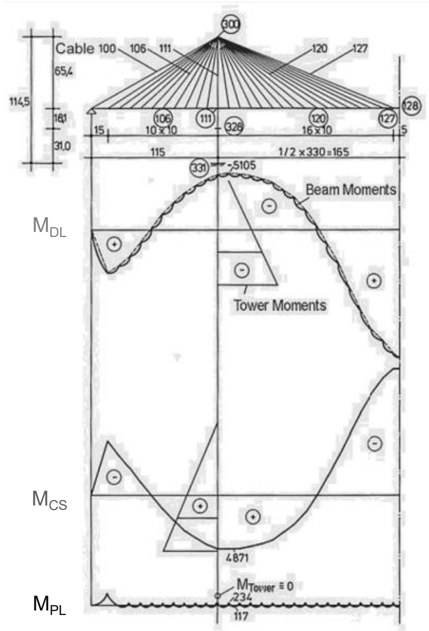


Extrapolating the concept of the propped beam shown on the previous slide for the case of a cable stayed bridge, it can be seen how by applying appropriate shortenings to each stay cable, the girder moments under permanent load can be balanced, while the tower moments are practically eliminated (see M_{PL} diagram). Note that the principle of superposition illustrated here does not hold in the case of large deformations (geometric nonlinearities) which is generally the case for cable-stayed bridges during erection. Therefore, a more rigorous iterative analysis is generally required, which considers all construction stages, including temporary members/structures if applicable, and accounts for the geometric nonlinearities.

Note, that if a cable-stayed bridge is modelled in an analysis software and the permanent loads are applied, i.e. as if the superstructure was constructed on falsework, the analysis will result in huge deflections at mid-span and the towers will lean towards each other, as is evident by the M_{DL} diagram above. In order to obtain the desired deck profile and a balanced moment diagram, appropriate cable shortenings must be applied, while in order to obtain plumb towers, the backstays must be shortened.

Illustrations Credit:

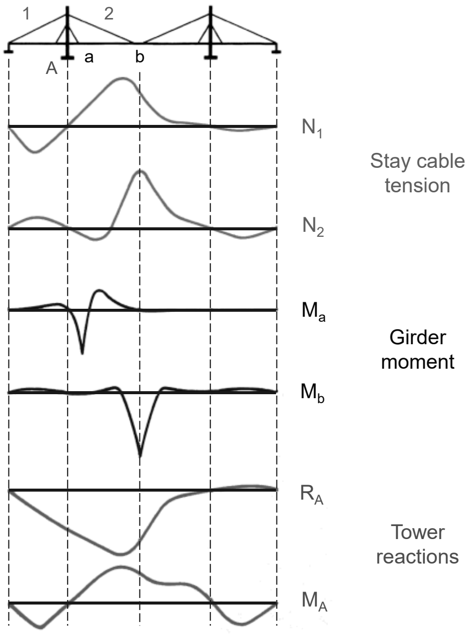
Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Basic load-carrying mechanism of a cable-stayed bridge:
  → Response to Live Load - Characteristic Influence Lines:
  Stay cables:
  - The backstay function is fundamental to the efficiency of the bridge
  - Backstays have very "broad" influence line: design controlled by fatigue in railway bridges (fatigue loads extending over large portion of span)

  Girder:
  - Behaviour similar to beam on elastic foundation
  - Function of girder stiffness, cable stiffness and cable spacing

  Towers / Anchor Piers:
  - Provided that the tower is anchored through backstays to an anchor pier, the tower resists mainly vertical reactions
  - In the absence of an anchor pier, the influence of the tower stiffness to the girder response is much more pronounced (see also multi-span cable-stayed bridges)



Note that the above influence lines correspond to the typical arrangement where the towers are stabilised through backstays and anchor piers.

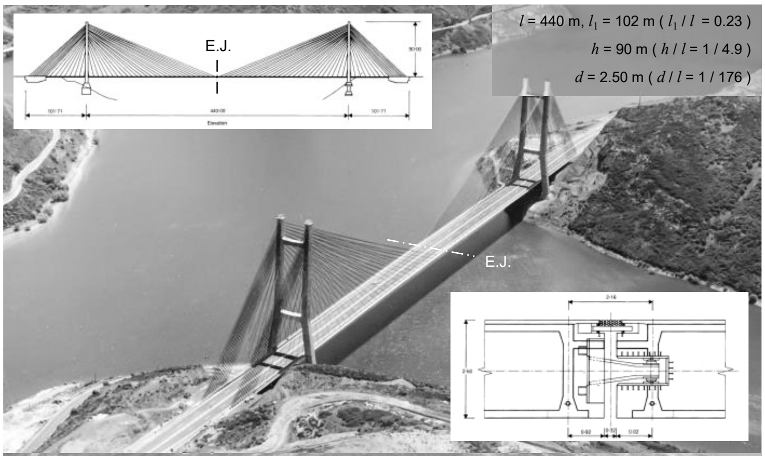
In the absence of an anchor pier, the influence of the tower stiffness in the structural response is much more pronounced. For this reason the girder is often integral with the tower to compensate for the lack of stiffness that the backstays and anchor piers would normally provide.

Illustrations Credit:

Rene Walther (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Support and articulation
    - Girder must be continuous through towers (highest axial compression), but can be articulated at mid-span (not recommended)
    - Girder is commonly articulated at anchor piers, but may also be made continuous with the approach span girder
    - The connection between the girder and towers / anchor piers in the vertical, longitudinal and transverse directions can be tailored to best fit the governing loading and site conditions:
      - ✓ The concepts presented in the Support and Articulation section are generally applicable



Carlos Fernandez Casado Bridge, León-Oviedo, Spain, 1983. CFCSL.

Photo Credit:

http://www.cfcsl.com/puente-carlos-fernandez-casado/

Illustrations Credit:

Rene Walther (1999), "Cable-Stayed Bridges," 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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    - The connection between the girder and towers / anchor piers in the vertical, longitudinal and transverse directions can be tailored to best fit the governing loading and site conditions:
      - ✓ The concepts presented in the Support and Articulation section are generally applicable


Pin Bearing


Fred Hartman Bridge, Baytown, TX, USA, 1995. LAP / URS


Rocker Bearing


Ting Kau Bridge, Hong Kong, 1997. Sclaich Bergermann Partner

Photo Credits:

By United States Coast Guard, PA2 James Dillard - U.S. Coast Guard Visual Information Gallery. U.S. Coast Guard Visual Information Gallery Home, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3499375

Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

https://sites.google.com/site/constructivedevelopments/ting-kau-bridge

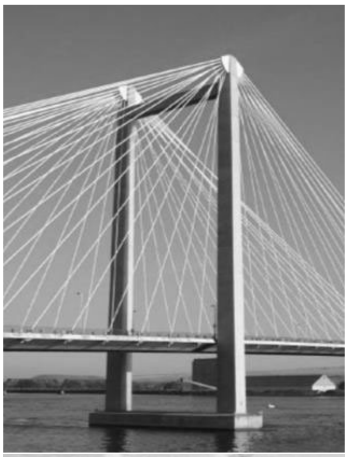
https://www.mageba-group.com/ca/fr/1023/Asie/Chine/19708/Ting-Kau-Bridge.htm

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Support and articulation

- Girder must be continuous through towers (highest axial compression), but can be articulated at mid-span (not recommended)
- Girder is commonly articulated at anchor piers, but may also be made continuous with the approach span girder
- The connection between the girder and towers / anchor piers in the vertical, longitudinal and transverse directions can be tailored to best fit the governing loading and site conditions:
  - ✓ The concepts presented in the Support and Articulation section are generally applicable


Floating Deck – No connection to tower

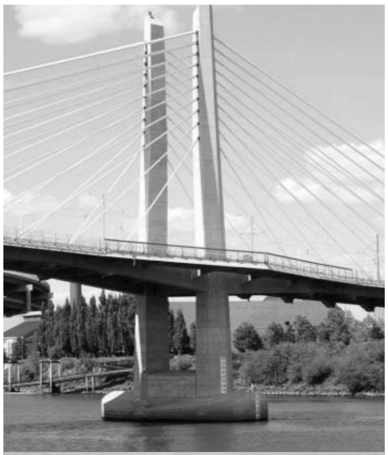

Integral Deck – monolithic connection to tower

Photo Credits:

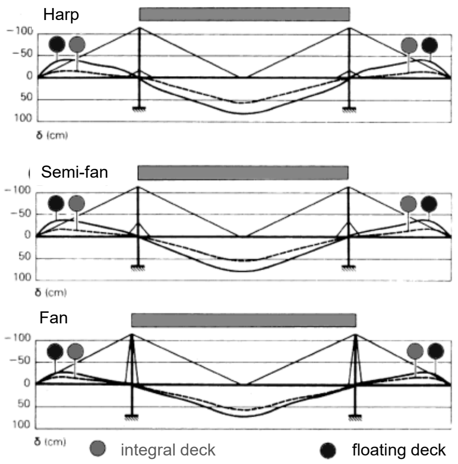
Left: https://www.bridgemeister.com/pic.php?pid=1774

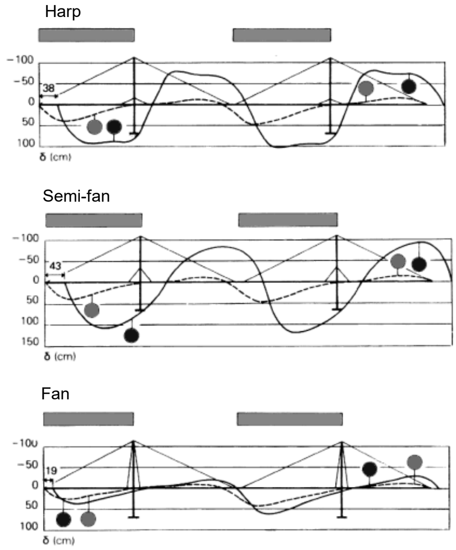
Right: https://www.travelportland.com/attractions/tilikum-crossing/

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Support and articulation – influence of girder/tower connection [*modified after Walther et al. 1999*]:

Deck deformations under LL for the two extreme cases (integral/floating):





Asymmetric LL causes longitudinal deck displacement

Vertical deflections can increase 3x when deck is released

LL effects are less sensitive to deck articulation for fan pattern

Walther et al. (1999) examines the influence of the connection between the girder and tower by comparing the two extreme cases: floating vs. integral deck. A floating deck under live load, especially when asymmetric, is subjected to higher deflections and bending moments than an integral deck. However, a floating deck can be advantageous when dealing with imposed deformations, e.g. due to creep, shrinkage, temperature and/or seismic effects. The optimum articulation scheme may consist of a hybrid solution, e.g. partial fixity to one tower and/or use of dampers/lock-up-devices.

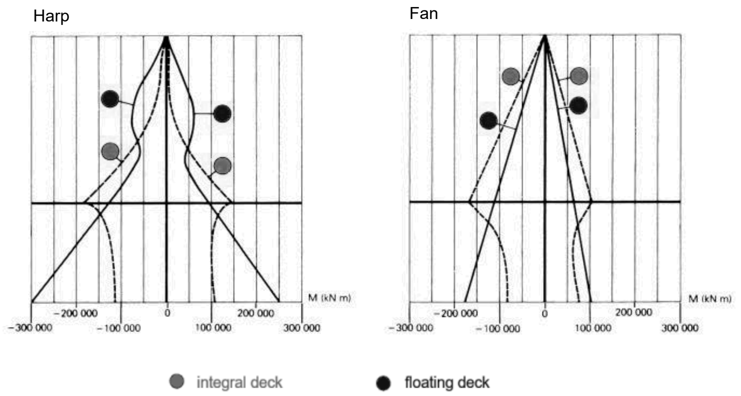
Note that the assumed geometric proportions for the above study are l_1/l = 0.43 and h/l = 1/4.25.

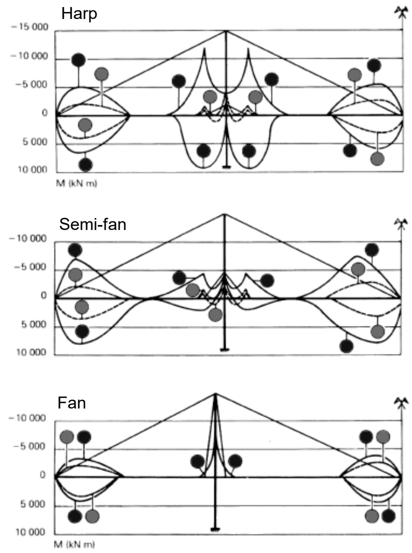
Reference: Rene Walther (1999), “Cable-Stayed Bridges,” 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Support and articulation – influence of girder/tower connection [*modified after Walther et al. 1999*]:

Tower & Deck moment envelopes under LL for the two extreme cases (integral/floating):





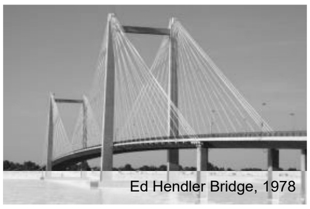
LL effects are less sensitive to deck articulation for fan pattern

See previous slide for notes.

Reference: Rene Walther (1999), “Cable-Stayed Bridges,” 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Support and articulation – Example



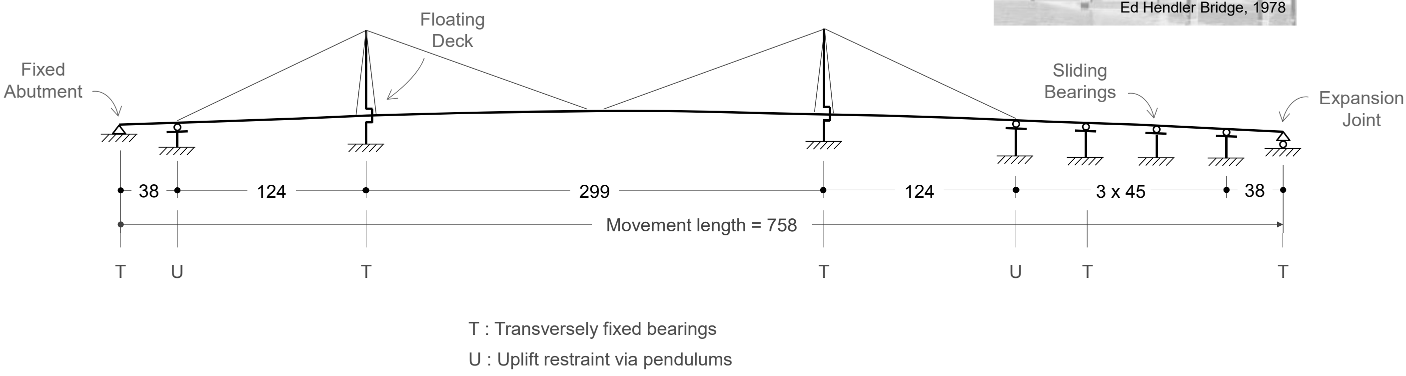


Photo Credit: https://www.bridgemeister.com/pic.php?pid=1774

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

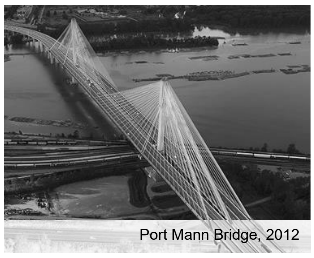
  → Support and articulation – Example

  E : Expansion joint

  F : Longitudinal fixed bearings

  U : Uplift restraint via sliding tie-downs

  D : Viscous dampers (longitudinal)



Port Mann Bridge, 2012

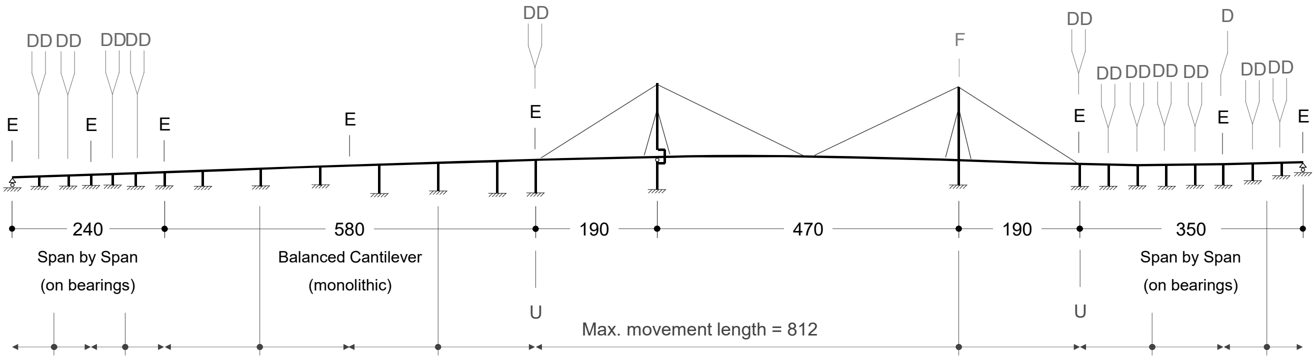


Photo Credits:

https://www.tylin.com/en/projects/port_mann_bridgehighway_1_project (Thomas Heinser Studio)

Google Street View

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

  → Tower stability

  - Towers are typically slender and subject to high axial compressive forces → 2nd order effects important
  - Towers are often most vulnerable during the construction phase: boundary and loading conditions are less favourable than in the final state
  - Flexural stiffness and strength are a function of the axial load

Buckling load depends on EI and kL:

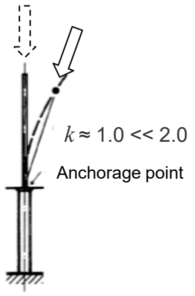
$$P_{cr} = \pi^2 \frac{EI}{(kL)^2}$$

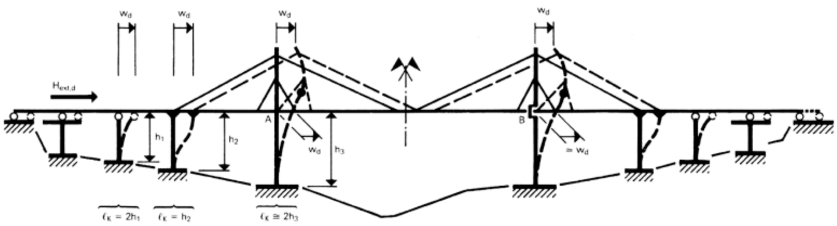
EI varies based on the level of cracking

$k_{\min} = 0.8$

$k_{\max} = 2.0$

$$\left(\frac{k_{\max}}{k_{\min}}\right)^2 = 6.25$$





Illustrations Credit:

Rene Walther (1999), “Cable-Stayed Bridges,” 2nd Edition, Thomas Telford

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  → Tower stability - Example

Arthur Ravenel Jr. (Cooper River) Bridge, SC, USA, 2005. Parsons Brinkerhoff Quade & Douglas

Consider the example of the Cooper River Bridge to illustrate how the boundary conditions for assessing the tower stability change during construction of the bridge.

Photo Credits (Slides 64-67):

https://structurae.net/en/structures/arthur-ravenel-jr-bridge

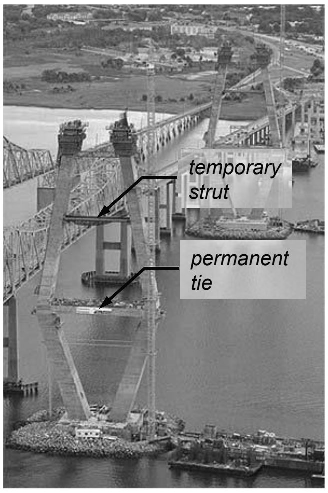
https://ravenelbridge.net/

Note: The latter link contains a series of photos documenting the erection process of the Cooper River Bridge and provides useful insights into certain construction processes/details.

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

  → Tower stability - Example



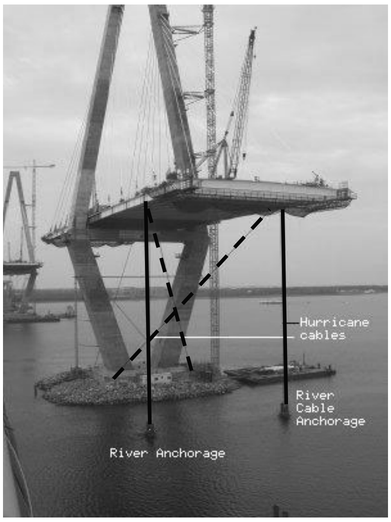
The inclined legs of the lower half of the diamond are erected in lifts. At a certain height, to control the bending moments at the base of the legs, a temporary tie is installed (pictured left).

Once the permanent tie is installed at the kinks of the legs, erection of the upper half of the diamond continues. At a certain height, to control the bending moments at the kink, a temporary strut is installed (pictured middle).

Once construction of the tower is completed, the superstructure is symmetrically erected in segments propped by the corresponding stay cables. The tower is behaving as a cantilever in the longitudinal direction (pictured right).

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Tower stability - Example



Once the superstructure reaches a certain length, in order to control the effects of unbalanced loading on the tower, either due to vertical or horizontal loading, temporary cables are installed. The vertical cables (typically installed on the back span side so that the main span provides the required navigation clearance) stabilise the tower against unbalanced vertical loading on the deck, either due to dead loads, construction equipment, or wind loads (pictured left). The “X” ties stabilise the tower against unbalanced wind loads that tend to twist the tower about the vertical axis (weather-vaning) (pictured left and right).

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Tower stability - Example

The tower is typically at its most “vulnerable” state just prior to landing at the anchor pier. Subsequently, backstay cables are installed that stabilise the top of the tower.

Note that some of the earlier cable-stayed bridges featured towers that were pin-supported at their base (see Strömsund Bridge, 1956 – Chapter 9.1). This was due to the limited computational capabilities of that period, when designers tended to try to reduce the degree of indeterminacy. Nowadays, the cost to temporarily support a pinned tower during erection would offset any cost-savings of reducing the final, in-service moments of the tower.

In general, earlier cable-stayed bridges often featured slender towers in an effort to minimise material quantities. However, overall cost of cable-stayed bridges is typically defined by the construction process and not necessarily the least material. Slender towers require stabilization during erection through temporary works, significantly increasing the overall cost. Contemporary towers are therefore designed heavier than in the past, using more material but resulting in overall less cost.

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Redundancy requirements: Accidental cable loss
    - Modern cable-stayed bridges are designed with closely-spaced stay cables so that accidental loss of a cable will not result in progressive collapse
    - Furthermore, stay cables are considered replaceable components and therefore cable exchange must be possible during service
    - Planned cable exchange is performed strand by strand and therefore imposes static loading to the structure
    - Accidental cable loss, depending on the cause, can be relatively sudden (i.e. relative to the eigenfrequencies of the bridge) and must therefore be treated as dynamic loading

Seohae Grand Bridge, South Korea, 2000, TYLI

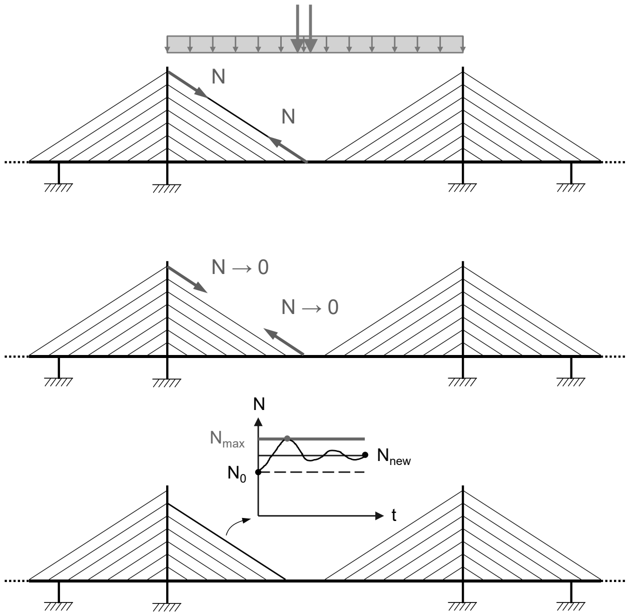
Some owners' requirements may exceed those recommended in codes/guidelines, e.g. consideration of loss of more than one cable at a time.

Photo Credit:

https://en.yna.co.kr/view/PYH20151204092300341

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  → Redundancy requirements: Accidental cable loss
  Time-history analysis approach:
  1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force in the cable for the considered load combination
  2. Remove stay cable in question from model and replace with corresponding reactions to tower and girder (initial conditions)
  3. Run time-history analysis by removing cable reactions (reduce cable reaction to zero over a short time step)
  4. Record response of structure over time, capture peak and final force effects and check that structure remains stable
  5. Repeat steps 1 to 4 for all cables



N_0 = Initial axial force in cable under consideration prior to cable loss

N_{max} = Peak value of axial force in cable under consideration after cable loss

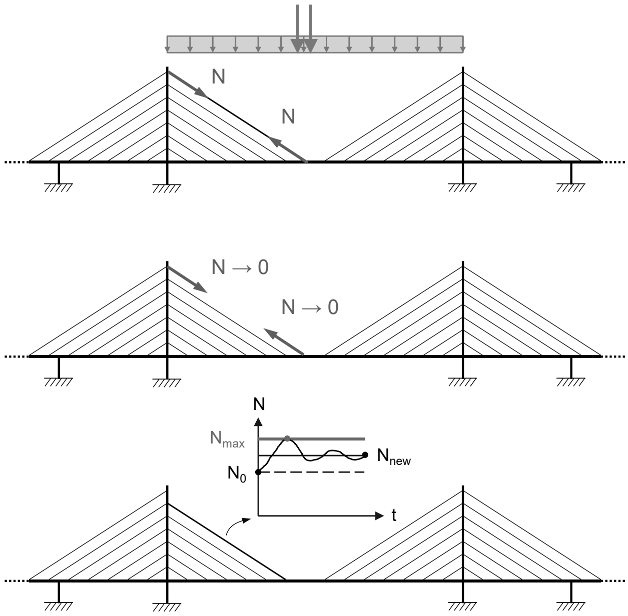
N_{new} = Final new value of axial force in cable under consideration after cable loss (after vibrations have been dampened).

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Redundancy requirements: Accidental cable loss

    Time-history analysis approach:
    - Most precise approach
    - Can consider geometric and material nonlinearities
    - Selected material damping coefficients and time-step of cable loss can affect response significantly
    - Labour/data intensive
    - Can be avoided if a dynamic amplification factor of 2.0 is used in conjunction with a static approach (conservative)
    - Can be used selectively to prove out dynamic amplification factors less than 2.0

$$N_{\max} = N_0 + \left(N_{new} - N_0\right) \cdot DAF \rightarrow \quad DAF = \frac{N_{\max} - N_0}{N_{new} - N_0}$$



DAF = Dynamic Amplification Factor

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

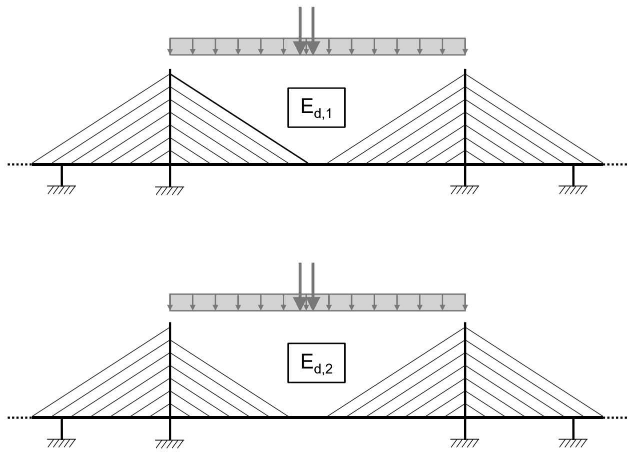
- Particularities of cable-stayed bridges:

→ Redundancy requirements: Accidental cable loss

Eurocode (static) approach:

1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and calculate design effect: $E_{d,1}$
2. Remove stay cable in question from model and calculate design effect under the same loading: $E_{d,2}$
3. Calculate the difference between the design effects: $\Delta E = E_{d,2} - E_{d,1}$
4. Total design effect = $E_d = E_{d,1} + 2\ \Delta E$

Dynamic Amplification Factor



Note that the requirement of the Eurocode approach to apply the same live load on both systems can be challenging. This is because if generated by influence lines, the governing load pattern will be different for the two systems. Therefore, one must capture the governing load pattern for the intact system and manually apply that pattern to the system with the removed cable.

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

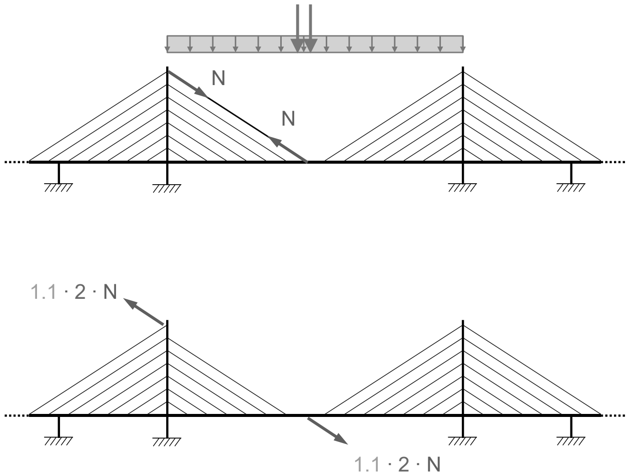
  → Redundancy requirements: Accidental cable loss

  PTI (static) approach:

  1. Apply LL that maximises the axial force of the stay cable in question to the intact structure and obtain the total axial force (N) in the cable for the following load combination:

     1.1 DC + 1.35 DW + 0.75 (LL+IM)

  2. Remove stay cable in question from model and replace with corresponding reactions (N) to tower and girder, applied in the opposite directions and multiplied with a load factor of 1.1 and a dynamic amplification factor of 2.0 (unless a lower factor can be determined from a non-linear dynamic analysis, but not < 1.5)
  3. Superimpose effects of Steps 1 & 2 to obtain total load effects



The threshold of 1.5 for the dynamic amplification factor was introduced to avoid very low factors due to manipulations in the dynamic analyses assumptions.

DC: dead load of structural components and nonstructural attachments

DW: dead load of wearing surfaces and utilities

LL: vehicular live load

IM: vehicular dynamic load allowance

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

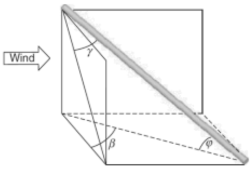
→ Stay cable vibration (see also lecture on Common Aspects)

Cable vibrations can be generated by:

- Wind: dry/wet galloping (most cases), buffeting or vortex-shedding (rarely)
- Loading of bridge girder or towers

Rain-wind-induced vibrations:

- Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
- Wind tunnel testing show that cables are particularly vulnerable when:
  - ✓ Smooth
  - ✓ Lightly damped
  - ✓ Declining in direction of wind
  - ✓ Modal frequencies = 0.5 … 3.3 Hz
  - ✓ Wind speed = 5 … 18 m/s
  - ✓ Relative yaw angle (γ) = 0 … 45 deg




Fred Hartman Bridge, Baytown, TX, USA, 1995. LAP / URS


Vibration-induced fatigue cracks at stay anchorage guide pipes

Photos:

Top: By United States Coast Guard, PA2 James Dillard - U.S. Coast Guard Visual Information Gallery Home, Public Domain, https://commons.wikimedia.org/w/index.php?curid=3499375

Bottom: https://puretechltd.com/solutions/cable-assessment/

Illustration:

Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

  → Stay cable vibration (see also lecture on Common Aspects)

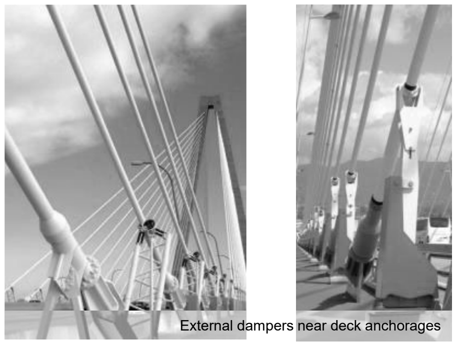
  Cable vibrations can be generated by:

  - Wind: dry/wet galloping (most cases), buffeting or vortex-shedding (rarely)
  - Loading of bridge girder or towers

  Rain-wind-induced vibrations:

  - Creation of water rivulets along a significant length of the cable → apparent modification in cable shape → galloping
  - Wind tunnel testing show that cables are particularly vulnerable when:
    - ✓ Smooth → provide surface modifications to HDPE pipe
    - ✓ Lightly damped → provide mechanical damping
    - ✓ Declining in direction of wind
    - ✓ Modal frequencies = 0.5 … 3.3 Hz
    - ✓ Wind speed = 5 … 18 m/s
    - ✓ Relative yaw angle (γ) = 0 … 45 deg

Types of surface modifications to HDPE pipe



External dampers near deck anchorages

Note that the parallel strand stay cables most commonly used in modern cable-stayed bridges have a relatively low density. As a result they feature a relatively low Scruton number, Sc:

$$Sc = \frac{m\xi}{\rho D^2}$$

where, m is the cable mass per unit length, ξ is the ratio of structural damping to critical damping, ρ is the air density, and D is cable diameter. The PTI recommendations include the following tentative stability criterion:

$Sc \leq 10$ for smooth circular cables, or

$Sc \leq 5$ for stay pipes with surface modifications (helix or dimples – see illustration above), provided that this is verified by wind tunnel testing.

For typical cable mass densities and diameters, a damping ratio ξ between 0.5% and 1.0% would be sufficient to supress rain-wind induced vibrations. Mechanical damping is required to achieve such damping ratios (the intrinsic damping of stay cables is lower, ranging from 0.05% to 0.3%). The effectiveness of damping devices should be verified by testing after installation.

References:

PTI (2018), DC45.1-18: Recommendations for Stay Cable Design, Testing, and Installation, Post-Tensioning Institute.

Irwin, P. A., "Wind Vibrations of Cables on Cable-Stayed Bridges," *Proceedings*, ASCE Structures Congress XV, Portland, OR, 1997

Illustration (Top): Gimsing, N.J. & Georgakis, C.T. (2012), "Cable Supported Bridges", Wiley

Photos (Bottom): https://freyssinet.co.uk/wp-content/uploads/2020/02/C-I-1-HD-STAY-CABLES-EN_V04.pdf

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

  → Time-dependent effects

  - The principles discussed for cantilever-constructed bridges with respect to:
    - ✓ Creep + shrinkage
    - ✓ Camber
    - ✓ Erection equipment weight
    - ✓ Prestressing
    - ✓ Change in structural system

    are also applicable to cable-stayed bridges
    - ➢ Note that the contribution of tower creep to the total girder deflection is significant.
  - Due to the relative flexibility of the girder-tower system during erection, it is easier to adjust the profile by adjusting the cable lengths compared to conventional cantilever-constructed bridges.
  - However, errors are cumulative and grow quickly, therefore accurate monitoring and record keeping during erection are paramount to ensure the correct final geometry


Puente Hisgaura, Colombia, 2018

Photos:

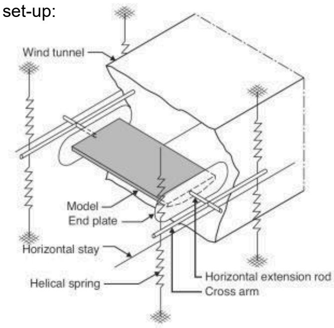
Top: https://www.eltiempo.com/colombia/otras-ciudades/video-sobre-fallas-en-el-puente-atirantado-hisgaura-en-santander-291214

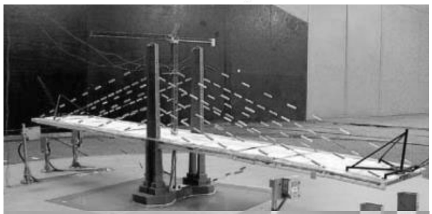
Bottom: https://oronoticias.tv/informe-especial-sobre-el-puente-hisgaura/

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - → Wind loading & aerodynamics
    - Code provisions apply to bridges with negligible dynamic response, i.e. road and rail bridges of spans up to 40 m (see Conceptual Design)
    - For cable-stayed bridges, input from wind specialists is required:
      - ➢ Definition of wind characteristics:
        - Wind speed vs. Return period
        - Wind vs. Directionality
        - Turbulence (terrain roughness)
      - ➢ Wind tunnel testing
        - Virtual testing (CFD) - preliminary
        - Sectional testing
        - Aeroelastic testing

Sectional test set-up:





Golden Ears Bridge, Vancouver, BC, 2009. Buckland & Taylor
Aeroelastic testing of full model during erection (RWDI)

In general, steel composite superstructures are more sensitive to wind loading that concrete superstructures (mass helps – see Chapter 9.1: Common Aspects).

The shaping of the leading edge of the cross-section is significant: Avoid bluff faces and solid traffic barriers (an H-shaped cross-section is aerodynamically unstable).

Adding chamfers to the corners of rectangular-shaped tower cross-sections helps to mitigate effects of vortex shedding.

Illustration (Top): Gimsing, N.J. & Georgakis, C.T. (2012), “Cable Supported Bridges“, Wiley

Photo (Bottom): Svensson (2012), “Cable-Stayed Bridges – 40 Years of Experience Worldwide,” Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Structural Response

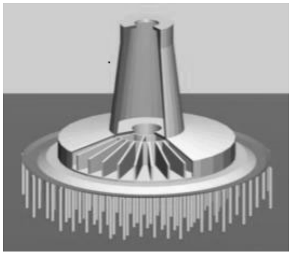
- Particularities of cable-stayed bridges:

  → Seismic design

  Depending on the site seismicity, the seismic design of cable-stayed bridges often extends beyond the standard code provisions:

  - Input ground motions are developed based on site-specific hazard analyses for multi-level events; identification of faults running through bridge alignment
  - Response is determined through non-linear, time-history analyses
  - For long-span bridges, spatial effects (asynchronous seismic excitation) may need to be considered
  - May involve complex detailing such as dampers, isolation bearings, fuses, special ductile elements

Rion Antirion (Charilaos Trikoupis) Bridge, Greece, 2004. Jacques Combault



Photos:

Top: https://en.wikipedia.org/wiki/File:Rio-Antirio_bridge_cropped.jpg

Bottom Left: https://www.iitk.ac.in/nicee/wcee/article/1115.pdf

Bottom Right:
https://www.fipindustriale.it/index.php?area=108&menu=99&page=302&lingua=1&idsession=95687544

Cable-supported bridges

Cable-stayed bridges – Construction

Reference: The structure and content of this section is partially adapted from an in-house training course by Dr. Dusan Radojevic (Senior Bridge Specialist) at COWI North America in 2017.

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
  - → Early collaboration between designer and contractor is essential to ensure an economic design and successful execution
  - → Erection method must be developed during the design process to ensure compatibility between design and erection and viability of the former
  - → Guiding principles:
    - Simplicity
    - Repetition / Modularity
  - → Common constructible girder types:
    - Precast concrete segmental
    - Cast-in-place concrete segmental
    - Composite


Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä

- ✓ Precasting → Repetition
- ✓ Simplicity in connections between segments
- o Economical if same section can be used for approaches: Cost of forms and erection equipment is amortised over greater length
- o Simple lifting concept; heavy equipment required

Photos:

Svensson (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
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    - Precast concrete segmental
    - Cast-in-place concrete segmental
    - Composite

Sidney Lanier Bridge, Brunswick, GA, USA, 2003. TYLI

- ✓ Repetitive & modular construction
- o Suitable for simple open cross sections
- o Alternative to precasting for shorter production runs (incl. approaches)
- – Form travellers are complex and expensive (cannot be amortised over the approaches); schedule may require four travellers
- – Traveller imposes significant demands on girder (closely-spaced stays required); traveller may need to be temporarily supported by stays (complex details / load transfer)

Photos:

Left: https://upload.wikimedia.org/wikipedia/commons/a/ab/SidneyLanierBridgeConstruction.jpg

Right: http://www.asbi-assoc.org/projectGallery/project.cfm?articleID=18A9C8F9-A05E-F86A-900CBC112CB02E93

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
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    - Repetition / Modularity
  - → Common constructible girder types:
    - Precast concrete segmental
    - Cast-in-place concrete segmental
    - Composite


Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT


Derrick crane over land


Gantry over water

✓ Repetitive & modular construction
○ Suitable for simple open cross sections
✓ Simple pre-fabrication of plate girders and precast deck panels
✓ No need for formwork (infill strips over girder flanges)
– Cross-section shape not aerodynamic → wind fairings typically needed

Photos:

Left: https://www.flatironcorp.com/project/port-mann-bridge-highway-1/

Top Right: https://www.fmmafco.com/projects/the-port-mann-bridge-project/

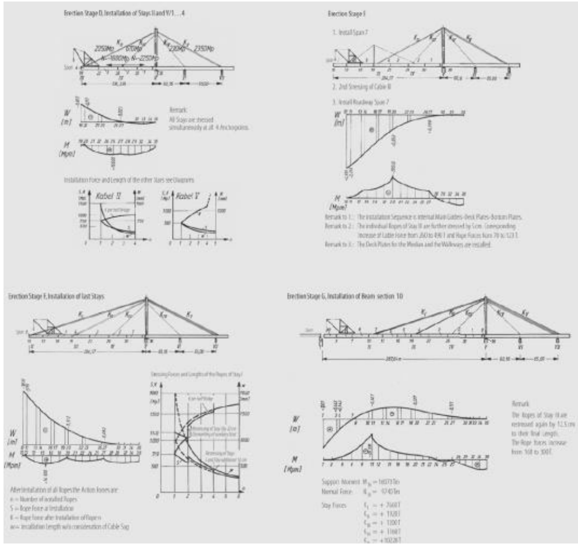
Bottom Right: https://www.deal.it/projects/port-mann-bridge-replacement

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:
  → Cable-stayed bridges are typically most vulnerable during erection
  → Geometry Control:
  Assembly of information and methodology, used to control positions and dimensions of structural elements during erection (*x*, *y*, *z*, *t*)
    - Goal: achieve target geometry and stress state at a reference stage (typically @ 10'000 days)
    - Final stress state is dependent upon final geometry and key erection stages ("locked-in" stresses, closures) → must track and control

  Key aspects:
    - Modelling of erection sequence
    - Survey monitoring during erection
    - Assessing and controlling during erection (perform adjustments as/if needed)

Sample Erection Manual:



Illustrations:

Svensson (2012), "Cable-Stayed Bridges – 40 Years of Experience Worldwide," Ernst & Sohn, Berlin

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:
  → Stay cable installation:
  Most effective method to control installation depends on girder type:
  - Flexible girder: based on stay length
    - ✓ Errors in load assumptions will result in different stay forces but not in girder geometry
    - – Requires accurate surveying of as-built structure at each stage to define stay length
  - Stiff girder: based on stay force
    - o Adjustment of stay length independent of the target force would result in overstressing the cables/girder; shims can be used to correct girder geometry (last resort)

  At end of construction, installation within tolerances (among cables and strands) is confirmed by lift-off tests, and final adjustments are made as needed.


Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT


St. Croix River Crossing, MN, USA, 2017. COWI / HDR

Successful stay installation based on stay length relies on accurate surveying and knowledge of the forces acting on the girder (construction equipment loads) during installation.

Successful stay installation based on stay force relies on accurate estimate of tower and girder stiffness to be able to compute the required stay installation forces.

It is not uncommon for the as-built stay forces to exceed the theoretical design values. This could be due to variation in force distribution among stays compared to the theoretical one or due to an overall higher as-built self-weight of the girder. Some owners will accept final verification and acceptance of the design for these higher as-built forces based on reduced dead load factors. The reasoning behind this approach is that the dead load of the girder has been directly measured via the lift-off tests and therefore the statistical uncertainty for the dead load has been reduced, thus justifying the use of a reduced load factor. A rational approach for final acceptance of stay forces has been included in the latest edition of the PTI Recommendations for Stay Cable Design, Testing and Installation (DC45.1-18).

Photo Credits:

Top: https://www.flatironcorp.com/project/port-mann-bridge-highway-1/

Bottom: https://www.roadsbridges.com/bridge-construction-final-construction-begins-st-croix-crossing-bridge

Cable-supported bridges – Cable-Stayed Bridges: Summary

Key Takeaways

- CSB most competitive typology for a wide range of spans (200…1000 m); have gradually replaced truss & arch bridges at the lower end and suspension bridges at the higher end of the range
- The efficiency of the cable-stayed bridge stems from the fact that all members (girder, tower, stay cables) are carrying loads primarily through axial (normal) forces and only minimal bending
- The backstay function is fundamental to the behaviour of CSB (stiffness, fatigue); in multispan CSB, stiffness is primarily achieved through the towers
- To achieve economy: start with minimalist solution, then add features only as needed
- Efficient construction method when simplicity and repetition/modularity is achieved; accurate monitoring and record keeping needed to control geometry
- Tall towers required; often most vulnerable during construction
- Inclined cables are susceptible to (rain-wind-)vibrations: provide surface modifications to HDPE pipe and mechanical damping
- Deck/girders are generally not replaceable