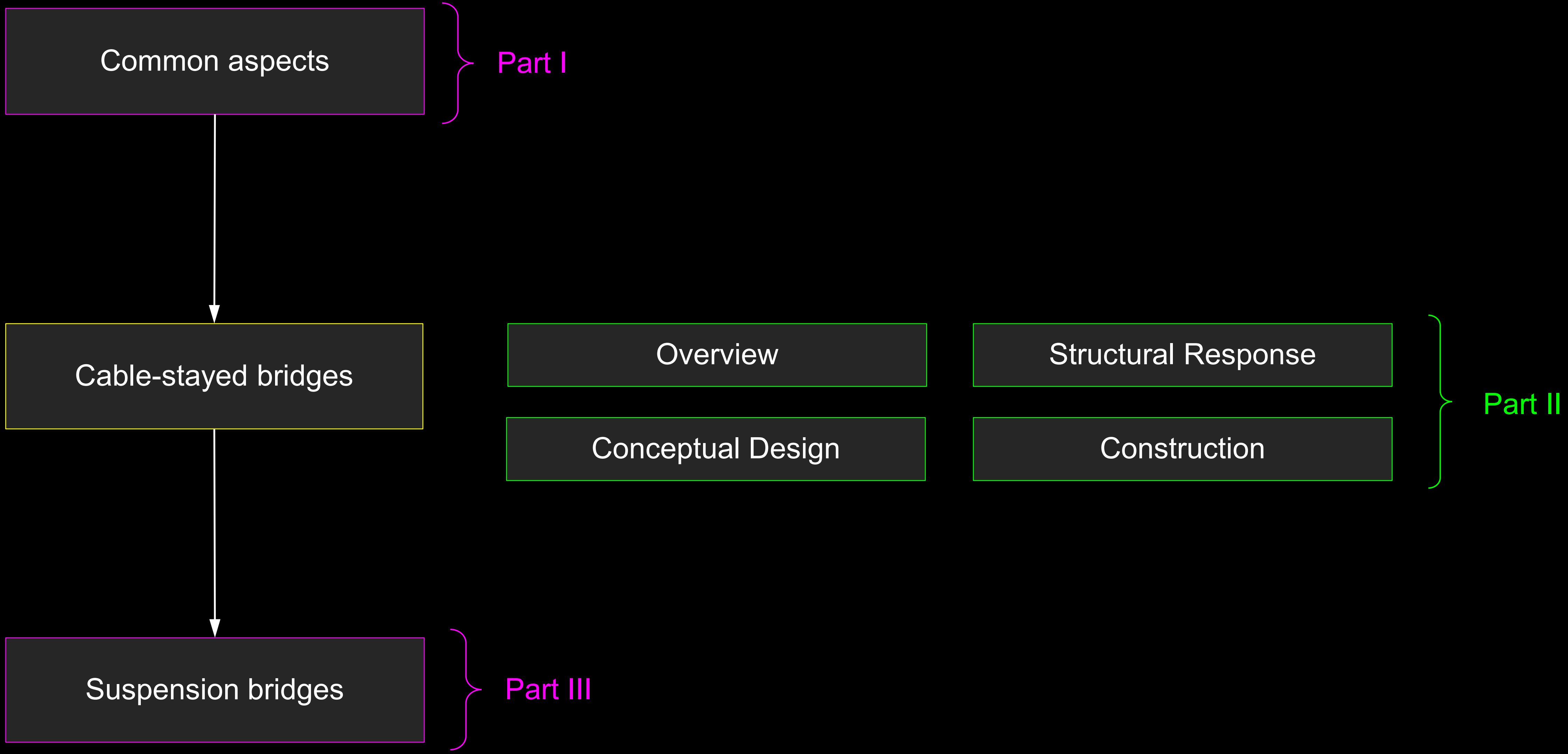
Cable-Stayed Bridges

(Schrägseilbrücken)



Common aspects

Part I

Cable-stayed bridges

Overview

Structural Response

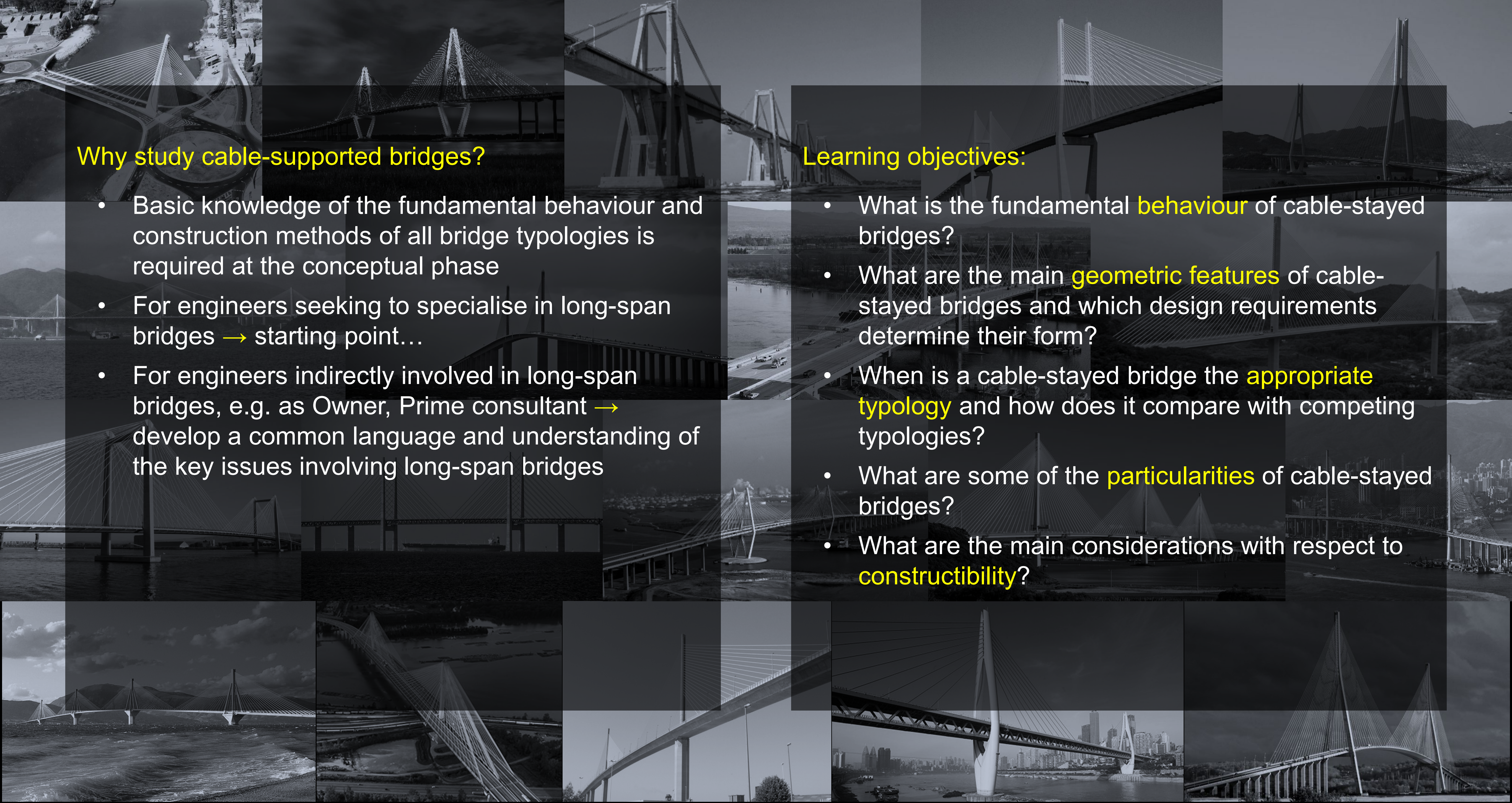
Conceptual Design

Construction

Part II

Suspension bridges

Part III



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

Cable-supported bridges – Cable-Stayed Bridges: Overview

Forth Rail Bridge
Construction: 1882 – 1890
(73 lives lost)
Total length = 2’467 m
Longest span = 520 m
Width = 9.8 … 37 m
Height = 110 m

Forth Road Bridge
Construction: 1958 – 1964
(7 lives lost)
Total length = 2’512 m
Longest span = 1’006 m
Width = 33 m
Height = 156 m

Queensferry Crossing
Construction: 2011 – 2017
(1 life lost)
Total length = 2’700 m
Longest span = 650 m
Width = 40 m
Height = 207 m

Cable-supported bridges

Cable-stayed bridges – Overview

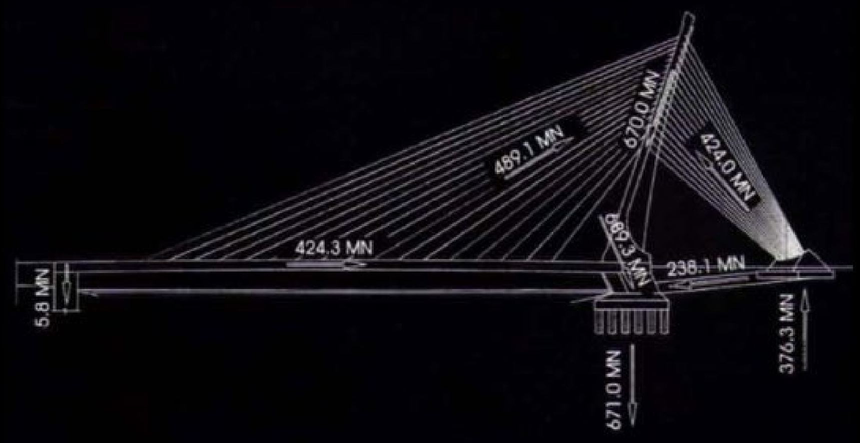
Definition and Classification

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



l = 125 m

h = 56 m ($h / (2l)$ = 1 / 4.5)

d = 2.0 m ($d / (2l)$ = 1 / 125)

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

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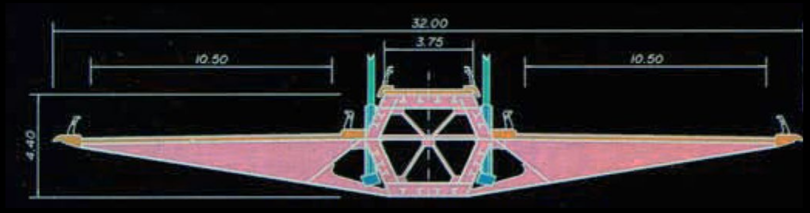

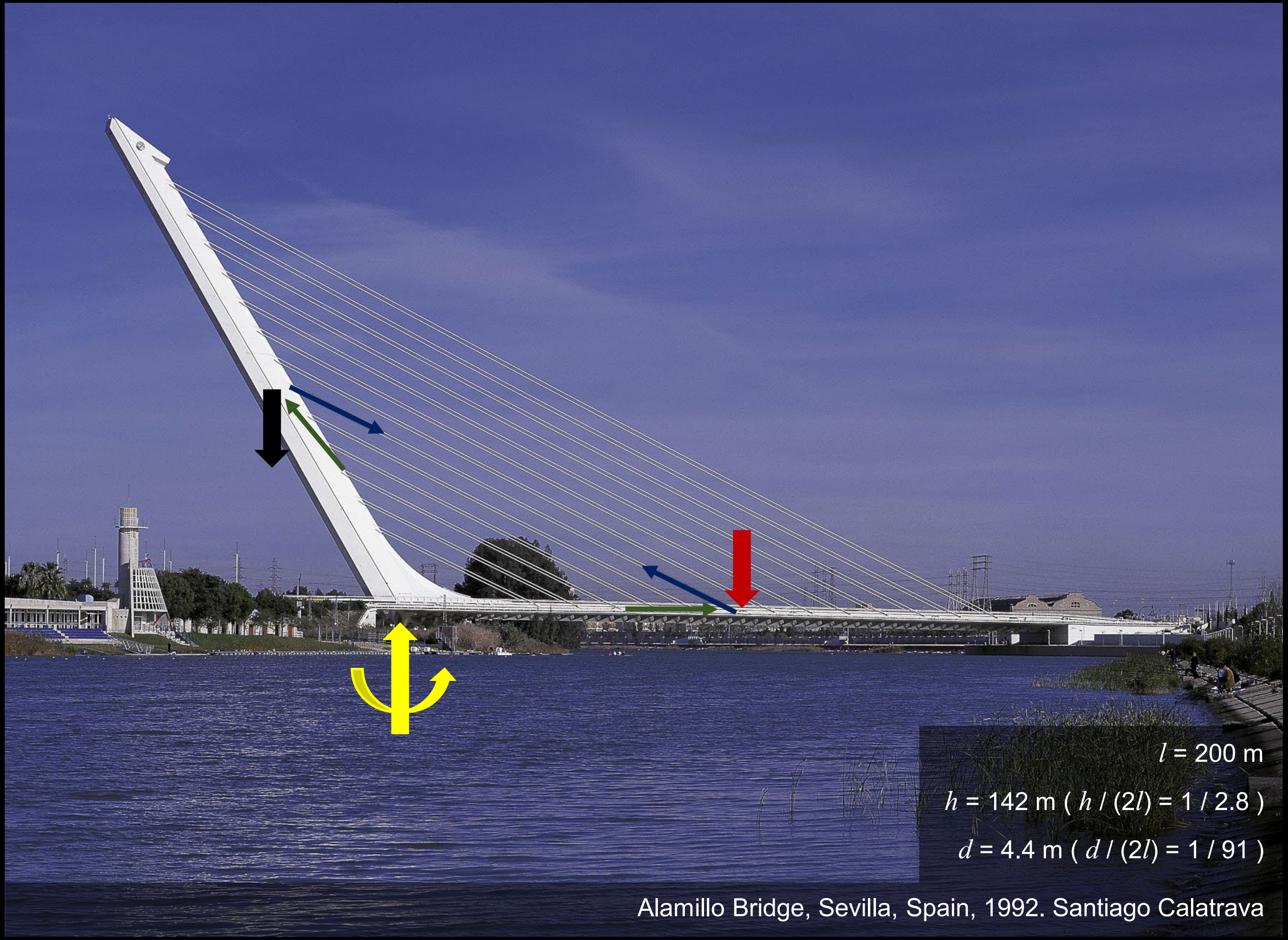

l = 200 m

h = 142 m ($h / (2l)$ = 1 / 2.8)

d = 4.4 m ($d / (2l)$ = 1 / 91)

Alamillo Bridge, Sevilla, Spain, 1992. Santiago Calatrava

Cable-supported bridges – Cable-Stayed Bridges: Overview

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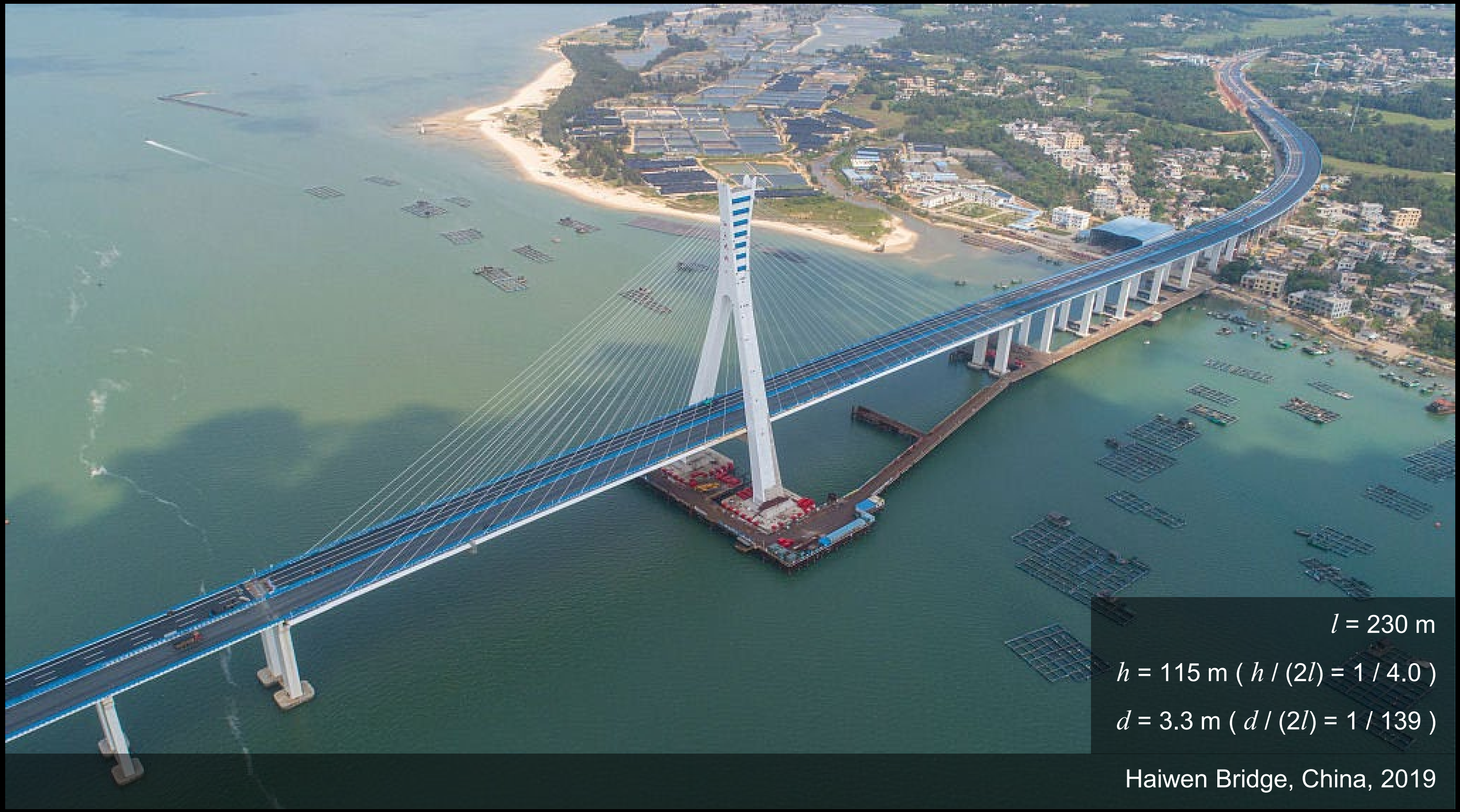

l = 230 m

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

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

Haiwen Bridge, China, 2019

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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

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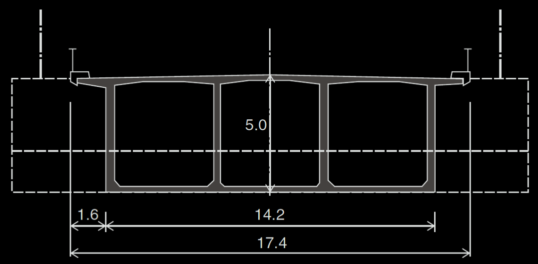

l = 235 m, d = 5.0 m (d / l = 1 / 47)

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

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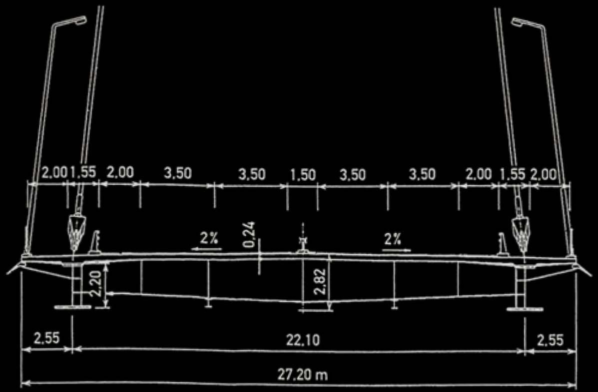

l = 560 m, l_1 = 300 m (l_1 / l = 0.54)

h = 113 m (h / l = 1 / 5.0)

d = 2.8 m (d / l = 1 / 200)

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

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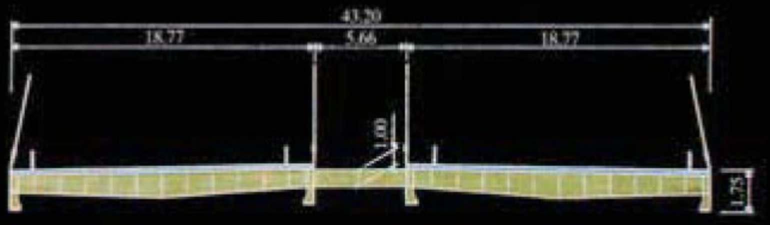

l = 475 m, l_1 = 127 m (l_1 / l = 0.27)

h = 130 m (h / l = 1 / 3.6), h_1 = 95 m (h_1 / l = 1 / 5.0)

d = 1.75 m (d / l = 1 / 271)

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

Cable-supported bridges – Cable-Stayed Bridges: Overview

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l = 650 m, l_1 = 221+104 m (l_1 / l = 0.50)

h = 145 m (h / l = 1 / 4.5)

d = 4.8 m (d / l = 1 / 135)

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

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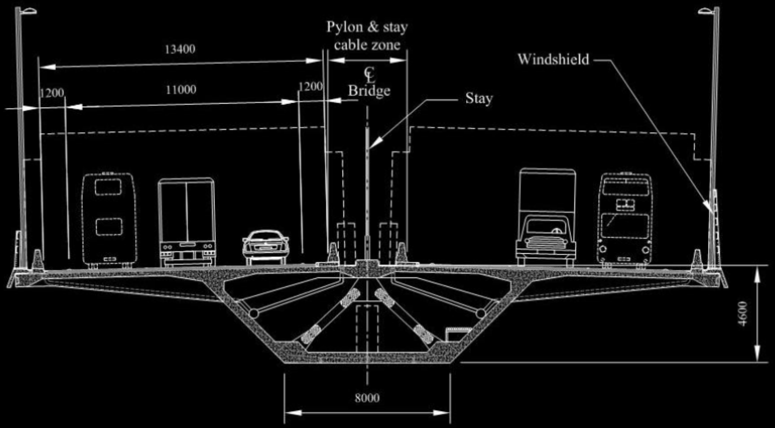


l = 318 m, l_1 = 205 m (l_1 / l = 0.64)

h = 55 m (h / l = 1 / 5.8), h_1 = 95 m (h_1 / l = 1 / 3.3)

d = 4.6 m (d / l = 1 / 69)

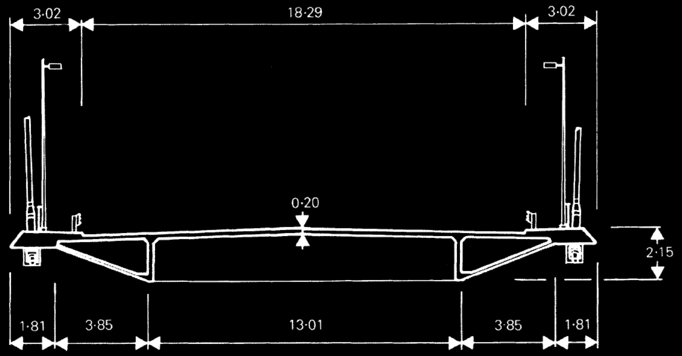
Mersey Gateway Bridge, Cheshire, UK, 2017. COWI / FHECOR

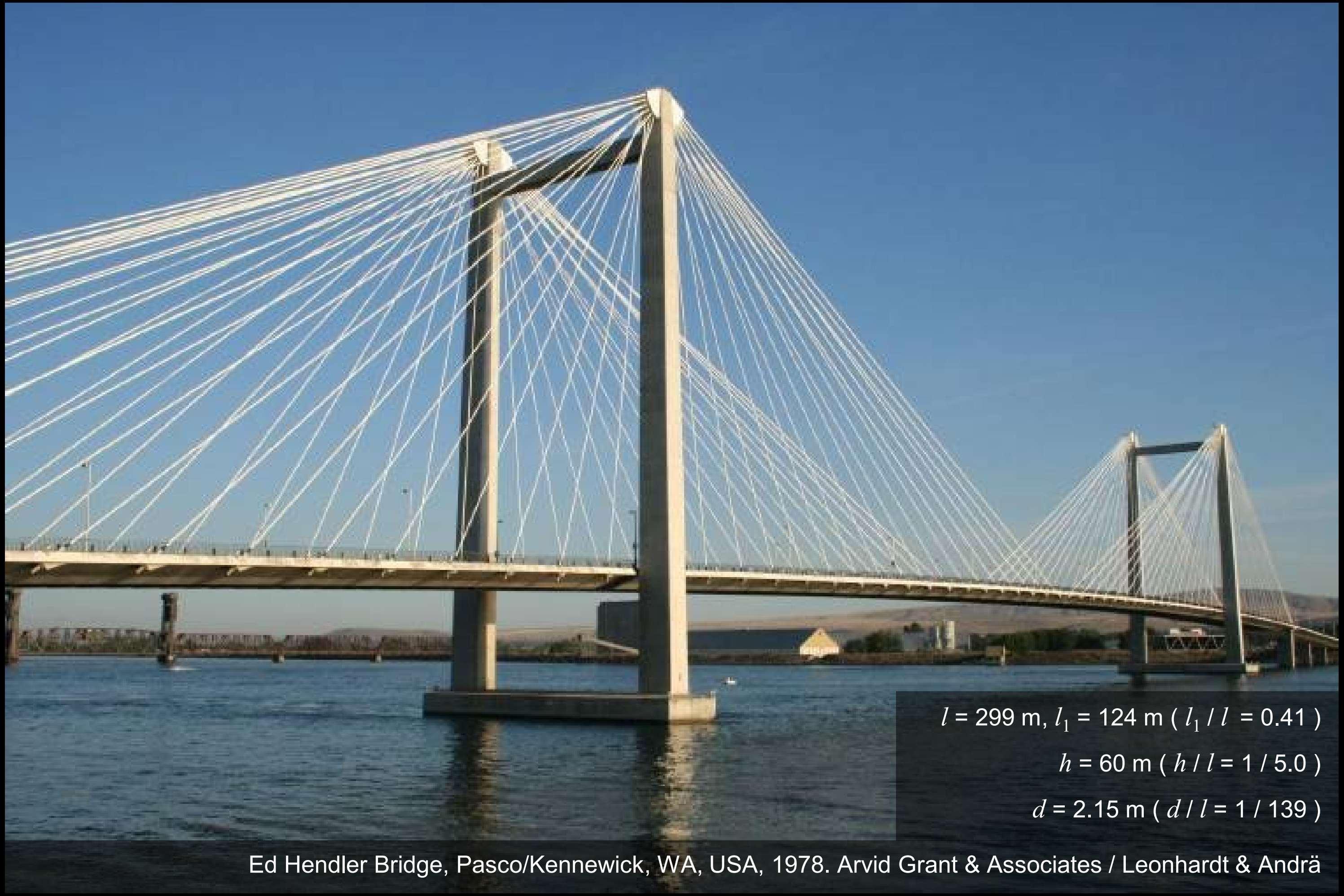
Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:

→ Stay Cable Arrangement:

  - Fan
  - Harp
  - Hybrid (Semi-Fan)





l = 299 m, l_1 = 124 m (l_1 / l = 0.41)

h = 60 m (h / l = 1 / 5.0)

d = 2.15 m (d / l = 1 / 139)

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

Cable-supported bridges – Cable-Stayed Bridges: **Overview**

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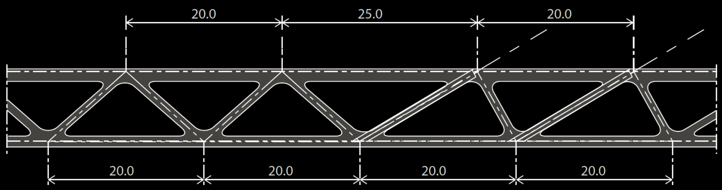

l = 490 m, l_1 = 160 m (l_1 / l = 0.33)

h = 133 m (h / l = 1 / 3.7)

d = 10.2 m (d / l = 1 / 48)

Øresund Bridge, Copenhagen, Denmark, 2000. COWI

Cable-supported bridges – Cable-Stayed Bridges: Overview

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l = 420 m, l_1 = 200 m (l_1 / l = 0.48)

h = 100 m (h / l = 1 / 4.2)

d = 4.5 m (d / l = 1 / 93)

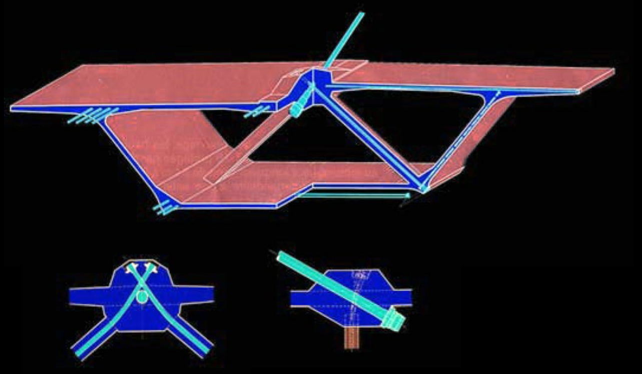
Puente Centerario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP

Cable-supported bridges – Cable-Stayed Bridges: Overview

- Cable-Stayed Bridges can be classified by:

→ Stay Cable Planes:

  - Single Plane
  - Two Vertical Planes
  - Two Inclined Planes
  - Multiple Vertical Planes
  - Multiple Inclined Planes



l = 320 m, l_1 = 143.5 m (l_1 / l = 0.45)

h = 72 m (h / l = 1 / 4.4)

d = 3.80 m (d / l = 1 / 84)

Brotonne Bridge, Normandy, France, 1977. Jean Muller

Cable-supported bridges – Cable-Stayed Bridges: Overview

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- Single Plane
- Two Vertical Planes
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- Multiple Vertical Planes
- Multiple Inclined Planes

l = 381 m, l_1 = 190.5 m (l_1 / l = 0.50)

h = 85 m (h / l = 1 / 4.5)

d = 1.80 m (d / l = 1 / 212)

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

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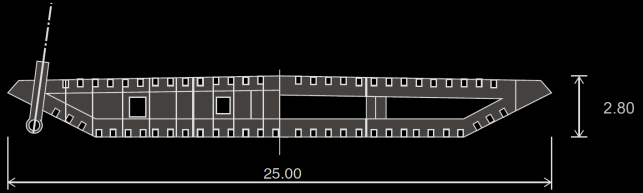

l = 890 m, l_1 = (270 + 50) m (l_1 / l = 0.36)

h = 180 m (h / l = 1 / 4.9)

d = 2.8 m (d / l = 1 / 318)

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

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  - Multiple Vertical Planes
  - Multiple Inclined Planes

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

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→ Stay Cable Planes:

  - Single Plane
  - Two Vertical Planes
  - Two Inclined Planes
  - Multiple Vertical Planes
  - Multiple Inclined Planes

l = 470 m, l_1 = 190 m (l_1 / l = 0.40)

h = 115 m (h / l = 1 / 4.1)

d = 2.4 m (d / l = 1 / 196)

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

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

l = 366 m, l_1 = 165 m (l_1 / l = 0.45)

h = 74 m (h / l = 1 / 5.0)

d = 4.5 m (d / l = 1 / 81)

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

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

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

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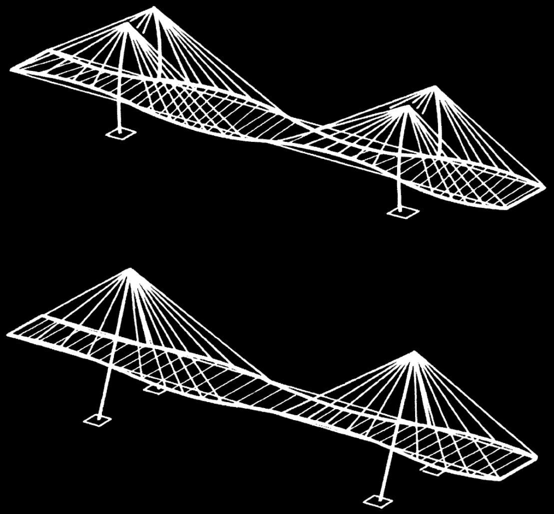

l = 405 m, l_1 = 176.5 m (l_1 / l = 0.44)

h = 85 m (h / l = 1 / 4.8)

d = 2.8 m (d / l = 1 / 145)

Second Meiko Nishi Bridge, Nagoya, Japan, 1997

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

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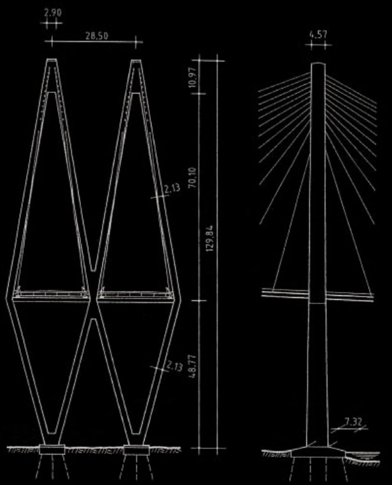

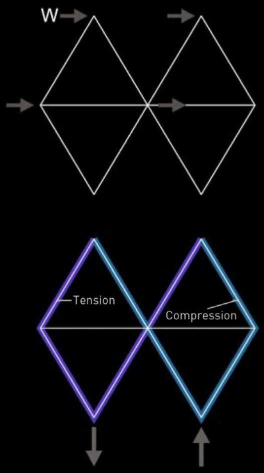

l = 381 m, l_1 = 147 m (l_1 / l = 0.39)

h = 80 m (h / l = 1 / 4.8)

d = 1.83 m (d / l = 1 / 208)

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

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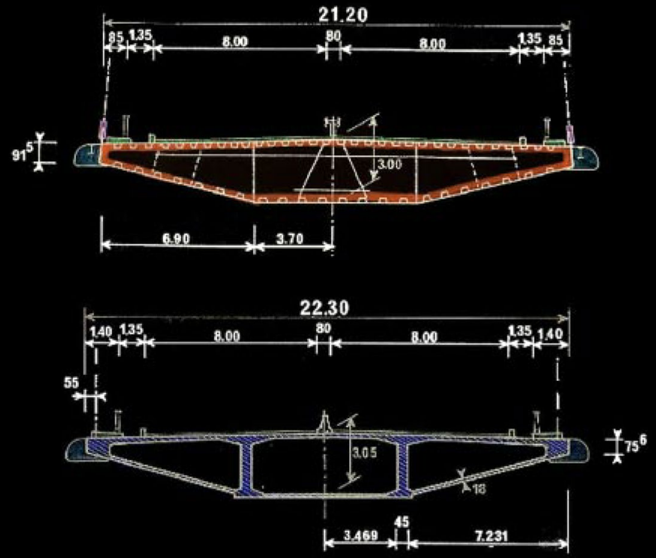

l = 856 m, l_1 = (96 + 5.5 x 43.5) m (l_1 / l = 0.39)

h = 155 m (h / l = 1 / 5.5)

d = 3.0 m (d / l = 1 / 285)

Pont de Normandie, France, 1995. Michel Virlogeux

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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

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

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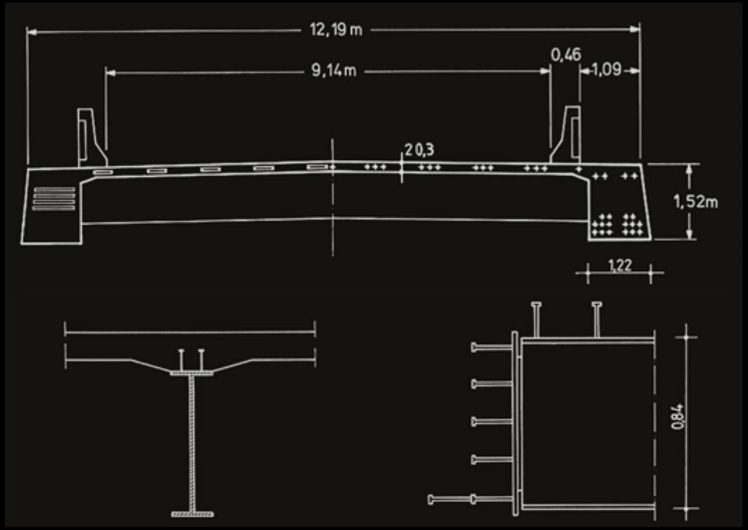

East Huntington Bridge, WV, USA, 1985. Arvid Grant / LAP

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Brotonne Bridge, Normandy, France, 1977. Jean Muller

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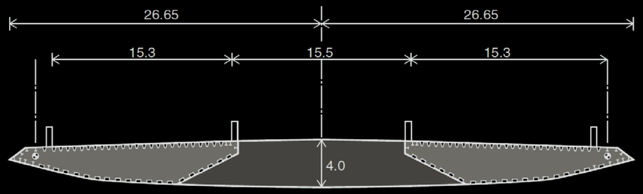

l = 1018 m, l_1 = 4 x 75 m (l_1 / l = 0.30)

h = 220 m (h / l = 1 / 4.6)

d = 4.0 m (d / l = 1 / 255)

Stonecutters Bridge, Hong Kong, 2009. Arup / COWI

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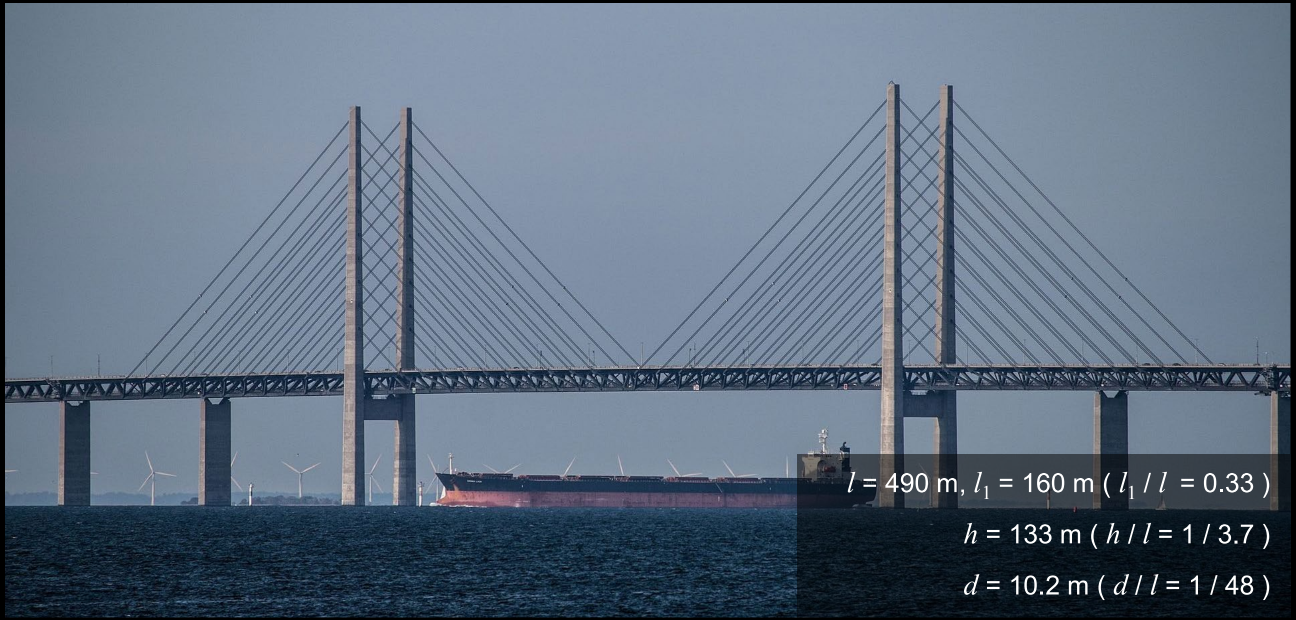

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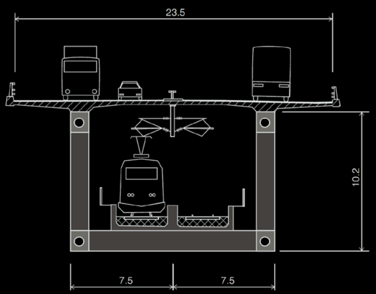
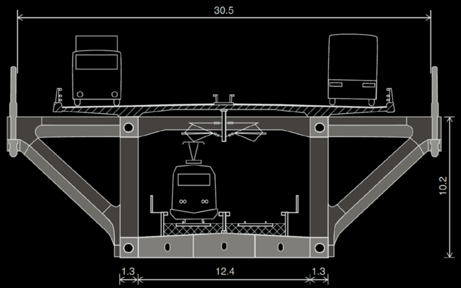
h = 133 m (h / l = 1 / 3.7)

d = 10.2 m (d / l = 1 / 48)





l = 140 m, d = 10.2 m (d / l = 1 / 14)

Øresund Bridge, Copenhagen, Denmark, 2000. COWI

Cable-supported bridges

Cable-stayed bridges – Conceptual Design

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

- Planning and bridge concept selection:

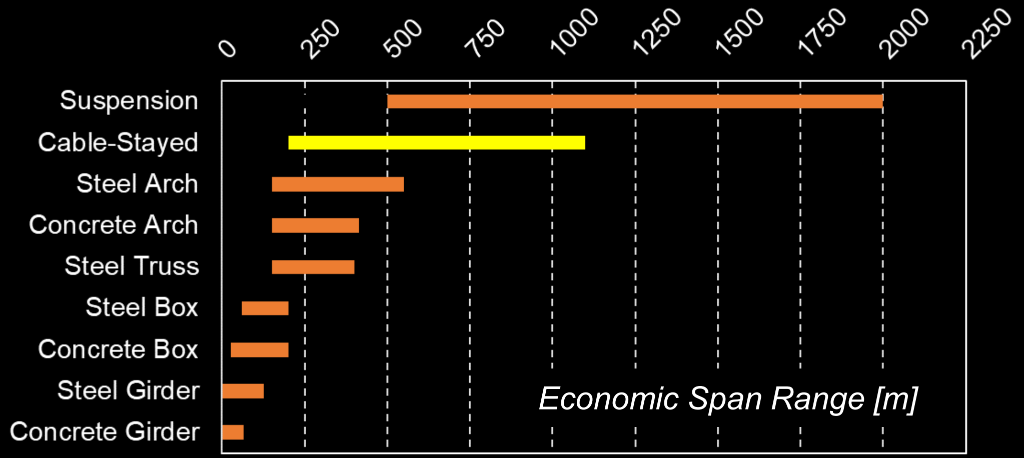
→ Cable-stayed bridges have become the most competitive bridge typology for a wide range of spans (200 … 1100 m)

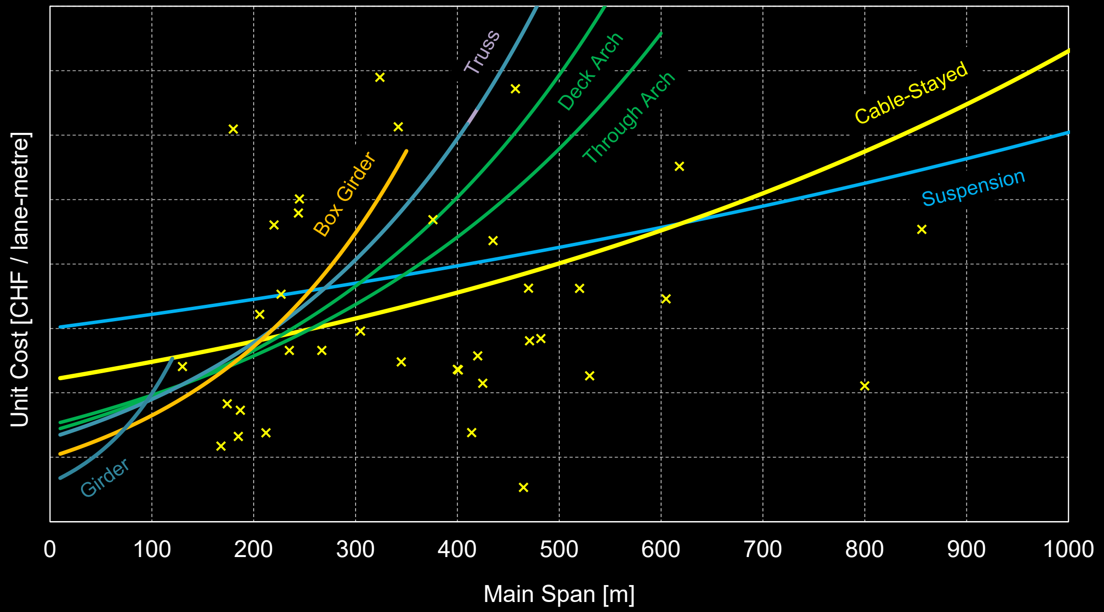
→ For very long spans (> 500 m) the only other alternative are suspension bridges

→ 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





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


main span = 304 m; total length = 481 m

width = 14.2 m (2-lane roadway)

pylon height = 142 m; clearance below = 49 m

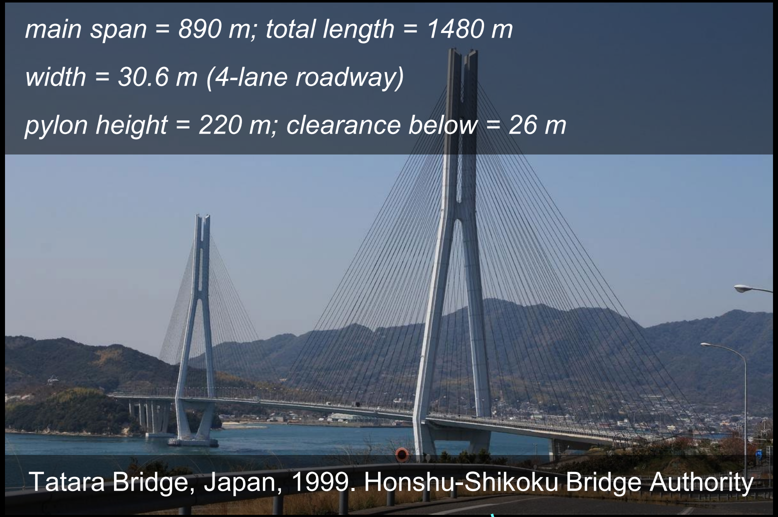
Franjo Tuđman Bridge, Croatia, 2002, University of Zagreb.


main span = 1018 m; total length = 1596 m

width = 51 m (6-lane roadway)

pylon height = 298 m; clearance below = 73 m

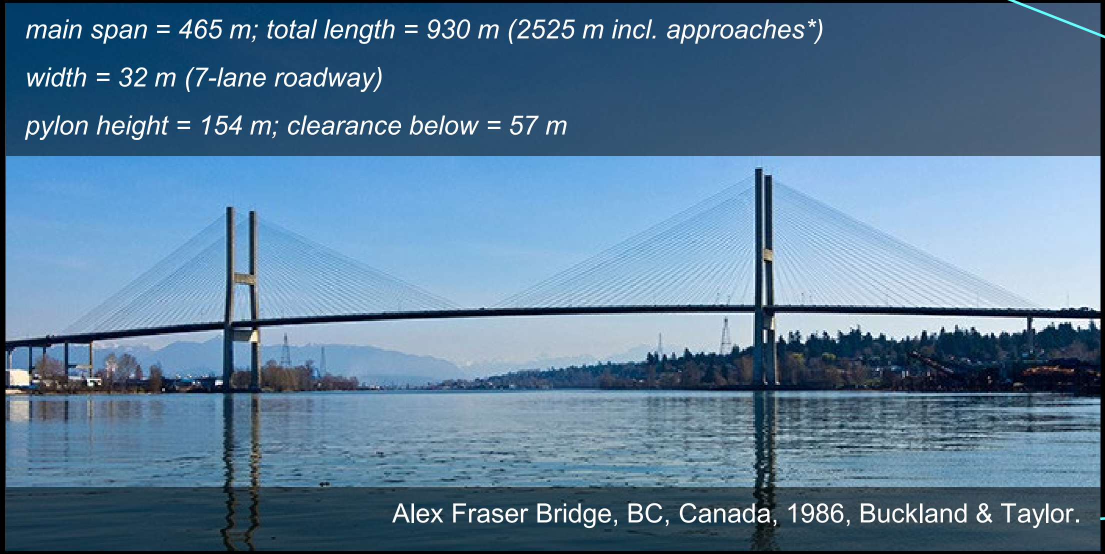
Stonecutters Bridge, HK, 2009. Arup / COWI


main span = 890 m; total length = 1480 m

width = 30.6 m (4-lane roadway)

pylon height = 220 m; clearance below = 26 m

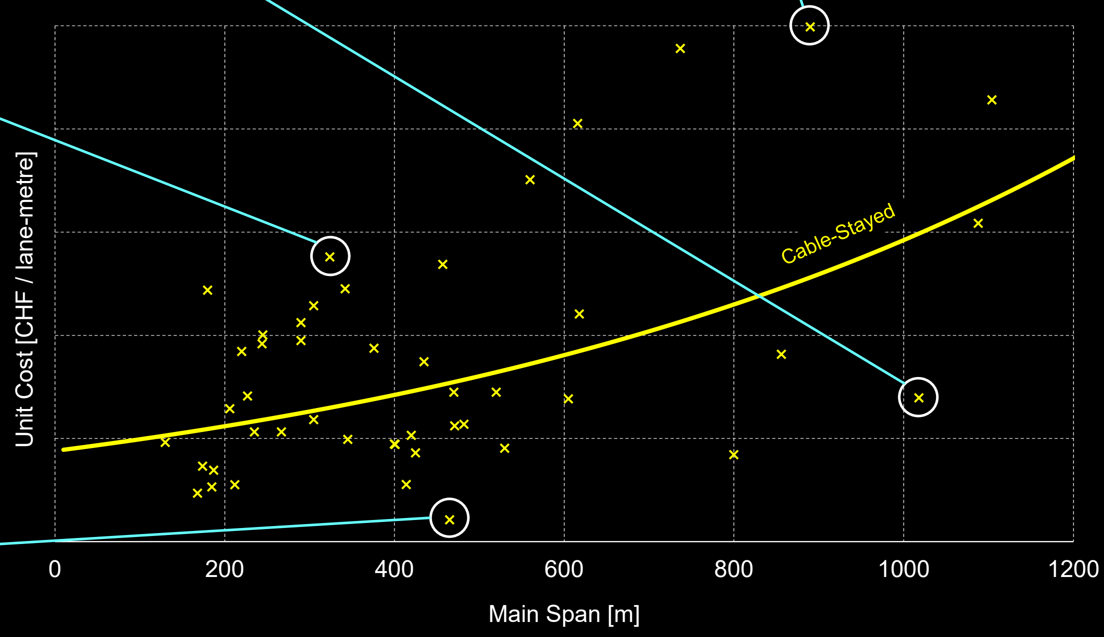
Tatara Bridge, Japan, 1999. Honshu-Shikoku Bridge Authority


main span = 465 m; total length = 930 m (2525 m incl. approaches)*

width = 32 m (7-lane roadway)

pylon height = 154 m; clearance below = 57 m

Alex Fraser Bridge, BC, Canada, 1986, Buckland & Taylor.



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)

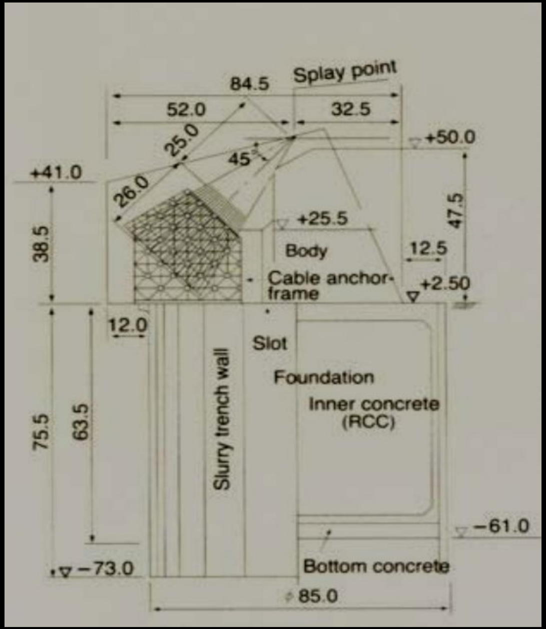
→ For very long spans (> 500 m) the only other alternative are suspension bridges

→ 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.

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

Suspension cable anchorage construction (Akashi Kaikyo Bridge):



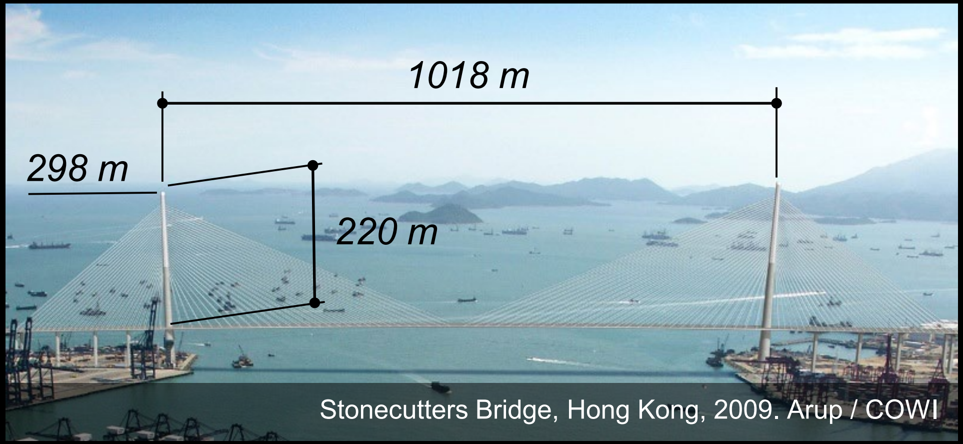
Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

- 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

  → 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

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

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

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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

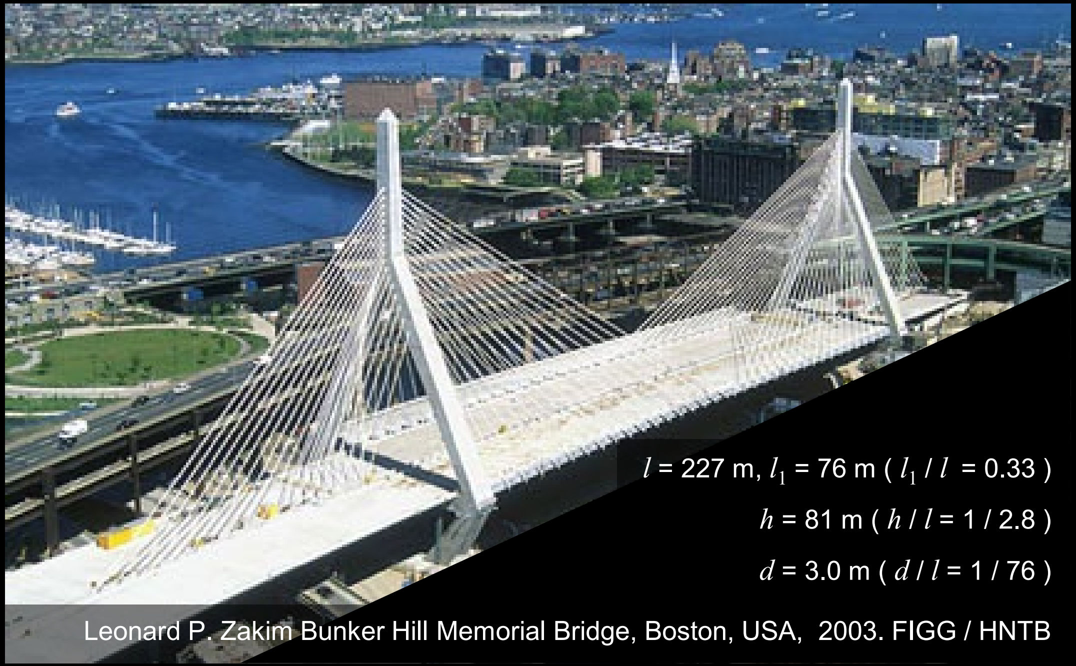

Bugrinsky Bridge, Russia, 2014. Albert Koshkin / Sibmost

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.



l = 227 m, l_1 = 76 m (l_1 / l = 0.33)

h = 81 m (h / l = 1 / 2.8)

d = 3.0 m (d / l = 1 / 76)

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

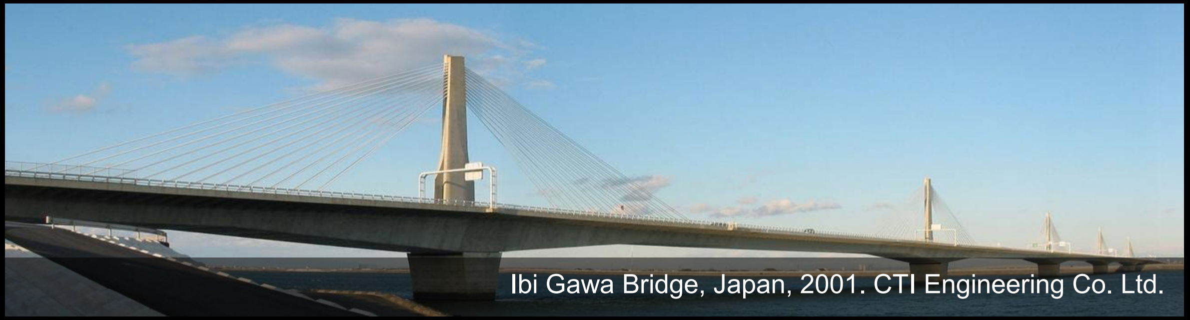
San Francisco – Oakland Bay Bridge: Cable-Stayed Alternative

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

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.

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

- Planning and bridge concept selection:

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→ However, for aesthetic reasons (e.g. to avoid high visual impact) other typologies are often preferable despite not being the most economical solution.

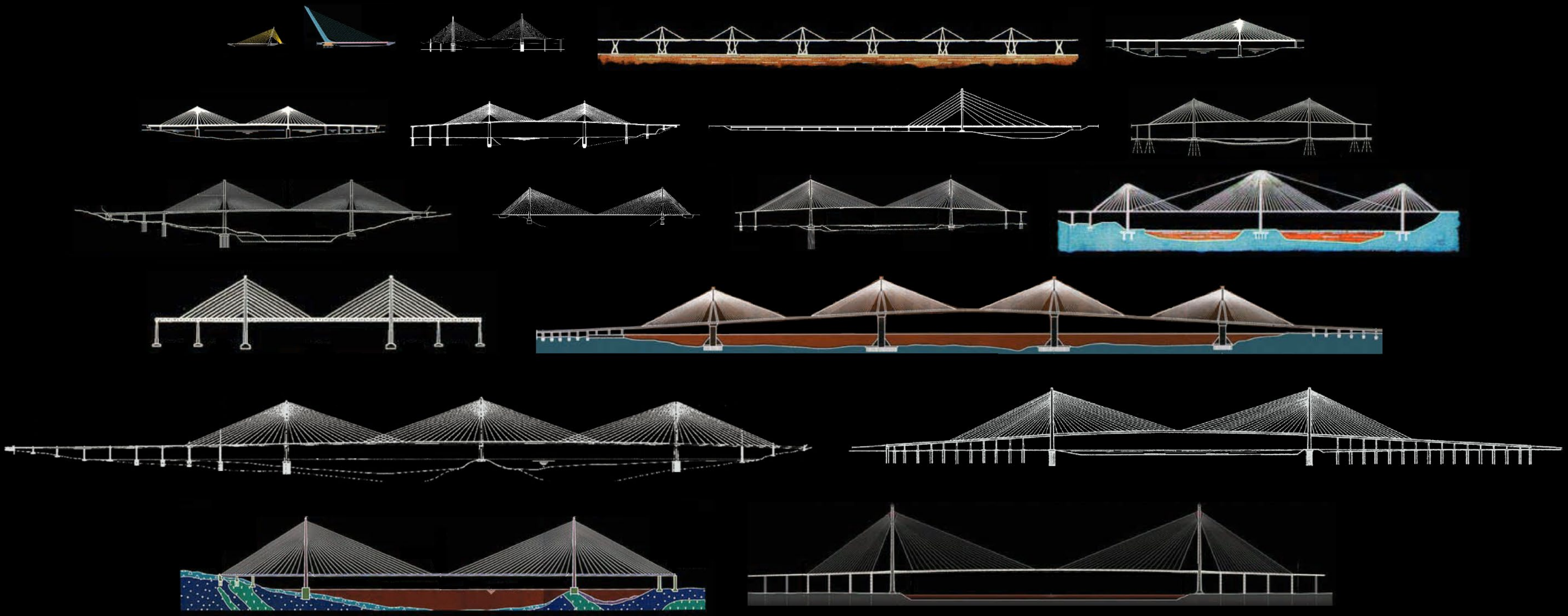
→ Also, height restrictions (e.g. due to proximity to an airport) may preclude the relatively tall towers required for a cable-stayed bridge. An extradosed bridge could be a viable alternative in this case (spans up to 270 m).

→ 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.

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



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

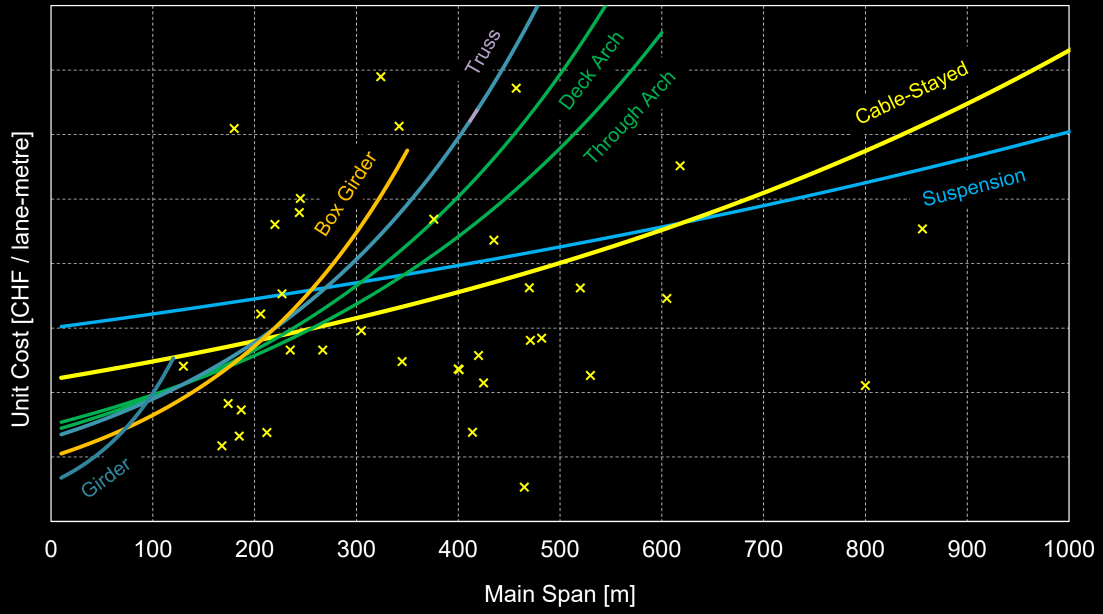
- Planning and bridge concept selection:

→ 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

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

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:

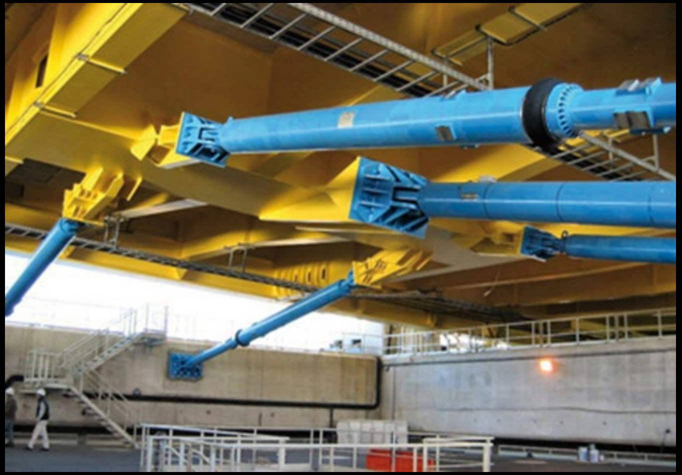
→ Wind (aerodynamic) effects:
  - Tower: “A” or Inverted “Y”
  - Girder: Streamlined box cross-section

→ 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





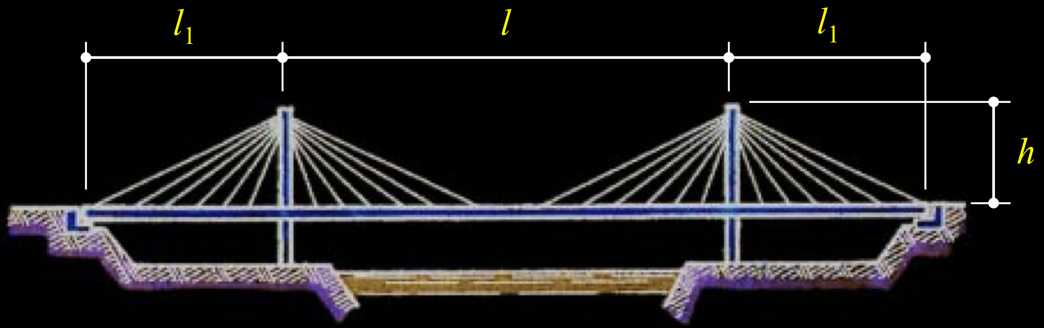

Cable-supported bridges – Cable-Stayed Bridges: Conceptual Design

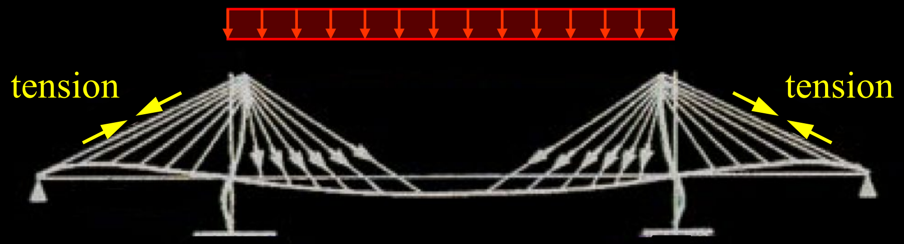
- Basic proportions of cable-stayed bridges:

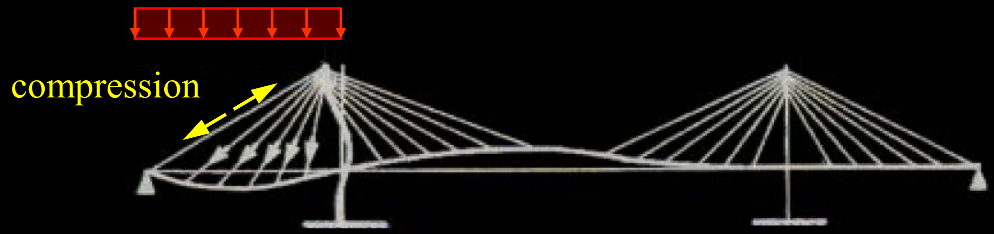
  The geometry of cable-stayed bridges is determined by the following ratios:

  → 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







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

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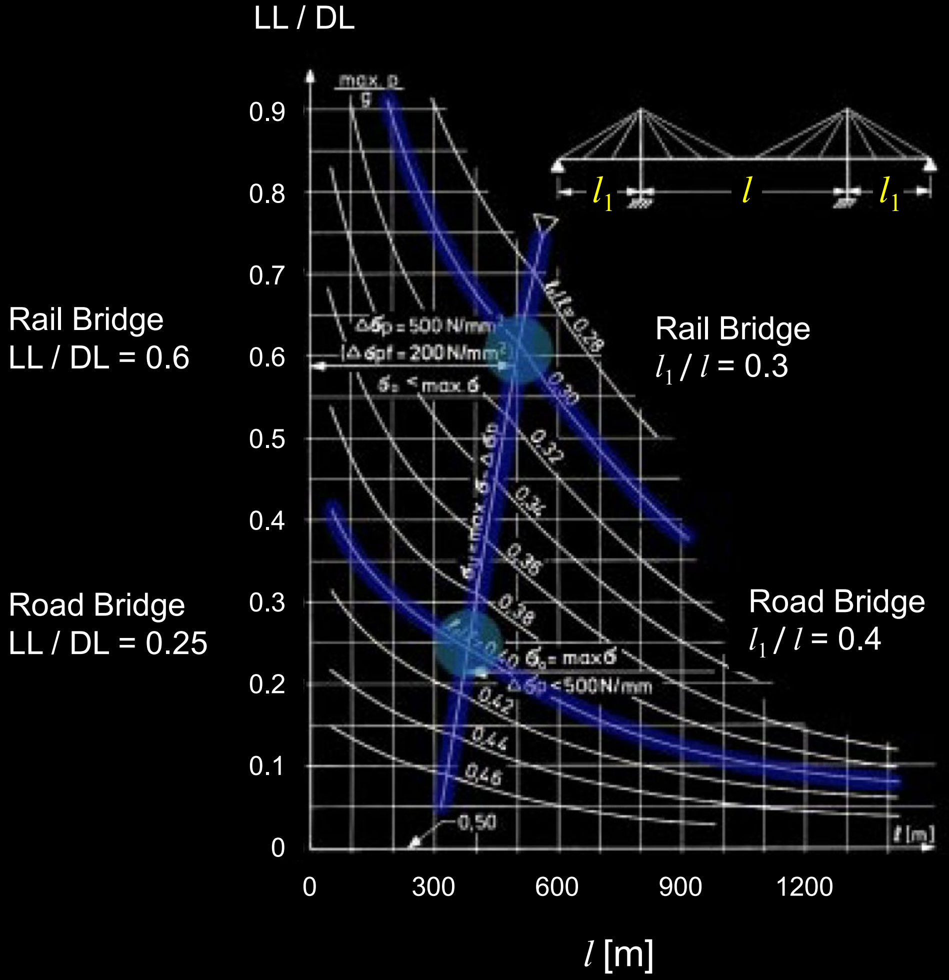
  - Backstays govern the stiffness of the bridge and are subject to significant stress reversals
  - l_1 / l ratio determines the fatigue stress range in the backstays and demands for tie-down devices / counterweights at anchor piers
  - Optimum l_1 / l ratio depends on LL / DL ratio:
    - Road bridges,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



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

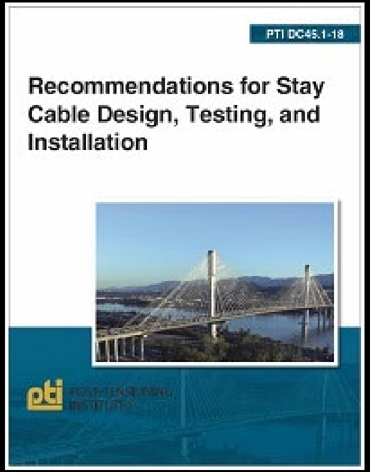
- Design Development:

→ 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:

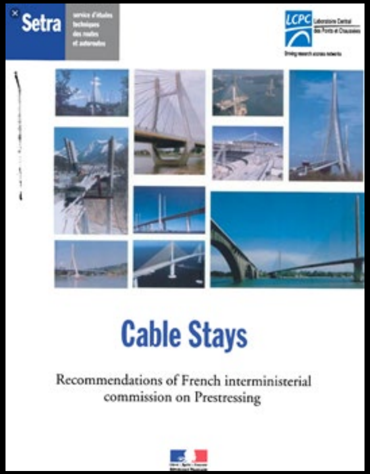
  - Load combinations
  - Serviceability requirements, e.g. deflection limits
  - Wind loading / Aerodynamic vibrations
  - Stay cable systems acceptance criteria
  - Progressive collapse requirements (e.g. accidental cable loss)

→ Guideline documents for stay cable design, testing and installation have been developed to supplement the standard bridge codes


PTI DC45.1-18

Recommendations for Stay Cable Design, Testing, and Installation

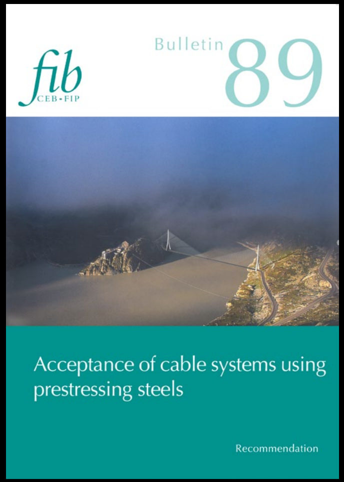
pti POST-TENSIONING INSTITUTE


Setra

LCPC

Cable Stays

Recommendations of French interministerial commission on Prestressing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Bulletin 89

Acceptance of cable systems using prestressing steels

Recommendation

Cable-supported bridges

Cable-stayed bridges – Structural Response

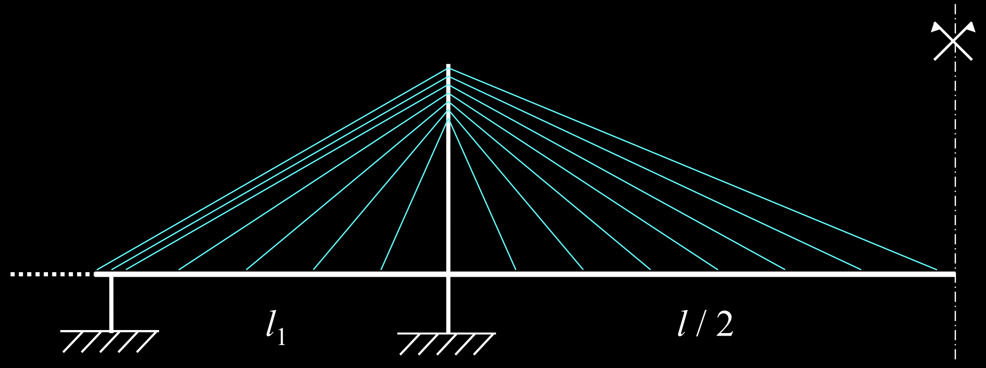
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

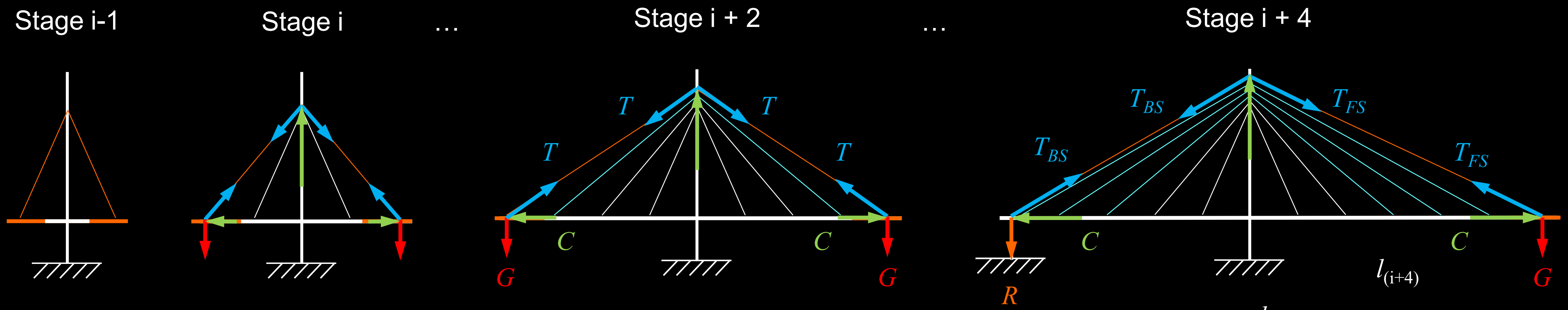
- Basic load-carrying mechanism of a cable-stayed bridge:

→ 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





$$R = G \cdot \frac{l_{(i+4)}}{l_1}$$

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

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

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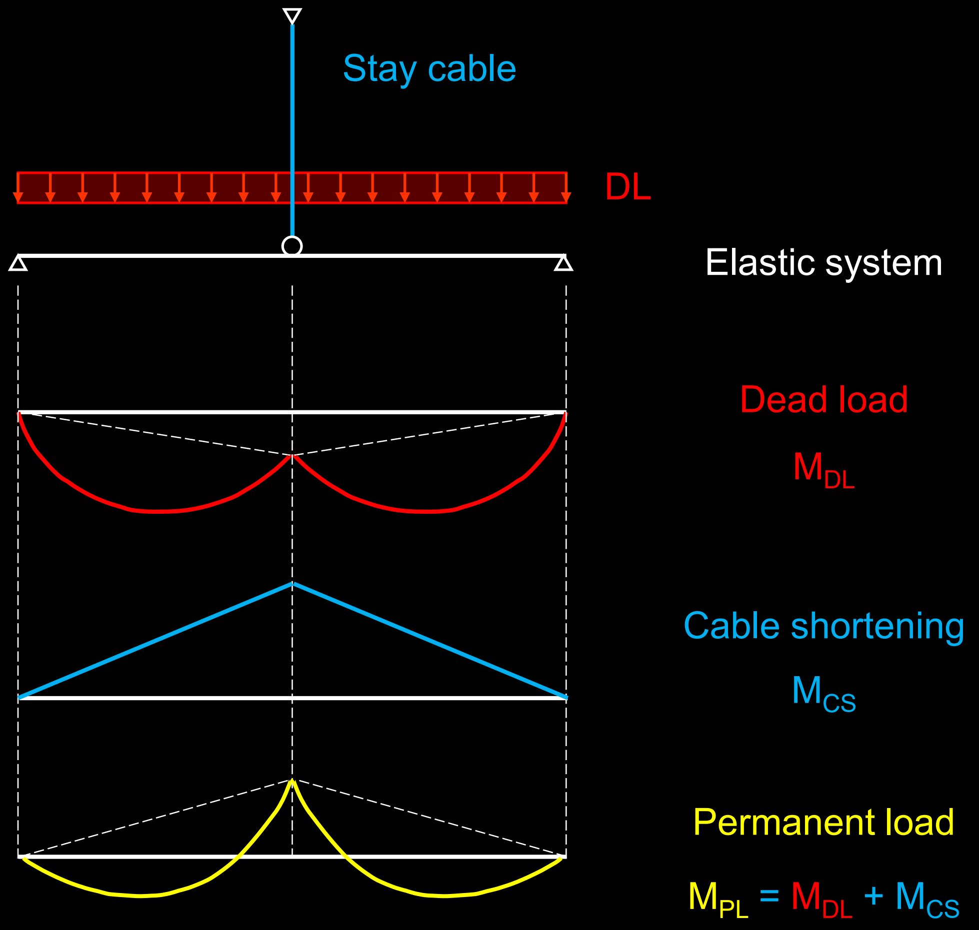
Girder:

- 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



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

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

→ Response to Dead Load:

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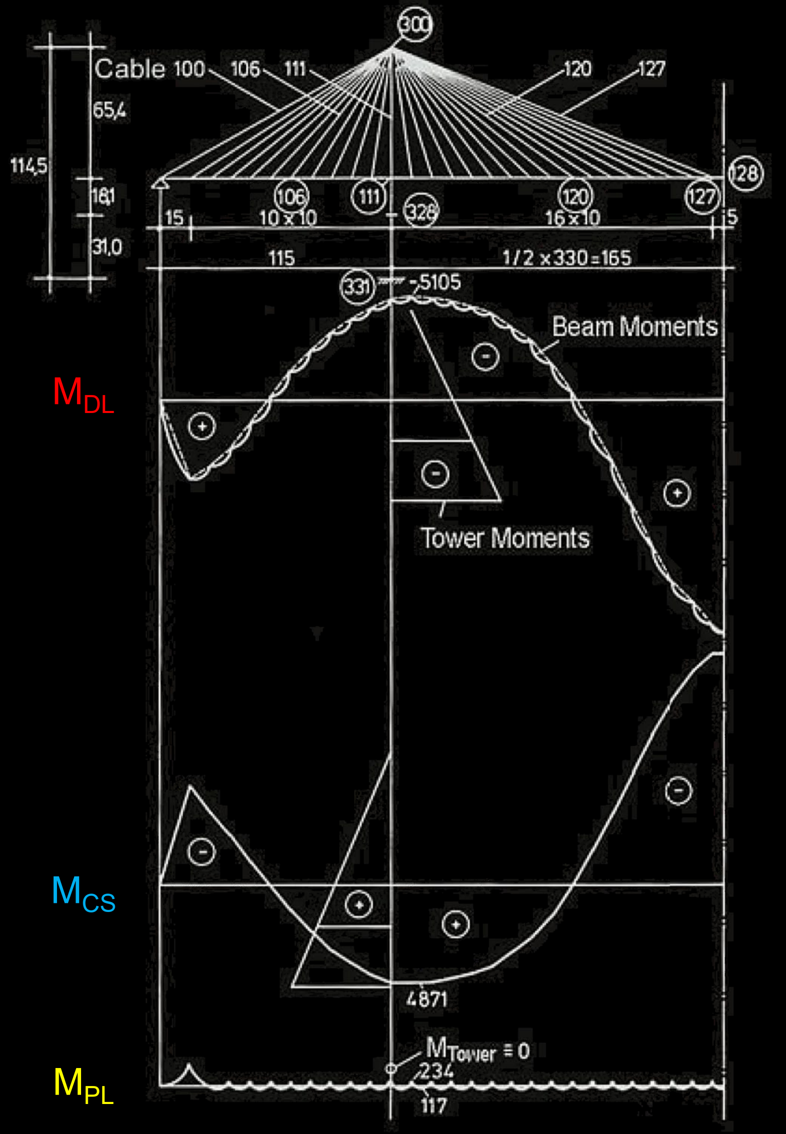


Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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

→ Response to Live Load - Characteristic Influence Lines:

Stay cables:

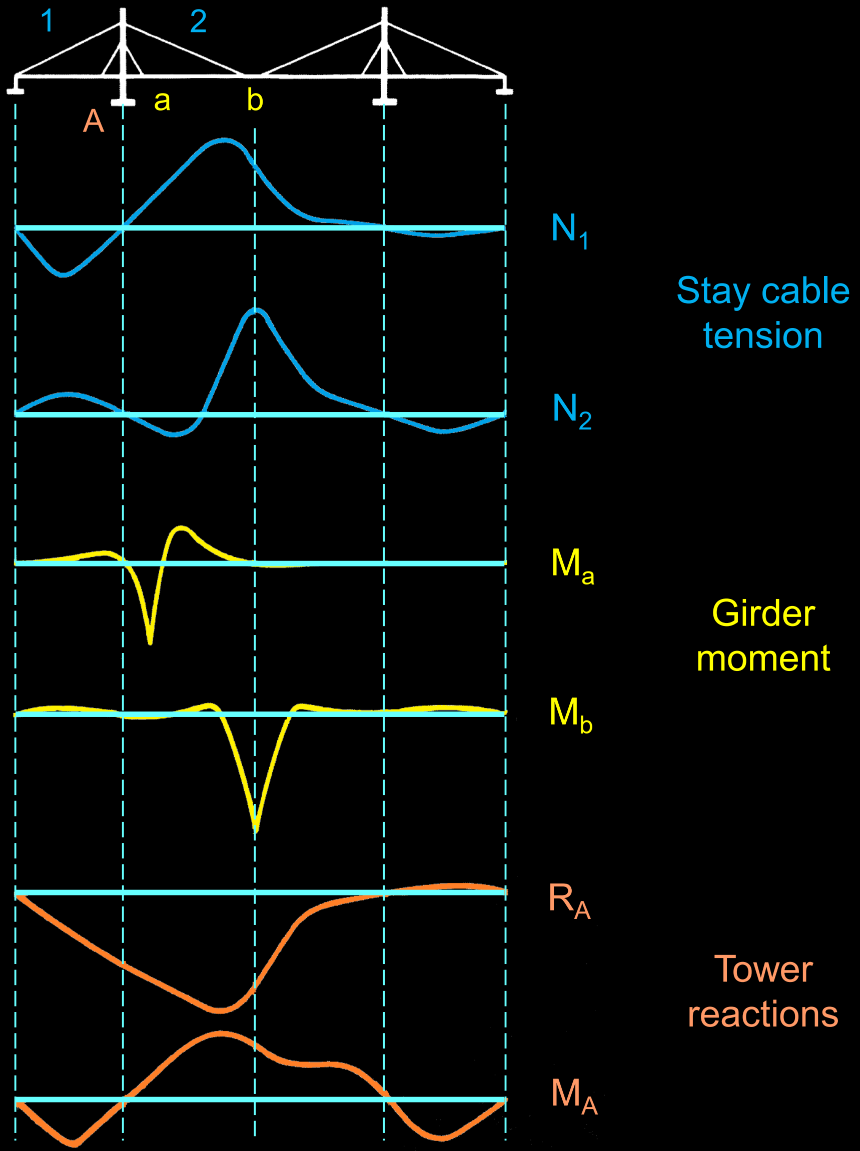
- The backstay function is fundamental to the efficiency of the bridge
- Backstays have very “broad” influence line: design controlled by fatigue in railway bridges (fatigue loads extending over large portion of span)

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)

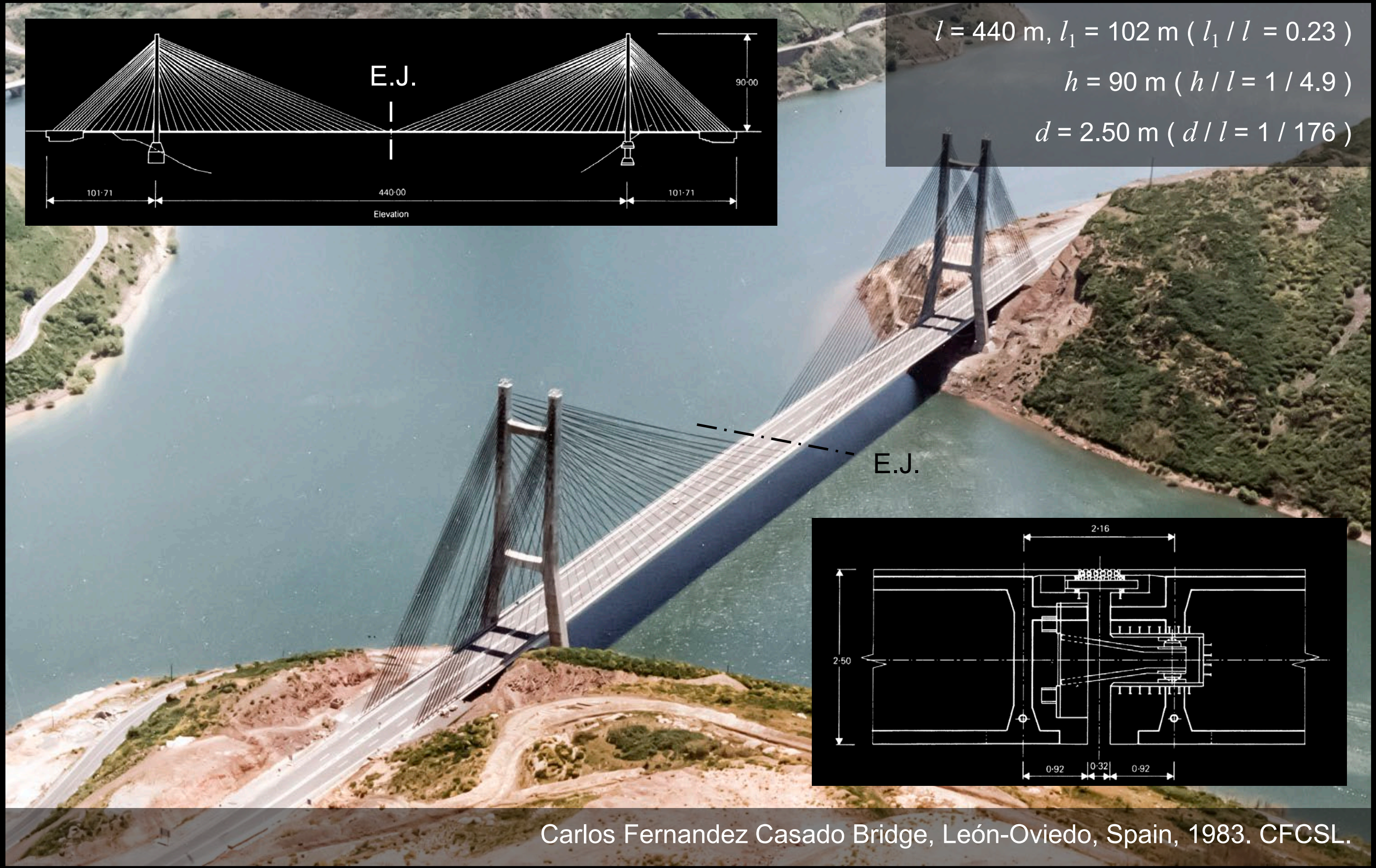


Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- 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



l = 440 m, l_1 = 102 m (l_1 / l = 0.23)

h = 90 m (h / l = 1 / 4.9)

d = 2.50 m (d / l = 1 / 176)

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

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

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    - ✓ 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

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

- Particularities of cable-stayed bridges:

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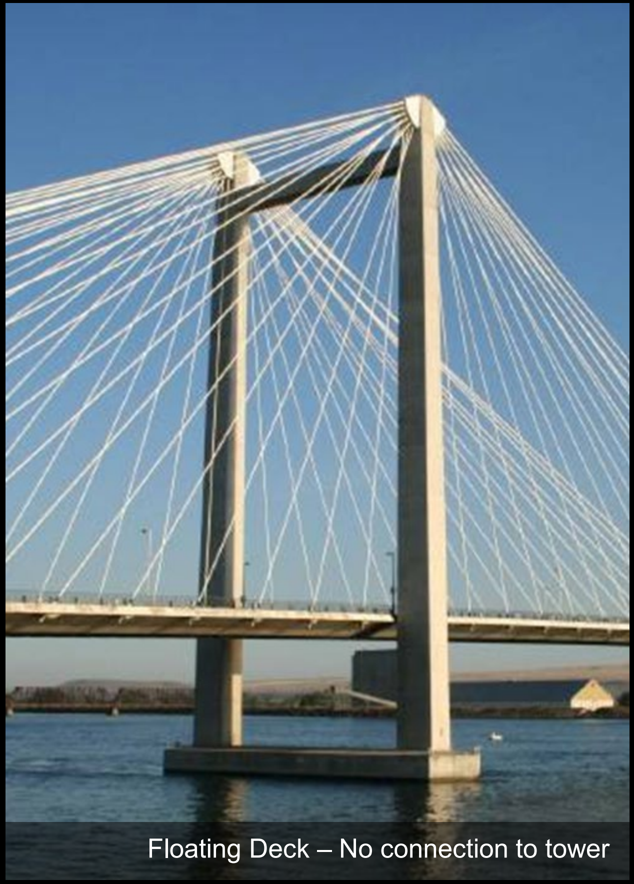
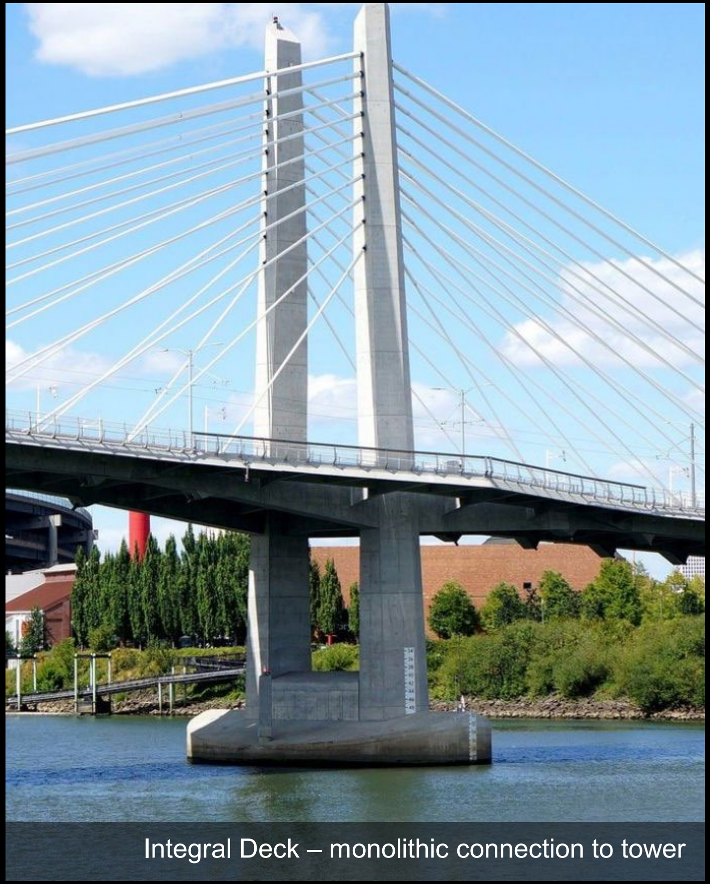

Floating Deck – No connection to tower

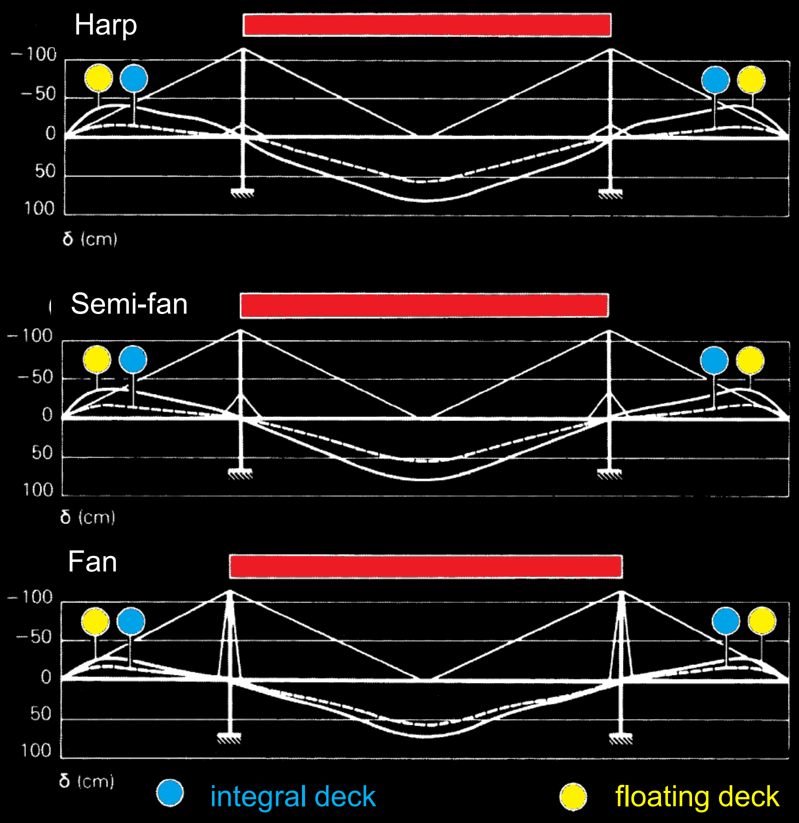

Integral Deck – monolithic connection to tower

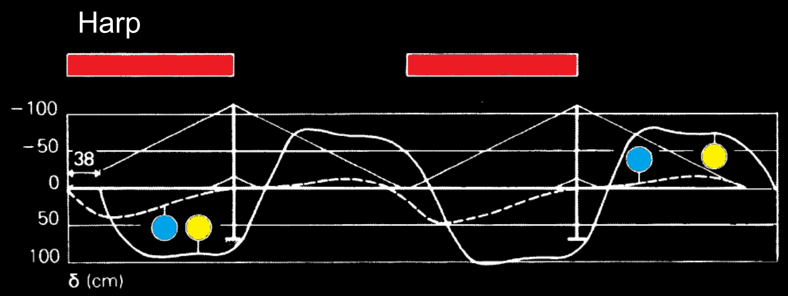
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

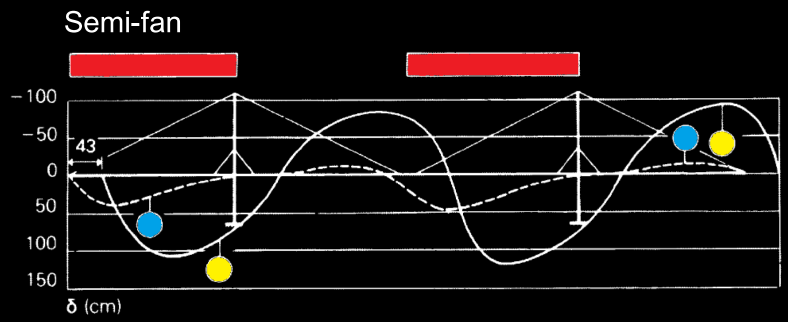
  → Support and articulation – influence of girder/tower connection [*modified after Walther et al. 1999*]:

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

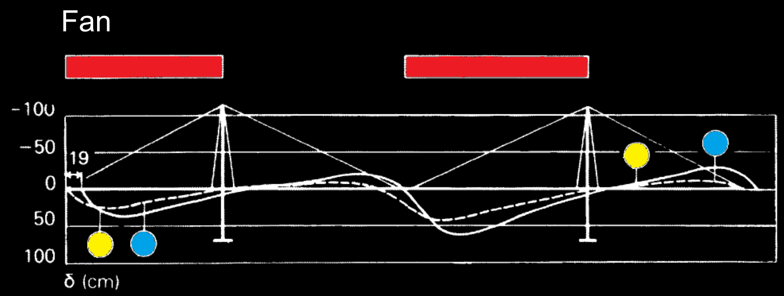




Asymmetric LL causes longitudinal deck displacement



Vertical deflections can increase 3x when deck is released



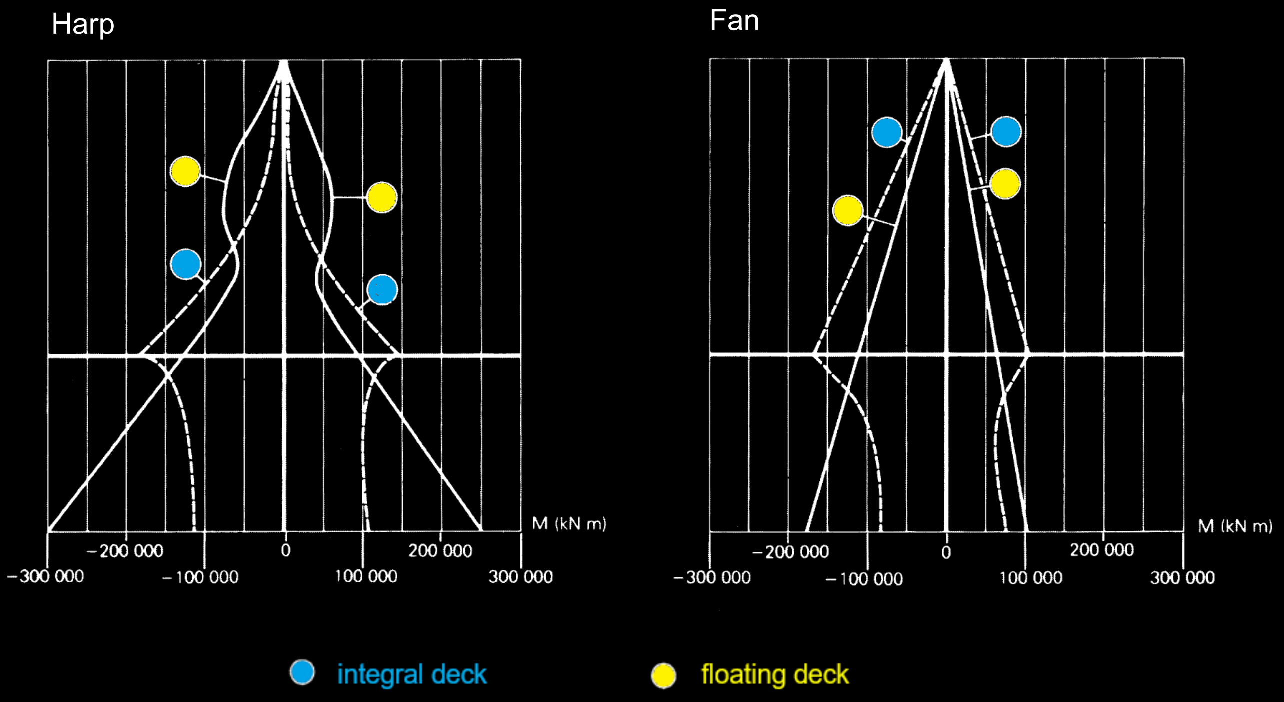
LL effects are less sensitive to deck articulation for fan pattern

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

- Particularities of cable-stayed bridges:

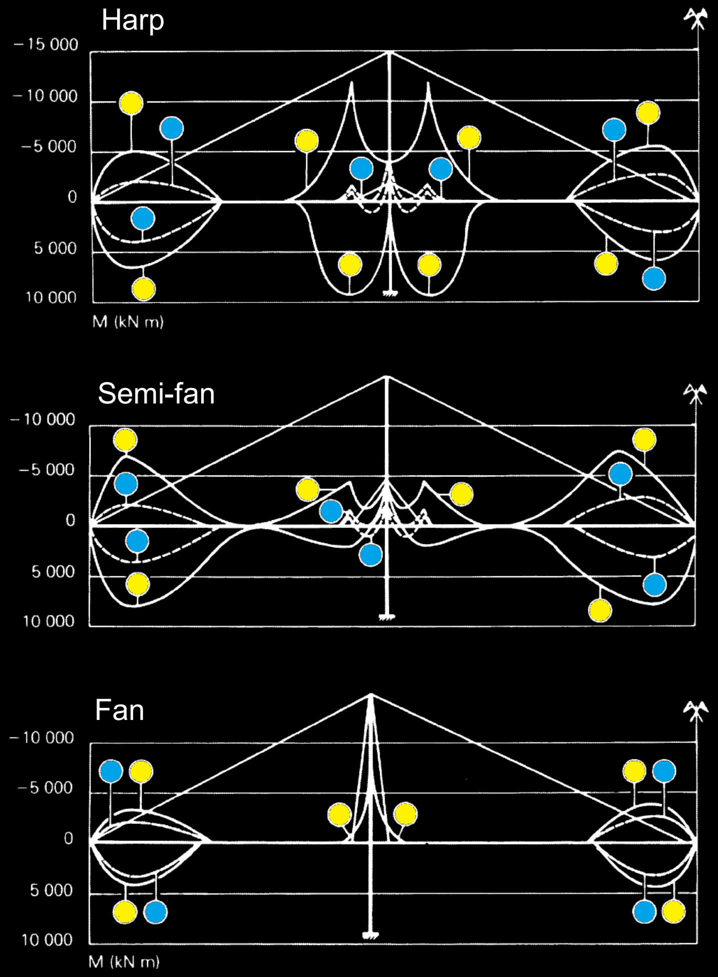
→ Support and articulation – influence of girder/tower connection [*modified after Walther et al. 1999*]:

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



● integral deck

● floating deck

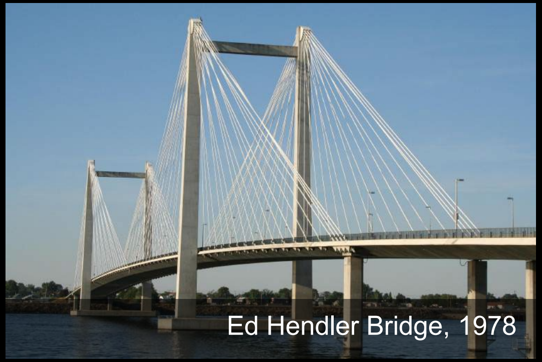


LL effects are less sensitive to deck articulation for fan pattern

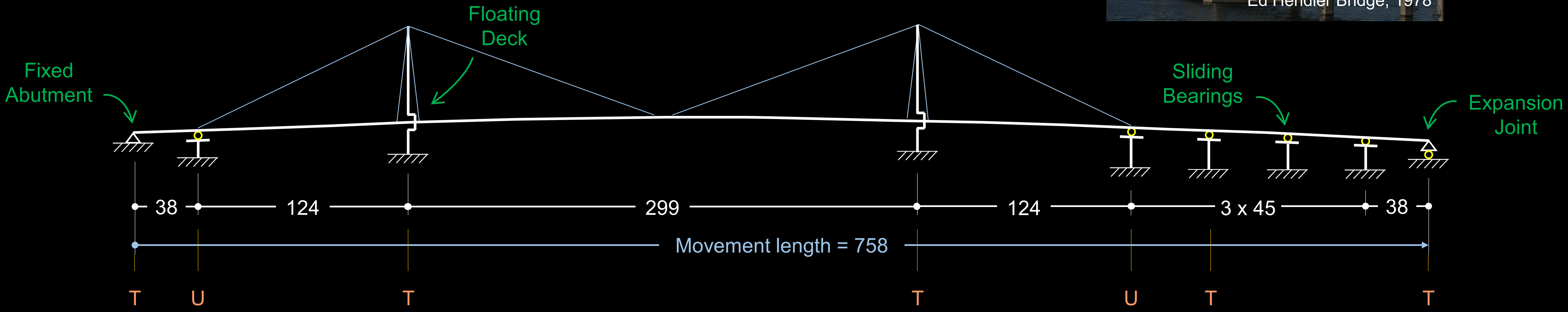
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:

→ Support and articulation – Example



Ed Hendler Bridge, 1978



T : Transversely fixed bearings

U : Uplift restraint via pendulums

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

- Particularities of cable-stayed bridges:

  → Support and articulation – Example

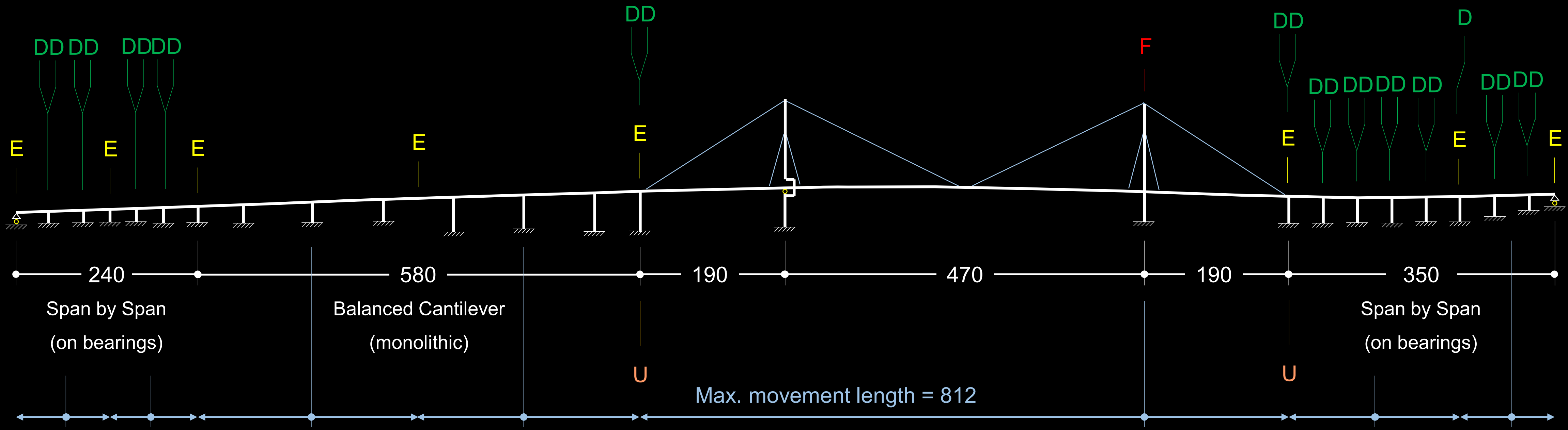
E : Expansion joint

F : Longitudinal fixed bearings

U : Uplift restraint via sliding tie-downs

D : Viscous dampers (longitudinal)

Port Mann Bridge, 2012



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 → 2^{nd} 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:

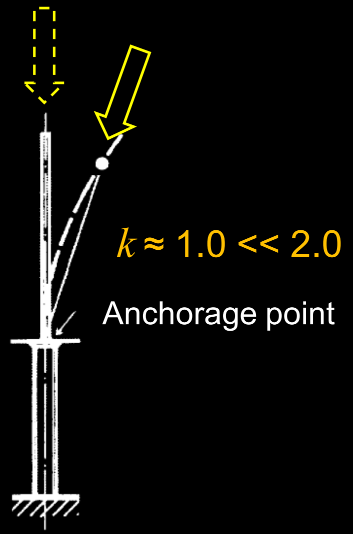
$$P_{cr} = \pi^2 \frac{EI}{(kL)^2}$$

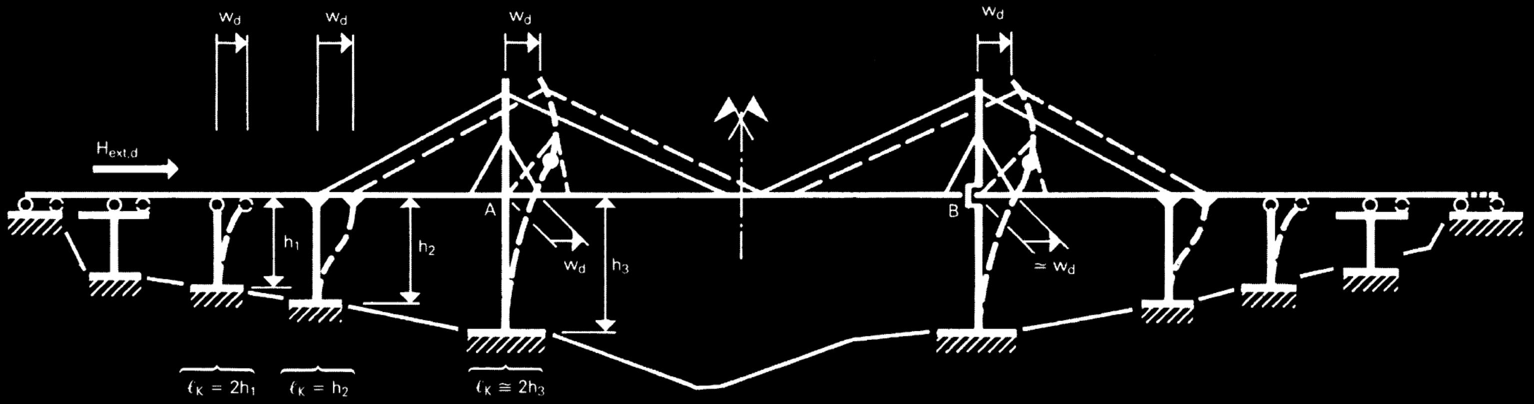
EI varies based on the level of cracking

$k_{\text{min}} = 0.8$

$k_{\text{max}} = 2.0$

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





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

- Particularities of cable-stayed bridges:

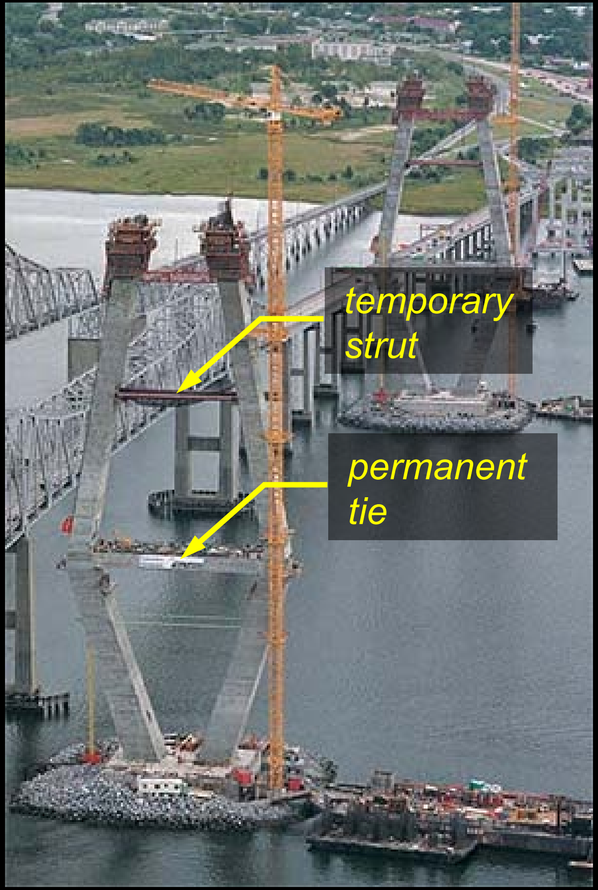
→ Tower stability - Example

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

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

- Particularities of cable-stayed bridges:

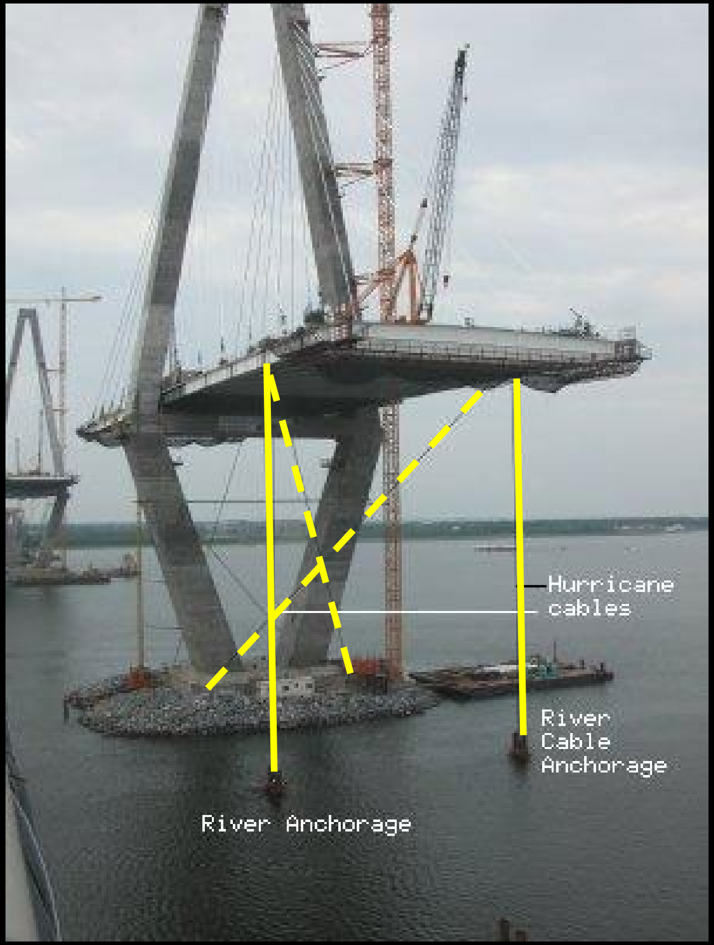
  → Tower stability - Example



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

- Particularities of cable-stayed bridges:

→ Tower stability - Example



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

- Particularities of cable-stayed bridges:

→ Tower stability - Example

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

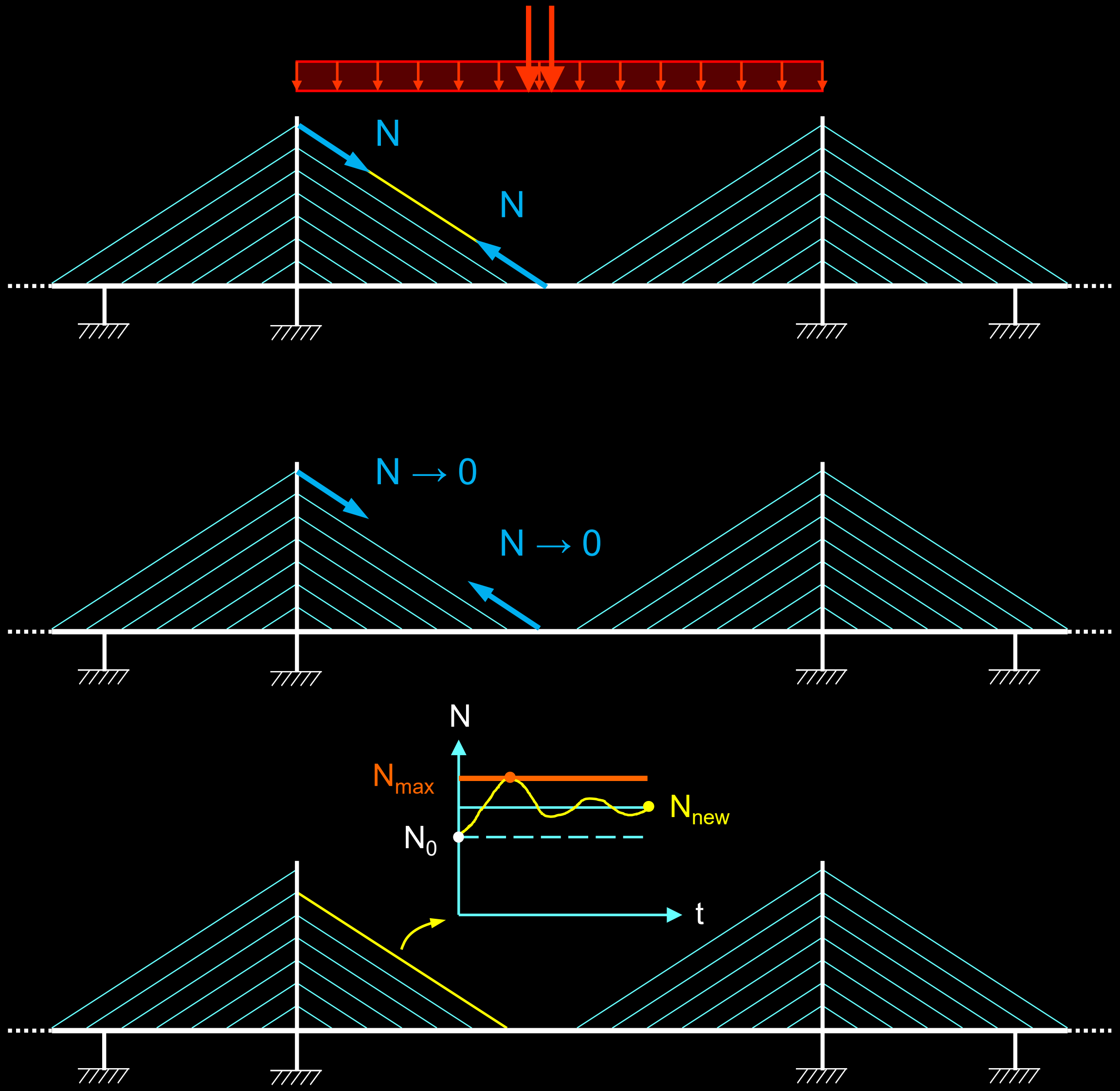
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- 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



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

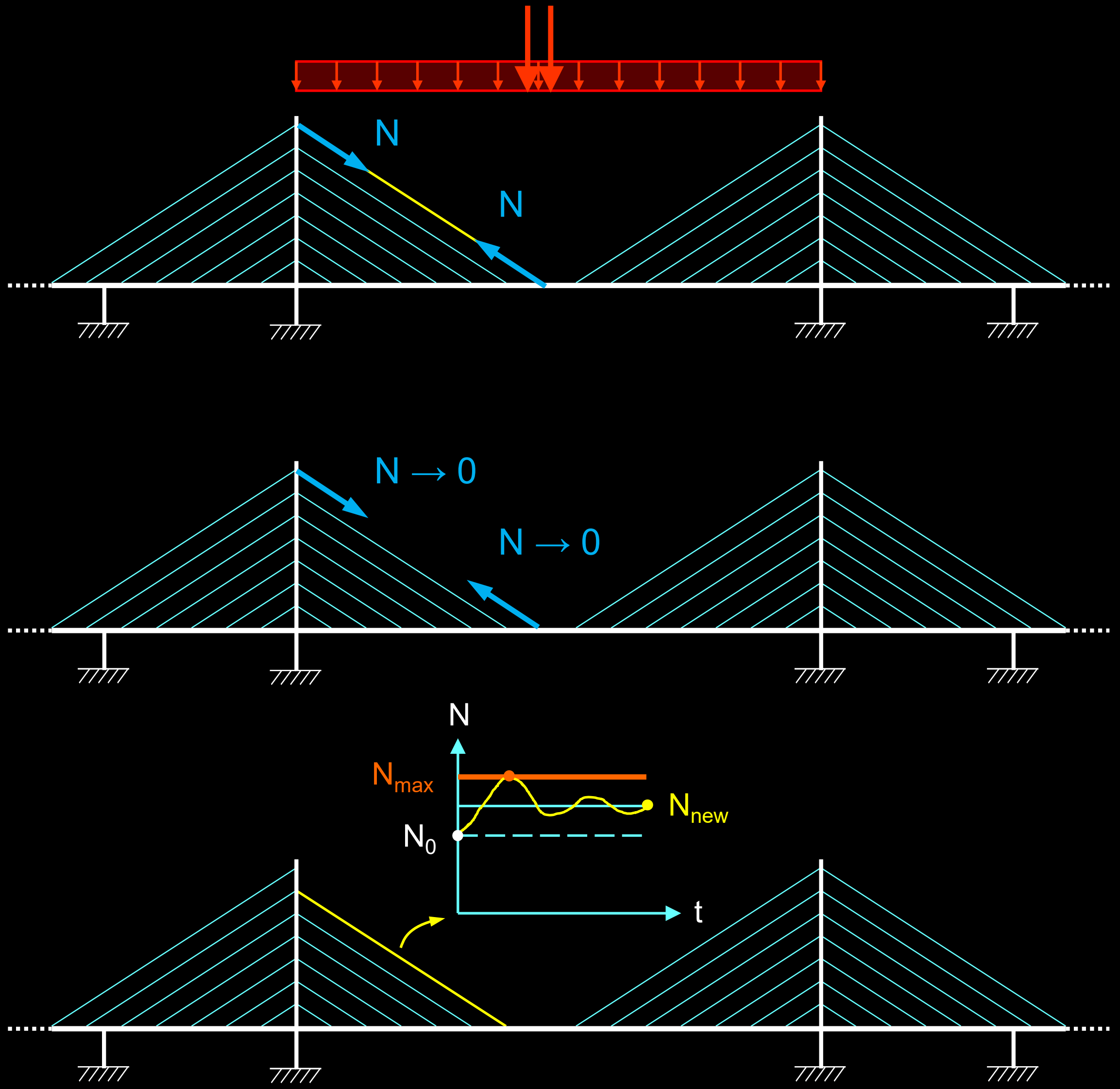
- Particularities of cable-stayed bridges:

→ 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

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



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

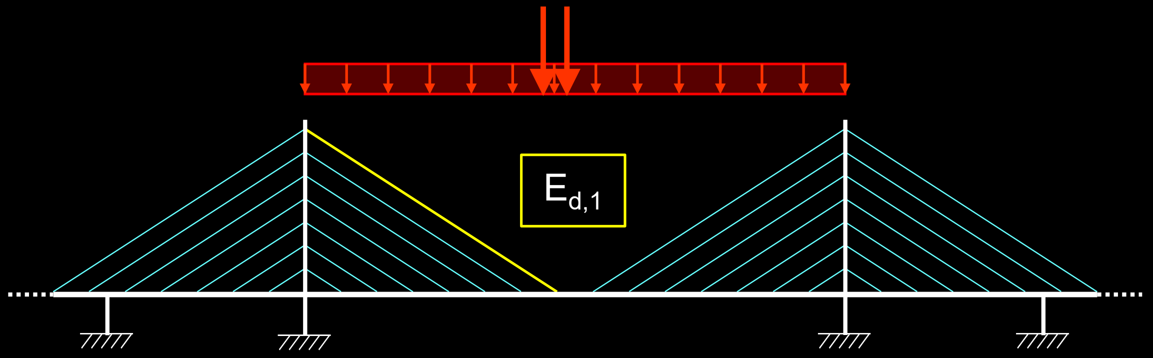
- Particularities of cable-stayed bridges:

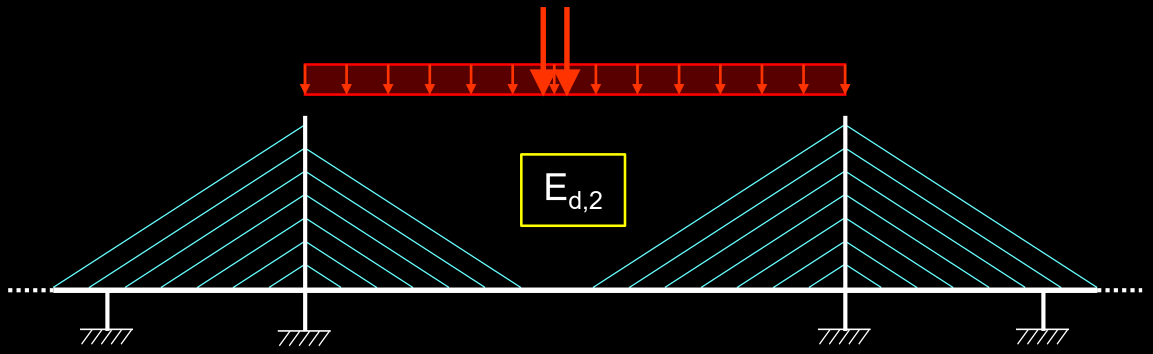
→ Redundancy requirements: Accidental cable loss

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





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

- Particularities of cable-stayed bridges:

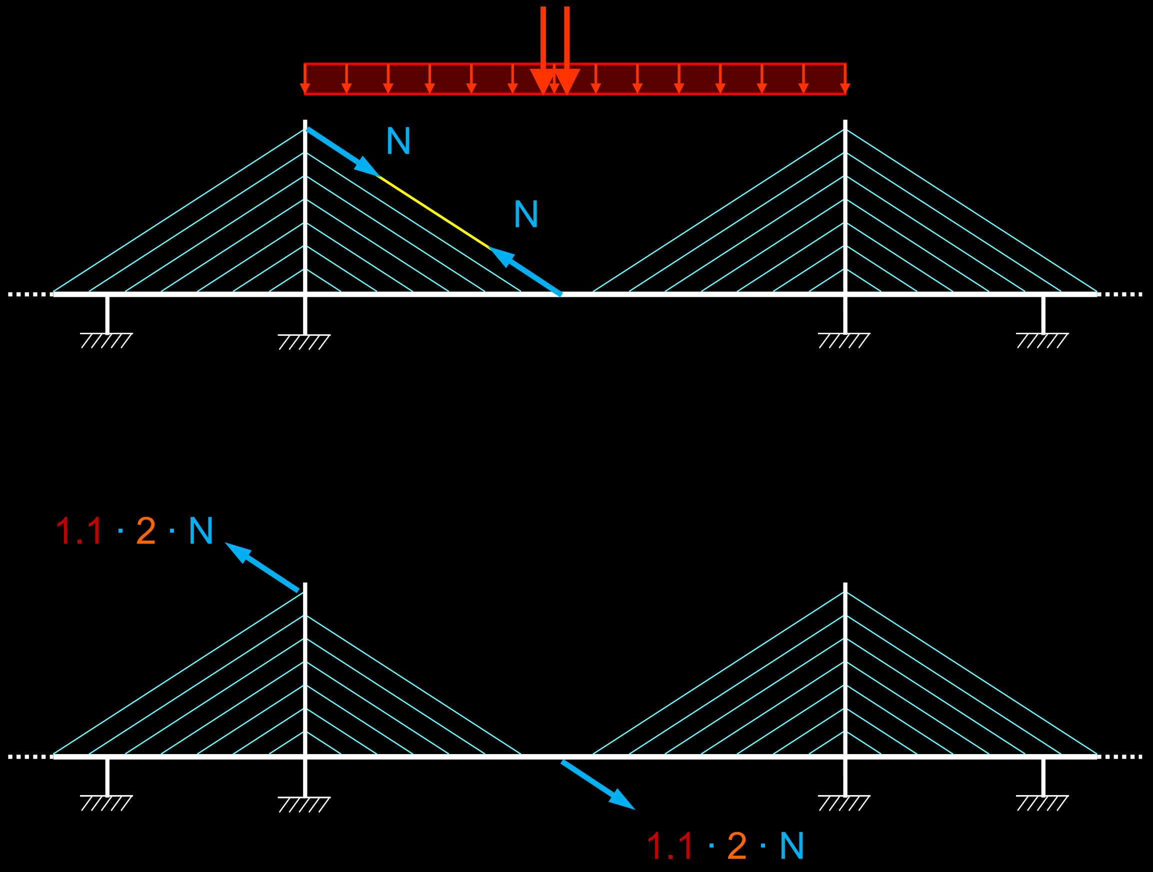
→ Redundancy requirements: Accidental cable loss

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



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

- Particularities of cable-stayed bridges:

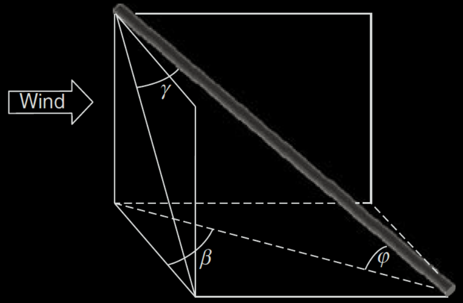
→ Stay cable vibration (see also lecture on Common Aspects)

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

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

- Particularities of cable-stayed bridges:

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

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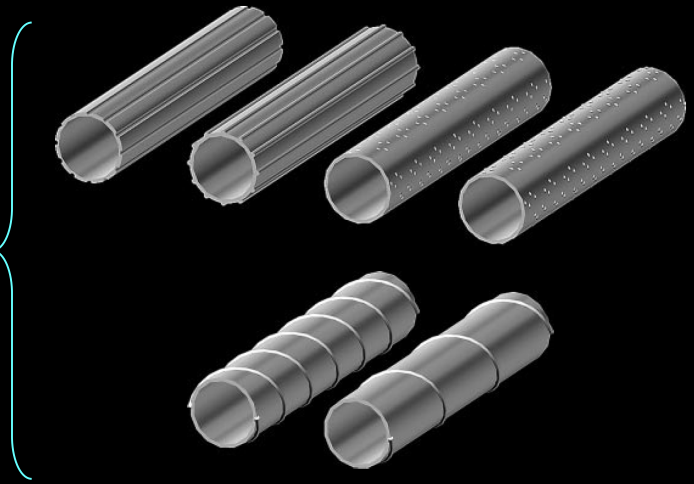
- Loading of bridge girder or towers

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

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

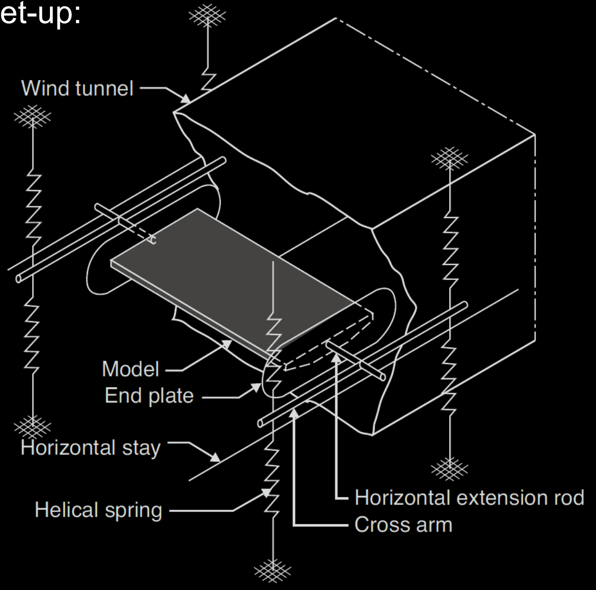
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

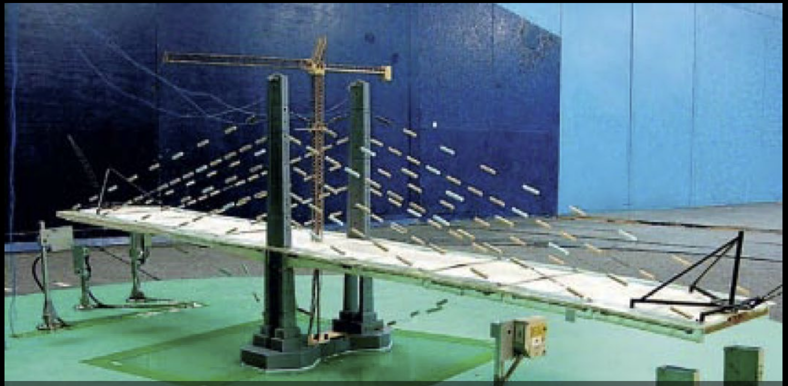
- Particularities of cable-stayed bridges:

→ 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)

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

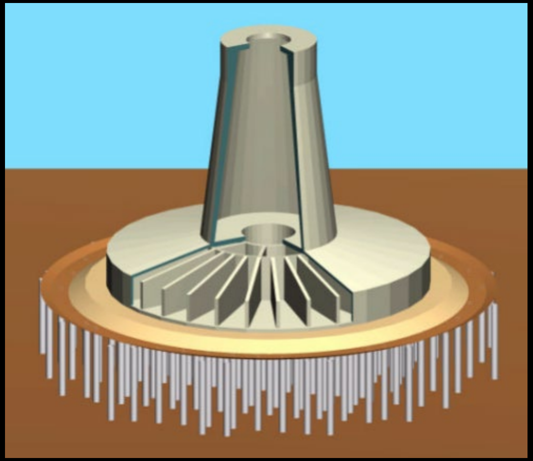
- Particularities of cable-stayed bridges:

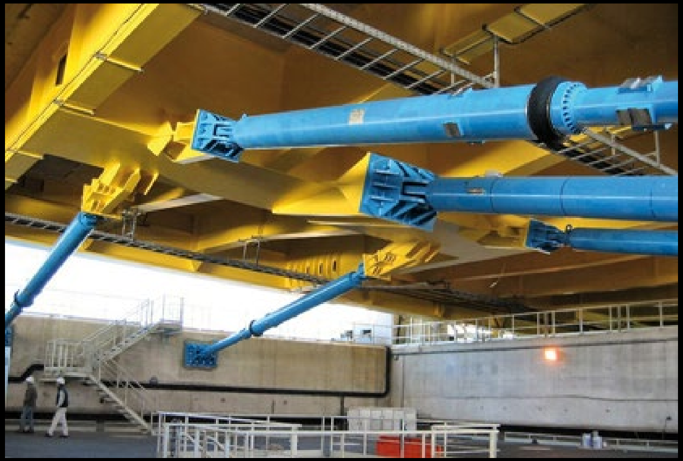
→ Seismic design

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





Cable-supported bridges

Cable-stayed bridges – Construction

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
- ○ Economical if same section can be used for approaches: Cost of forms and erection equipment is amortised over greater length
- ○ Simple lifting concept; heavy equipment required

Cable-supported bridges – Cable-Stayed Bridges: Construction

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    - Composite


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

- ✓ Repetitive & modular construction
- ○ Suitable for simple open cross sections
- ○ 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)

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:

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→ Erection method must be developed during the design process to ensure compatibility between design and erection and viability of the former

→ Guiding principles:

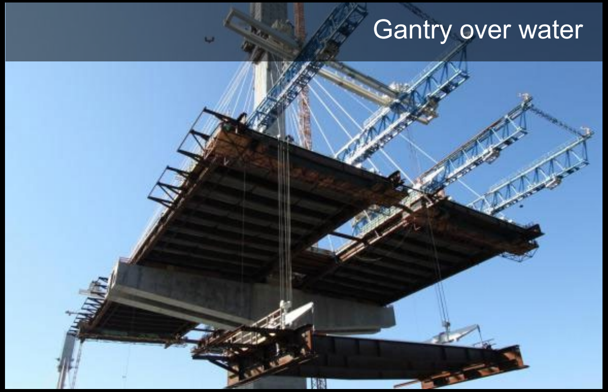
  - Simplicity
  - Repetition / Modularity

→ Common constructible girder types:

  - Precast concrete segmental
  - Cast-in-place concrete segmental
  - Composite


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

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:

→ Cable-stayed bridges are typically most vulnerable during erection

→ Geometry Control:

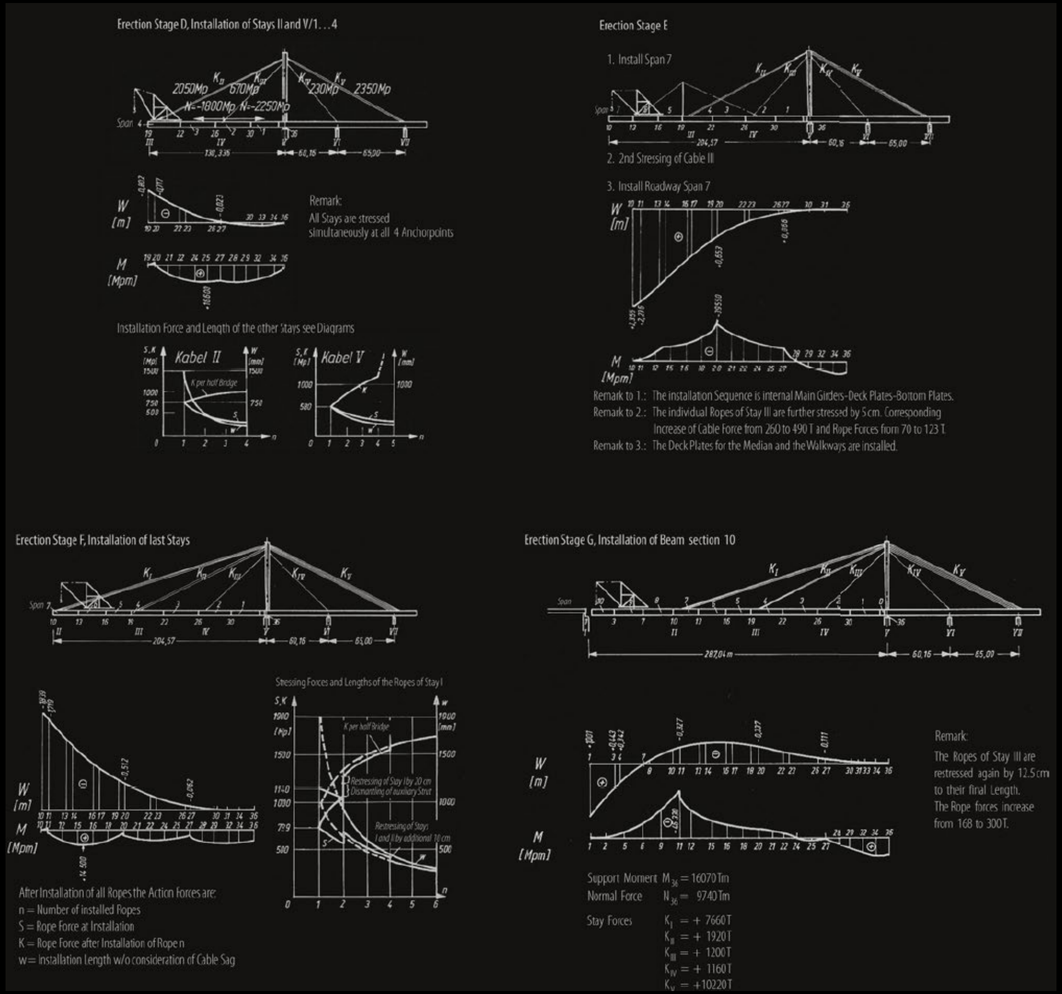
Assembly of information and methodology, used to control positions and dimensions of structural elements during erection (x, y, z, t)

- 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:



Erection Stage D, Installation of Stays II and V/1…4

Remark:
All Stays are stressed simultaneously at all 4 Anchorpoints

Installation Force and Length of the other Stays see Diagrams

Erection Stage E

1. Install Span 7
2. 2nd Stressing of Cable III
3. Install Roadway Span 7

Remark to 1.: The installation Sequence is internal Main Girders-Deck Plates-Bottom Plates.
Remark to 2.: The individual Ropes of Stay III are further stressed by 5 cm. Corresponding Increase of Cable Force from 260 to 490 T and Rope Forces from 70 to 123 T.
Remark to 3.: The Deck Plates for the Median and the Walkways are installed.

Erection Stage F, Installation of last Stays

Stressing Forces and Lengths of the Ropes of Stay I

After Installation of all Ropes the Action Forces are:
n = Number of installed Ropes
S = Rope Force at Installation
K = Rope Force after Installation of Rope n
w = Installation Length w/o consideration of Cable Sag

Erection Stage G, Installation of Beam section 10

Remark:
The Ropes of Stay III are restressed again by 12.5 cm to their final Length.
The Rope forces increase from 168 to 300T.

Support Moment M_{36} = 16070 Tm
Normal Force N_{36} = 9740 Tm

Stay Forces
K_I = + 7660T
K_{II} = + 1920T
K_{III} = + 1200T
K_{IV} = + 1160T
K_V = +10220T

Cable-supported bridges – Cable-Stayed Bridges: Construction

- Erection:

→ Stay cable installation:

Most effective method to control installation depends on girder type:

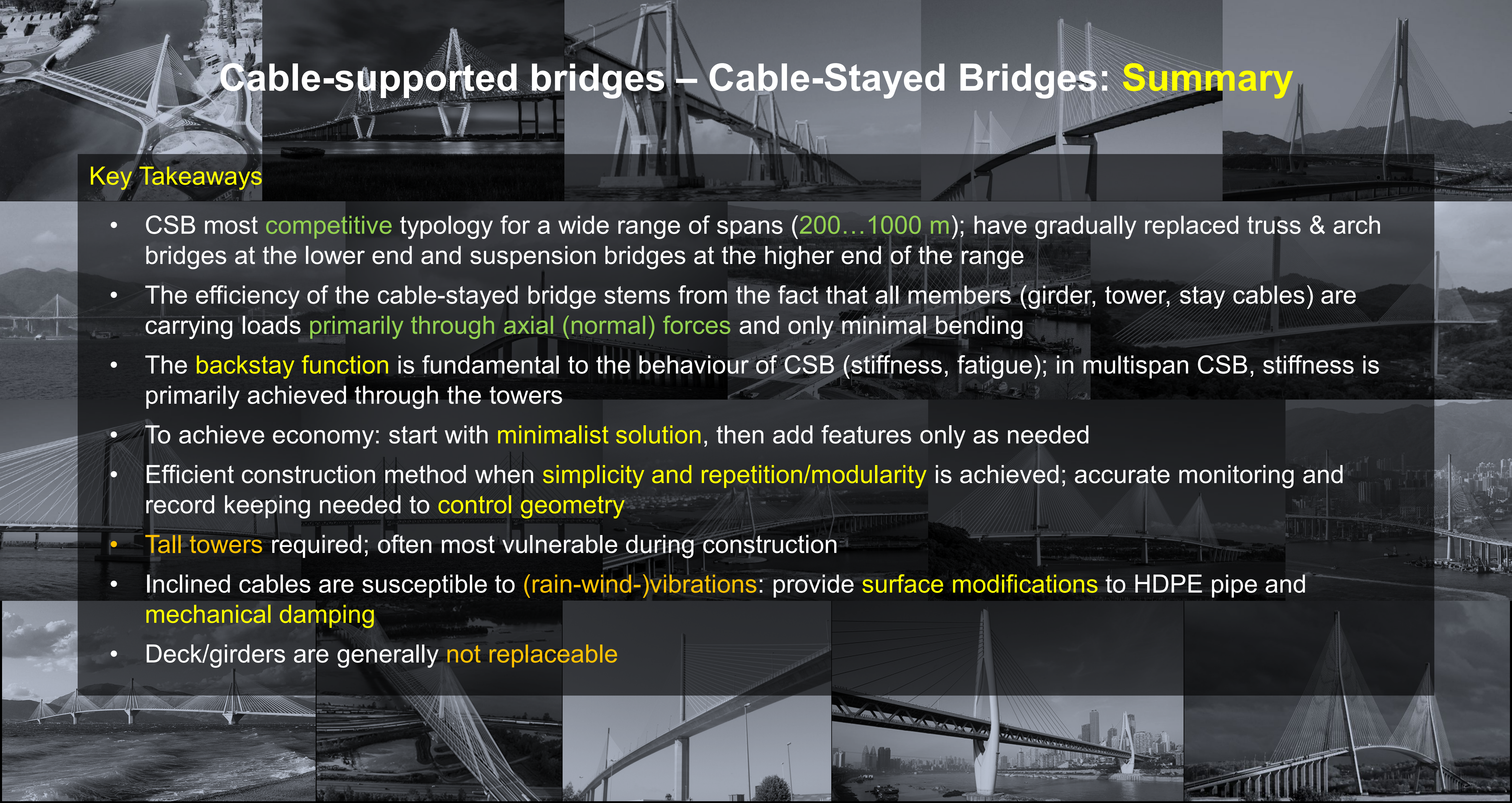
- Flexible girder: based on stay length
  - ✓ Errors in load assumptions will result in different stay forces but not in girder geometry
  - – Requires accurate surveying of as-built structure at each stage to define stay length
- Stiff girder: based on stay force
  - ○ Adjustment of stay length independent 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

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