Cable-Stayed Bridges

(Schrägseilbrücken)
Common aspects

Suspension bridges

Cable-stayed bridges

Overview

Conceptual Design

Structural Response

Construction
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

![Lérez River Bridge in Pontevedra, Spain, 1995. Carlos Fernandez Casado, S.L.](image)
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Rion Antirion (Charlados Trikoupis) Bridge, Greece, 2004. Jacques Combault
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Mersey Gateway Bridge, Cheshire, UK, 2017. COWI / FHECOR
Cable-supported bridges – Cable-Stayed Bridges: Overview

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  → Stay Cable Arrangement:
    • Fan
    • Harp
    • Hybrid (Semi-Fan)
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    - Single Plane
    - Two Vertical Planes
    - Two Inclined Planes
    - Multiple Vertical Planes
    - Multiple Inclined Planes

Puente Centerario (Panama Canal Second Crossing), Panama, 2004. TYLI / LAP
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Tatara Bridge, Hiroshima, Japan, 1999. Honshu-Shikoku Bridge Authority
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• Cable-Stayed Bridges can be classified by:

  → **Tower Configuration:**
  • Single Tower
  • “H” Tower
  • “A” Tower
  • Diamond Tower
  • Double Diamond Tower
  • Inverted “Y” Tower
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Second Meiko Nishi Bridge, Nagoya, Japan, 1997
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- 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
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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 … 1,100 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

• 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-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
    • The axial deck thrust generated by the horizontal component of the stay cables becomes too high
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 500 m

• **Concrete true arch bridges**: Require specific ground conditions to resist thrusts, spans up to 425 m

• Steel true arch bridges: High life-cycle costs, spans up to 530 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
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.
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 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).
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 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
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?
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
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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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, \(l_1/l = 0.4 \ldots 0.5\)
    ▪ Rail bridges, \(l_1/l = 0.3 \ldots 0.4\)
→ 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)
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.
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
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
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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

\[ M_{PL} = M_{DL} + M_{CS} \]
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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→ 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
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 $kL$:

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

$EI$ varies based on the level of cracking

$$k_{min} = 0.8$$

$$k_{max} = 2.0$$

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

Anchorage point

$k \approx 1.0 << 2.0$
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

- Particularities of cable-stayed bridges:
  - Tower stability - Example
Cable-supported bridges – Cable-Stayed Bridges: Structural Response

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

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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
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

$$N_{\text{max}} = N_0 + (N_{\text{new}} - N_0) \cdot DAF \rightarrow DAF = \frac{N_{\text{max}} - N_0}{N_{\text{new}} - N_0}$$
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 ($\gamma$) = 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

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    - 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
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:
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
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

- ✔ 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 equipment

Ed Hendler Bridge, Pasco/Kennewick, WA, USA, 1978. Arvid Grant & Associates / Leonhardt & Andrä
Cable-supported bridges – Cable-Stayed Bridges: Construction

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→ Common constructible girder types:
  • Precast concrete segmental
  • Cast-in-place concrete segmental
  • Composite

✓ 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)

Sidney Lanier Bridge, Brunswick, GA, USA, 2003, TYLI
Cable-supported bridges – Cable-Stayed Bridges: Construction

- Constructibility Aspects:
  - **Early collaboration** between designer and contractor is critical to ensure an economic design and successful execution.
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- Common constructible girder types:
  - Precast concrete segmental
  - Cast-in-place concrete segmental
  - Composite

  - 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

Port Mann Bridge, Vancouver, BC, Canada, 2012. TYLI / IBT
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)
Cable-supported bridges – Cable-Stayed Bridges: Construction

• Erection:
  → Cable-stayed 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 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.